THE ROLE OF BLANKET PEAT MOORLAND MANAGEMENT IN THE GENERATION AND AMELIORATION OF DISCOLOURATION OF SURFACE WATER SUPPLIES

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ABSTRACT

Discolouration of surface waters in upland catchments (with associated costs of water treatment and resources) has increased particularly since the severe droughts in the 1970s and mid 1990s. Such discolouration is a major concern for many water companies whose catchment areas include upland moorland, particularly those areas located on deep blanket peat soils.

The principal aim of this study was to evaluate the role of catchment management in the production of discoloured surface runoff and DOC flux from catchments used as gathering grounds for public water supply. The investigation focused on blanket peat moorlands in the Ladybower catchment from which water is treated at Bamford Treatment Works. Whilst other workers have considered management techniques for water colour amelioration at laboratory and plot scale, no previous study had evaluated the impact of these approaches at a catchment scale with a sufficient degree of experimental control. Baseline relationships between meteorological inputs and hydrological responses were established during a calibration period prior to intervention in management. Six catchments were instrumented and the relationships between water discolouration and hydrological and land management characteristics were identified. Suitable pairings of catchments were determined with similar characteristics. One catchment was then treated to a management practice, whilst the management on another was not affected. It was then possible to assess the impact of management on the treated catchment in comparison with the untreated catchment. Following controlled intervention in management on three of the catchments (gullies blocked, cessation of burning and removal of grazing), all study sites were monitored for a further three years to identify and quantify changes in hydrological response, water discolouration and DOC flux and predict responses post-management intervention.

The results found that water colour and DOC flux increased on all catchments irrespective of changes in land management, although in the final year there was some recovery. On the paired control sites, where management was not manipulated and similar meteorological conditions prevailed; there were no statistically significant changes from that predicted for true colour and runoff. On the manipulated catchments there were significant changes from that predicted by the control which suggests that management practices contributed to changes on these catchments. Whilst the true colour increased at the gully-blocked site ($p = 0.09$), the observed colour was lower than predicted on the catchments where burning had ceased ($p = 0.891$) and grazing was removed ($p<0.01$). On all catchments there was a reduction in runoff and DOC flux from that predicted; significant at the gully-blocked catchment and where grazing was removed ($p<0.01$), but where burning ceased the change was only weakly significant ($p = 0.085$) or not significant ($p = 0.4$) respectively. Although the results have identified changes in hydrological conditions and colour/DOC response following the manipulation of practices, there is an on-going need for investigation of longer term effects of such interventions, to identify sustainable catchment management practices and to ameliorate further deterioration of surface water quality.

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1 INTRODUCTION

1.1 Purpose of the Study

The principal aim of this study was to evaluate the role of upland catchment management in the generation and amelioration of discoloured surface water supplies, using a paired catchment approach. Whilst other workers have considered management techniques for water colour amelioration at laboratory and plot scale, no previous study has evaluated the impact of these approaches at a catchment scale where a sufficient degree of experimental control has been maintained. This study in the catchment of the River Ashop, Derbyshire, has involved a high degree of cooperation from Severn Trent Water, the National Trust and Natural England (previously English Nature). It seeks to consider the impact of three management practices on the runoff of discoloured water. These are:

i) Blocking of gullies in the eroding peat;

ii) Management of burning;

iii) Grazing density and grazing exclusion.

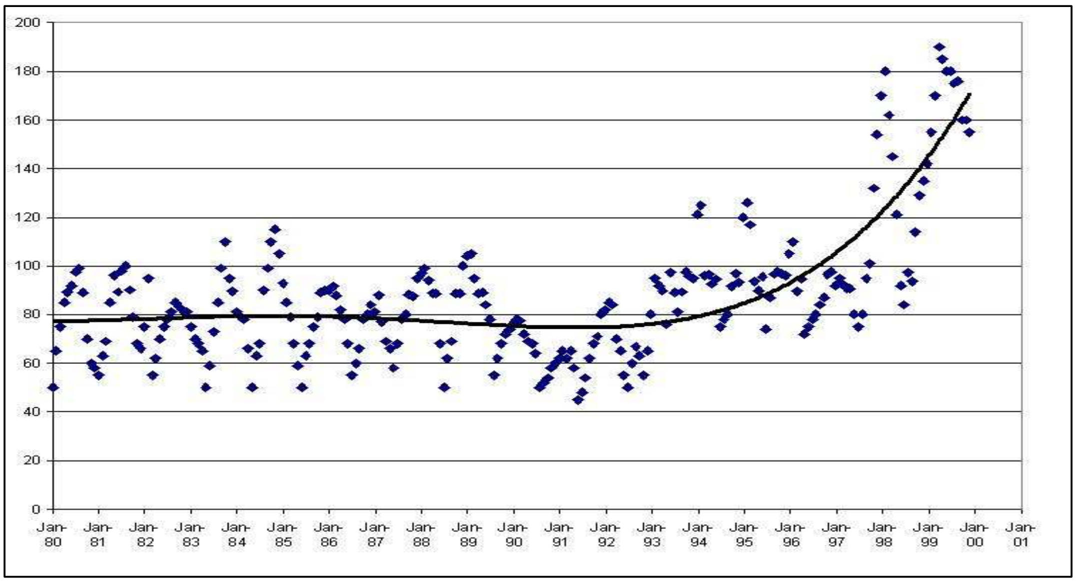
1.2 Background to Water Discolouration in Water Supplies

Water supply in the UK has been of increasing concern to water companies, government organisations and the general public, particularly in the light of recent problems from two extremes: droughts and flooding (Gray 2008). Concern about water purity has focused attention on the quality of water supplies and whilst the problem experienced in the UK might be considered minor when compared globally, there is still a concern over the potential deterioration of supply and its treatment which may result in rising costs (Pattinson *et al* 1995, Gray 2008).

Terrestrial water supplies contain natural organic matter (NOM) which occurs following the interactions between the hydrological cycle, biosphere and geosphere. The organic matter can impart colour to water and although discoloured water may be considered a relatively minor problem at a national level, it is a major concern to those water companies and consumers whose supply comes directly from upland catchments predominantly covered in peat soils. The use of such areas as major gathering grounds for water supply makes its discolouration particularly relevant as upland reservoirs supply one third of water consumed in the UK (Mitchell and McDonald 1991). The percentage of water supplied by this method is much greater in areas of the country where upland catchments are large and rainfall is high such as the Pennines and Wales. In these areas direct supply reservoirs are used almost exclusively and the problem of water discolouration is well recognised.

The issue of discoloured water is not a new one, but a significant aspect of this problem is that it is on the *increase*. Since the droughts experienced in the mid 1970s and 1990s, the incidence and significant of colour "flushes" has become more apparent. The levels of colour, especially in the Pennines, have been shown to be non-stationary, both temporally and spatially over the last thirty years. Figure 1.1, for example, shows the levels of water colour recorded at Ewden Beck in the Pennines from 1980-1999 by Watts *et al* (2001) and shows the non-stationarity of colour with a significant rise in the mid 1990s. They found that the normal seasonal flushing out of colour was disrupted both during and following drought periods (seen at Ewden 1990-1992 and 1997-1998) with colour levels being reduced immediately after a severe drought, followed by an increase in colour on recovery (Watts *et al* 2001).

Figure 1.1: Water Colour (°H) at Ewden, 1980-1999 (adapted from Watts *et al* 2001)



1.3 The Problem of Water Discolouration in Water Supplies

1.3.1 Aesthetics of Water Discolouration and their Regulation

Whilst water colour in itself is not thought to be harmful to health, its appearance can be aesthetically unappealing and can result in a rapid increase in consumer complaints (Martin 1992, Pattinson 1994, Gray 2008). The standards for drinking water quality in England and Wales are controlled by a number of bodies. The World Health Organisation (WHO) set guidelines for drinking water in 1993 and the European Union (EU) have issued a number of directives to control drinking water quality standards by the member states (Europa 2006). Each member state has since transposed the Directives into their own statutory legislation.

Most of the present standards for drinking water quality in the UK derive from the EC Directive 80/778/EEC Water Supply (Water Quality) Regulations, recently updated by the Drinking Water Directive (EC98/83). The objective of the Drinking Water Directive is to protect the health of the consumers in the European Union and to ensure the water is "wholesome and clean" (free of unacceptable taste, odour, and colour) and has a pleasant appearance (Europa 2006)

These standards have been implemented in England and Wales under the Water Supply (Water Quality) Regulations 2000 which set the present standard for colour in treated drinking water at 20 mgl^{-1} PtCo (°H) (HMSO 2000). Colour which breaches this level is easily observed by the consumer and accounts for over 50% of public complaints to water companies (Drinking Water Inspectorate 2003).

1.3.2 Health Risks Associated with Water Discolouration

Twenty-three water companies in England and Wales are responsible for supplying wholesome and clean potable drinking water to consumers which must comply with the Water Supply (Water Quality) Regulations 2000 and so achieve the set parameter of 20 mgl^{-1} PtCo (°H) (measurable at the consumers taps') (Gray 2008).

In order to accomplish this in terms of water colour, it is necessary to remove natural organic matter (NOM) (humic and fulvic acids and non-humic hydrophyllic material) through treatment processes such as coagulation, adsorption and membrane filtration, but this usually only removes NOM of a higher molecular weight (Scott *et al* 2001, Sharp *et al* 2006).

Certain health risks have been tentatively associated with these treatment processes. For example, coagulants such as aluminium-based substances have been linked with dialysis encephalopathy (dementia) and Alzheimers disease (Kim *et al* 2002).

The use of oxidants such as chlorine, chloramines and ozone to treat water can lead to the formation of disinfection by-products (DBPs) (White, S *et al* 2003). Increasing concentrations of NOM can create raised levels of by-products such as trihalomethanes (THMs) or haloacetic acids (HAAs) which are recognised as human carcinogens (Galambos *et al* 2004). Ozone, used to remove micro organisms, is also associated with organic and inorganic DBPs. However, the health risks associated with such treatment processes should be kept in context as the likelihood of contracting rectal, colonic or bladder cancer is negligible compared to difficulties arising from abandoning the chlorination treatment process (Woodruff *et al* 2001, Chow *et al* 2003). Although drinking water discoloured by carbon does not appear to be associated with health risks *per se*, the consumers desire to consume a "sparkling" glass of water may well put them at risk due to the reaction of the chlorination treatment on DBPs.

1.3.3 Carbon Loss

Blanket bogs make up much of the upland catchment areas used for water supply and these are essentially unbalanced ecosystems where the rate of accumulation of plant biomass exceeds that lost by decomposition. As a result they are also recognised globally as an important component of terrestrial carbon storage, sometimes referred to as a 'sink' as they contain a high proportion of partially decomposed organic matter of which approximately 50% is organic carbon (Garnett *et al* 2001, Holden *et al* 2006a).

Carbon may be released from peat into water in a number of forms including dissolved organic carbon (DOC) and particulate organic carbon (POC) as a result of the process of humification (Worrall *et al* 2002) and subsequent release of humic and fulvic acids (Scott *et al* 2001, Dawson *et al* 2002). Dissolved organic carbon (DOC) is made up of a mix of humic macromolecules that are known to impart a strong yellow/brownish colour to water (Glatzel *et al* 2003, Evans *et al* 2005a). Water colour and DOC are known to be strongly associated in the uplands (Freeman *et al* 2001a, Worrall *et al* 2003) and therefore the increase in water discolouration may suggest that the loss of carbon is also increasing.

Recent research has therefore focused on investigating the fluvial carbon flux from peatland catchments which are also the providers of water supply. Hope *et al* (1997), Dawson *et al* (2002) and Worrall *et al* (2003) have all estimated DOC flux and identified it as the most significant form of carbon export. For example, Hope *et al* (1997) estimated 77% of DOC contributed to the annual fluvial carbon loss for British rivers as a whole during 1993.

Estimating the losses of water colour (and DOC) from a peat catchment in response to environmental factors such as climate change and land management practices is therefore important in understanding the long-term response of peatlands and their capacity to continue to act as a sink for carbon.

1.4 The Treatment of Water Colour

1.4.1 Traditional Treatment – Water Treatment Works

Water colour (associated with dissolved organic matter) has traditionally been reduced at water treatment works (WTW) and the removal of natural organic matter (NOM) from potable water supplies has been recognised as important in terms of its potential to form carcinogenic disinfection by-products (DBPs) if insufficiently removed (see Section 1.3.2). The presence of NOM can significantly affect aspects of water treatment such as oxidation, coagulation, adsorption, application of disinfectants and stability (Matilainen *et al* 2002). These various treatment processes can remove NOM from raw water directly or indirectly and in varying degrees, depending on the operational conditions and specific characteristics of NOM. In particular, the molecular weight distribution affects the removal of colour, with high molecular weight (HMW) NOM more amenable to removal than low molecular weight (LMW) (Collins *et al* 1986).

Traditional treatment with trivalent coagulants was used at WTWs for the removal of NOM in the past and this proved to be a successful approach, but in the last ten years the rapid changes in organic levels have generated significant operational difficulties in the UK during certain periods of the year when the organics are high (Sharp 2005). This has resulted in inadequate removal of NOM, the formation of fragile flocs and increased particulates into the downstream processes such as filtration. Insufficient removal of NOM can produce the potentially carcinogenic disinfection by-products (DBPs) formed when the residual organics react with chlorine during disinfection (Singer 1999). Table 1.1 shows the current options and effectiveness of DOC removal.

Table 1.1: Options and Effectiveness of DOC Removal used at Water Treatment Works

Treatment process	Percentage Removal (%)	Reference
Membrane filtration	80-90	Amy and Cho, 1999 Pikkarainen *et al* 2004
Ion exchange/adsorption	60-80	Fu and Symons 1990 Summers and Roberts, 1998
Ozonation/biodegradation	25-75	Goel *et al* 1995 Graham 1999
Coagulation with cationic additives	10-60	Croué *et al* 1993, Edzwald 1993, Volk *et al* 2000

The use of membranes and activated carbon are recognised as being highly efficient, but costly and therefore the current preference for the removal of NOM is the more cost-efficient, but less effective coagulant with metal additives such as alum and ferric salts used in conjunction with physical separation processes such as sedimentation or dissolved air floatation (Sharp *et al* 2006). According to researchers however, this only removes 10-60% of NOM (Croué *et al* 1993, Edzwlad 1993, Volk *et al* 2000). Therefore a pro-active approach of reducing NOM at source, that is, within the catchment, may be considered a possible alternative. This is discussed in Section 1.4.2.

1.4.2 Alternative Treatment – Sustainable Catchment Management

The problem of water colour may be exacerbated by traditional upland management practices, although there has been a lack of scientific evidence to support this theory (Stewart *et al* 2004, Glaves *et al* 2005). Moorland management practices such as burning and grazing are known to contribute to blanket bog erosion and degradation (Anderson *et al* 1997, Bragg and Tallis 2001, Evans 1997, 2005). Anderson (1986) and Tallis (1998) found burning regimes caused the onset of widespread erosion and exposure of bare peat, whilst intense grazing reduces the competitive vigour of plants through processes of feeding, trampling and poaching (RSPB 1995, MacDonald *et al* 1998a, 1998b, Evans 1997, 2005c). Natural erosion of gullies and increased drainage from catchments has also been associated with desiccation of the peat (Poesen *et al* 2003, Evans *et al* 2006). These practices are closely linked to water discolouration by increasing the rate of humification and run-off.

During the last thirty years attitudes to UK upland management have also changed emphasis from land utilisation for grazing and game management towards environmental protection. The UK and National Park Biodiversity Action Plans recognise blanket bog as a target habitat in need of protection and conservation, with many of the upland areas designated as Sites of Special Scientific Interest (SSSI) and nominated as candidate Special Areas of Conservation (SACs). Organisations such as Natural England are a major instigator in its protection and conservation.

More recently, it has been acknowledged that organic soils, and in particular peatlands provide a major proportion of the global supply of terrestrialised carbon (Clymo 1984, Freeman *et al* 2001a). Changes in the water budget are likely to have large effects on peatland carbon sequestration in the future, most immediately through the control of decomposition of vegetation into peat in the upper soil layers (acrotelm) (Hilbert *et al* 2000). The negative feedback into the carbon cycle from global climate change (i.e. the role reversal of the carbon store becoming a 'source' instead of a 'sink') may infer that even small changes in soil carbon stocks may contribute significantly to climate change (Cox *et al* 2000).

Landowners and farmers play an important role in the management of blanket peat moorlands with individual management practices and views having a significant impact on these upland catchments. Major landowners such as the National Trust and water companies such as United Utilities may be in a strong position to influence farmers and game keepers managing their estates. Catchment management through encouragement and enforcement of sustainable practices may be a potential supporting mechanism to the traditional approaches used at the WTWs. Pro-active measures such as rewetting catchments, sustainable burning regimes and appropriate grazing densities, may offer a more preventative and therefore more sustainable strategy for the reduction of water colour and carbon loss whilst safeguarding the ecology of these areas.

1.5 Project Aims and Objectives

The principal aim of this study was to examine the role of blanket peat moorland management in the generation and amelioration of discoloured surface water supplies, using a paired catchment approach. This was achieved by the following objectives:

i) To establish baseline relationships between meteorological inputs and hydrological responses during a calibration period prior to intervention in blanket peat moorland management;

ii) To identify paired catchments of similar morphological, pedological and land management characteristics and establish similarities;

iii) To determine the relationships between meteorological inputs and changes in water quality, runoff and DOC export on control (management unaltered) and treated (management manipulated) sites during the pre- and post-management periods;

iv) To quantify changes in hydrological behaviour, water colour and DOC export following controlled intervention in blanket peat moorland management and observe catchment responses where natural drainage processes are altered, prescribed burning stopped temporarily and grazing removed;

v) To develop a paired catchment model as a means of predicting the outcome of management manipulation on hydrological behaviour, water colour and DOC export as a means of discussing the future generation or amelioration of discoloured surface water supplies;

The project was particularly timely and relevant as it coincided with the Defra review of the Heather and Grassland Burning Code (Defra 2007) which included consideration of the implications of burning on upland moorland and the potential effects on water quality. Defra also commissioned a review of Blanket Bog Management and Restoration (O'Brien *et al* 2007) which addressed the main ecosystem services provided by upland blanket bogs, the potential causes of degradation, and a review of techniques currently in use to "restore" such land types. In addition, Natural England has published a number of research reports which consider the effects of prescribed burning on hydrology and water quality (EN Research Report No. 550: *Review of the Impacts of Heather and Grassland Burning in the Uplands on Soils, Hydrology and Biodiversity* (Tucker 2003) and EN Research Report No. 667: *A History of Burning as a Management Tool in the English Uplands. 1: Estimates of the Areal Extent of Management Burning in English Uplands* (Yallop *et al* 2005).

1.6 Structure of Thesis

The thesis is structured into ten chapters. Chapter two presents a review and detailed critique of existing literature on the composition of water colour/dissolved organic carbon (DOC) and the potential causes for its increase from sources generating largely from peat soils high in organic matter in the uplands of the UK. The causes discussed include chemical, physical and biological changes that may occur in the soils as a result of changing hydrological and climatic conditions. The effects of traditional land management practices, that is, prescribed burning and grazing on water quality and quantity are discussed, together with the impact of naturally eroding gully systems. The chapter concludes with a section on modelling of water colour/DOC as a tool to predict changes in and so determine if manipulation of land management may be beneficial to water quality.

Chapter three describes the geographical extent of water discolouration and DOC from a global and national perspective before focussing on the regional extent of water colour generating from the uplands of the UK. The trends in water colour for the south Pennines are discussed before describing the Ashop catchment where the research was completed. The site description includes sections on geology and pedology, topography and landform, vegetation and landuse. The treatment of water at Bamford Water Treatment Works (WTW) from the Ashop and surrounding catchments is also discussed.

Chapter four describes the methodologies used to complete the research. The chapter commences with an overview of the paired catchment experiment and the cluster analysis used to determine appropriate catchment pairings. The chapter then details the field and laboratory methodologies to determine changes in water quality, and methodologies to monitor hydrological conditions at the sites.

Chapter five is the first of the results chapters and describes the meteorological conditions which prevailed on the Ashop during the study. Changes in rainfall and temperature and their relationship to water colour are discussed. Monthly data from the Meteorological Office Rainfall and Evapotranspiration Calculation System (MORECS) are compared with monthly water colour data.

Chapter six discusses the changes in spatial colour and temporal annual, monthly and daily water quality across the sites; the relationship between water colour and metals (iron, aluminium and manganese), and the potential influence of land management on the observed data.

Chapter seven describes the spatial and temporal changes in runoff and DOC flux across the sites during the study and discusses the observed differences following land management manipulation on the treated sites.

Chapter eight discusses the use of a paired catchment model to determine changes in DOC, runoff and DOC flux at the treated sites where land management had been manipulated through the installation of gully blocks, cessation of burning and removal of grazing.

Chapter nine is primarily the discussion chapter and provides a synthesis of the previous eight chapters, comparing the results with previous research. The implications of the study are discussed in context with current legislation and future changes, particularly with regard to carbon loss and climate change.

Chapter ten provides a conclusion to the thesis and discusses the major findings of the study, limitations of the research and recommendations for sustainable catchment management to ameliorate water quality and carbon loss. Finally, future research requirements are suggested to further our knowledge of water quality and carbon processes.

2 REVIEW OF WATER COLOUR AND DOC: PROCESSES AND POTENTIAL CAUSES OF DETERIORATION

2.1 Introduction

An understanding of the origins, processes and potential causes of water colour in the catchment is essential in order to propose appropriate sustainable catchment management practices as a support mechanism to minimise water discolouration and potentially ameliorate water quality. This chapter reviews literature related to three major themes regarding the generation and amelioration of water colour. These are:

i) The properties of water colour and DOC;

ii) The processes involved in the generation of water colour and DOC;

iii) The potential causes of water colour and DOC which may exacerbate its production.

The chapter also reviews the techniques used to predict water colour as a tool for pro-active water treatment and catchment management to ameliorate water quality whilst minimising the degradation of catchments used for upland water supplies.

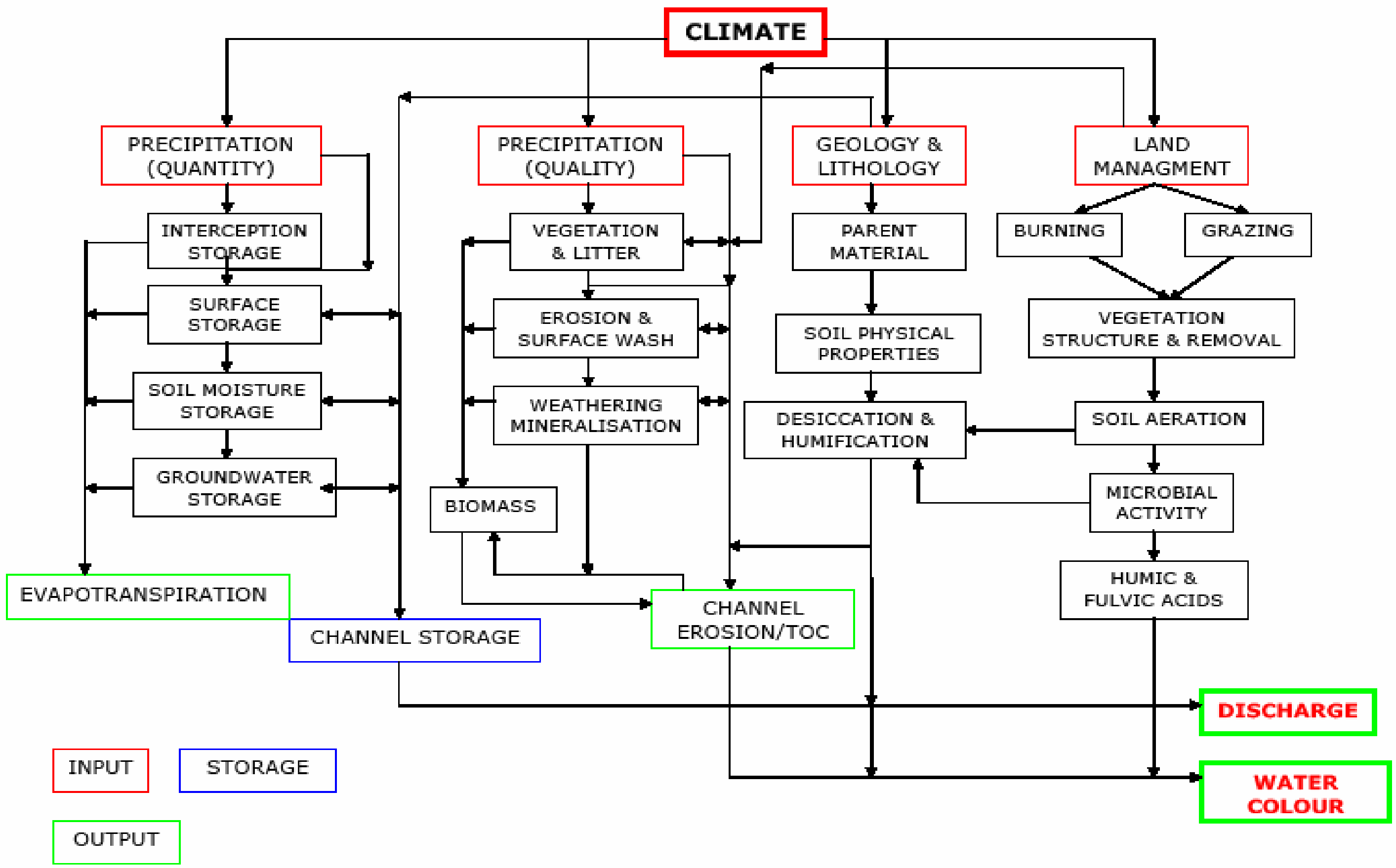
The processes that produce changes in water colour and runoff from upland catchments are numerous and complex. Figure 2.1 presents a flowchart of the interactions of the main factors contributing to water colour and DOC to be discussed in the chapter.

2.2 The Properties of Water Colour

2.2.1 Humic Substances in Surface Waters

Previous research has concentrated on methods of treatment for colour removal and methods of colour coagulation, but treatment processes have been hampered due to the lack of knowledge of the chemical structure of the colour-producing organics. Authors such as Shapiro (1964) and Steelink (1977) reported differences in physical properties, molecular weight and particle size of colour compounds. Natural colour has been reported as being in true solution by some authors (e.g. Meilli 1992) and being in colloidal dispersion by others (e.g. Hassett and Anderson 1979) and this has led to some confusion over the physical characteristics of colour. However, there is some agreement over the chemical and spectral properties of colour with most analysts agreeing on a similar chemical composition of carbon, hydrogen and oxygen, with small traces of nitrogen.

Figure 2.1: Catchment-Scale Factors and Processes of Water Colour and Discharge Generation



Water colour is the visual component of fulvic acids, humic acids and humin which are collectively referred to as Humic Substances (HS). HS are made up of a complex mixture of compounds of aromatic and aliphatic groups with carboxyl, hydroxyl, phenol and methoxyl of major significance (Hayes 1987). They have generally been characterised as yellow to black in colour, of high molecular weight, and refractory (Aitken *et al* 1985). They are ubiquitous in natural water, but the amount and composition depends on the contributing soils, surface waters and ground waters (Malcolm 1985). Their occurrence in water is dependent on size, ranging from dissolved through colloidal to particulate phases, although the dissolved phase predominates in streams. HS are measured as dissolved organic matter (DOM) and particulate organic matter (POC). However, there is thought to be a sufficient degree of difference in magnitude by which the two can be separated through filtration using a 0.45 µm filter (Danielson 1982, Giller and Malmqvist 1998).

HS are a heterogenous mix of sugars, lipids, amino acids and proteins which are bound to large humic molecules and colloids. The stream HS are composed of both stream fulvic acids (low molecular weight) and stream humic acids (high molecular weight). Aquatic humic acids are those stream HS which are insoluble and form precipitates at pH1 whilst stream fulvic acids are those stream HS which are soluble at pH1. Humin components remain insoluble in water at any pH value (Malcolm 1985, Hayes 1987).

Dissolved Organic Carbon (DOC) is the carbon component of DOM and is important in terms of peatland carbon budgets and their relationship to the global carbon cycle (Freeman 2001a, Charman 2002, Worrall *et al* 2003, Worrall and Burt 2007). Increased levels of DOC are directly related to changing levels of water colour and increased acidity from runoff caused by higher levels of organic acids. However, the DOC of organically coloured stream waters is extremely variable ranging from ~ 5-50 $mg.Cl^{-1}$ with the proportion of DOC as HS varying considerably. Although ~ 90% of HS in uncoloured water occurs as fulvic acids, there is a general trend in which the proportion of humic acid increases above 10% with increasing DOC concentrations in organically coloured waters (Malcolm 1985). Similar findings were made by Christman (1970) who reported that 15-25% of colour in natural waters was due to fulvic acid and 75-85% to humic acid. Scott *et al* (1998) in their study of DOC concentrations at Dun Fell, Cumbria also reported comparable results.

The origin of stream HS has been debated and a common misconception often upheld is that stream HS are the same as soil HS from which they are largely derived. However, Waksman (1938) argued that aquatic HS differed from soil humus in source and composition. The allochthonous source of soil, litter and decaying terrestrialised vegetation make up one part of HS, whilst the remainder is made up from the autochthonous source during decomposition of plant and animal residues. This theory is supported by analysis of aquatic HS which found up to 90% fulvic acids and only ~ 10% humic acids made up the HS in streams despite humic acids being a major component of soil HS (Malcolm 1985, Thurman 1985).

Another, more recent aspect of HS is the detailed characterisation of hydrophillic and hydrophobic acids which form the structure of HS. Hydrophilic acids have been found to account for only 20-30 % of DOC in stream waters (Steinberg 2003). Some of these acids are slightly coloured and have a lower molecular weight and a greater number of acidic functional groups per carbon atom than stream fulvic acids (Malcolm 1985). These results are supported by recent studies in the UK of water draining from peatlands in Yorkshire which found that 68-79% of total DOC was made up of hydrophobic material (Sharp 2005, Sharp *et al* 2006) and are consistent with the view that as DOC in water increases the majority of additional organic matter is likely to be hydrophobic in character (Malcolm 1985). This is of particular concern to water companies as the hydrophobic nature of the acids generally makes the water more difficult and costly to treat (Sharp 2005). The distribution of hydrophobic and hydrophyllic acids and how they are affected by allochthonous and autochthonous sources is discussed in Section 2.3.

2.2.2 Measurement of Aquatic Humic Substances, Colour and DOC

The actual concentration of humic matter in water requires quantification by water companies in order to treat the water appropriately. However, this can only be determined after isolation of the HS and gravimetric determination of the dried isolate (Hautala *et al* 2000). This is not an easy or rapid method by which to measure aquatic humus content and therefore alternative methods have been sort by using measurements of colour (Engstrom 1987, Hongve and Akesson 1996), measurements of absorbance at different wavelengths (1977, Hautala 2000) and fluorescence (Visser 1983).

The measurement of colour of water is widely accepted as a simple way to estimate the humus content in natural water (Hautala *et al* 2000). The HS readily absorb visible light, most strongly at the blue-end of the spectrum which gives water high in DOC a characteristic brown colouration (Stevenson 1994). Hongve and Akesson (1996) however, found the visual method of colour measurements not particularly precise and advocated absorbance measurements by spectrophotometry for colour measurement. The UV is used therefore as a qualitative and quantitative tool to analyse HS in surface waters. Several wavelengths have been used ranging from 250-465 nm depending on the chemical site justification (e.g. Edwards and Cresser 1987, Kalbitz *et al* 2000, Hongve and Akesson 1996). However, 400 nm is the most frequently used as it is appropriate for measuring natural colour (Thurman 1985, Dobbs and Watts 1987) and has since been recognised as the standard wavelength in which water colour should be measured in the UK by the British Standards Institute (BSI) and subsequently adopted by water companies (HMSO 1981, 1988, British Standard Institute 1995, Severn Trent Laboratory 2002). Table 2.1 shows the wavelengths applied for characterisation of aquatic HS, in particular water colour and DOC.

Table 2.1: Spectrophometric Wavelengths and Characteristics for Measurement of Colour and DOC in Humic Substances (adapted from Hautala *et al* 2000)

Wavelength (nm)	Correlative Characteristics	Characterisation	References
250, 330, 350	DOC, TOC	330 nm selected arbitrarily by Moore (1985) to test predictive power	De Haan *et al* (1982), Moore (1985), Edwards and Cresser (1987)
254	TOC, DOC, COD, BOD		Dobbs *et al* 1972, Reynolds & Ahmad (1997)
285	DOC	Measurement of aromatic character of HS	Kalbitz *et al* (1999)
410	Colour	Selected for comparability with Hazen units	Hongve & Akesson (1996)
410	Colour, DOC	Absorbance of HS increased as wavelength decreased	Hautala *et al* 2000
456	Colour	Effect of turbidity following filtration negligible	Bennett & Drikas (1993)
465	Colour, DOC	Absorbance in visible spectrum is a standard parameter for quantitative analysis of humates	Steelink (1977)

Many water companies in the UK have recorded colour measurements in two different ways. Water colour measured as absorbance at a wavelength of 400 nm has historically been the accepted unit of measurement. However, following an EC Directive (80/778/EEC), the standard unit of colour measurement changed to degrees Hazen (°H) and was implemented by the European Member States from January 1990. UK legislation (Water Supply (Water Quality) Regulations 1989, Water Supply (Water Quality) Regulations 2000) incorporated the standards set out in European Community (EC) Directives (Council Directive 80/778/EEC, Council Directive 98/83/EC). The Hazen standard unit is defined as "*the colour produced by 1mgl^{-1} platinum in the form of chloropatinic acid in the presence of 2mgl^{-1} of cobaltous chloride hexahydrate*" (HMSO 1981 p 7). It was generally accepted colour values expressed in absorbance per metre (aum^{-1}) could be converted into °H by a conversion factor of 15 (20°H = 1.5 aum^{-1}) (Watts *et al* 2001). However, previous studies (e.g. McDonald and Mitchell 1990, Mitchell and McDonald 1991) suggested a single conversion factor could not generally be applied across the full range of colour values or between samples from different sites as raw waters have different spectra to that of the platinum cobalt solutions used to determine Hazen units (HMSO 1981, Watts *et al* 2001). Watts *et al* (2001) therefore advocated that a conversion factor should be determined where possible for study sites in order to improve accuracy of data and enable comparison with historic data to identify trends in water colour.

2.3 Factors Influencing Water Discolouration

Water colour visually represents the various forms of dissolved organic matter (DOM) present in water and is largely generated by the allochthonous sources of soil, litter and decaying terrestrialised vegetation and autochthonous sources created during decomposition of plants and animal residues. It is therefore important to consider the relationship between the level of DOM present in soil and that present in surface waters. The ability of discoloured water to leach from the soils to surface waters is dependent on a number of natural and anthropogenic factors, that is, the reservoirs present, and the transfer processes which are in turn influenced by climatic, edaphic, physico-chemical, hydrological, atmospheric, topographic and management factors.

In the last 20-30 years there has been an increase in water colour and DOC concentrations in surface waters across the UK uplands (e.g. Freeman *et al* 2001a, Watts *et al* 2001, Worrall *et al* 2003, Evans *et al* 2005a). Studies at key upland sites include Plynlimon, Wales (e.g. Kay *et al* 1989, Neal *et al* 2001, 2005), Moor House NRR, County Durham (e.g. Robinson 1985, Garnett *et al* 2001, Worrall *et al* 2003) and the south Pennines (e.g. Edwards *et al* 1987, Tipping and Smith 2000, Pattinson *et al* 1994, O'Brien *et al* 2005). The research is summarised in Table 2.2 and the main findings discussed in Sections 2.3 and 2.4, and their context to this investigation is discussed in Chapter 9.

2.3.1 Meteorological Factors

Charman (2002) explains that "standing on a peatland surface, one is supported by a giant bubble of water, held together by a mass of living and dead plant material". The fact that peatland consists of over 95% water by weight (Heathwaite and Gottlich 1993) indicates that one of the most characteristic features of peatlands is that they are (or should remain) wet (Wheeler *et al* 2002). Rydin and Jeglum (2006, p4) noted that "the overriding physical condition controlling peatlands is the high water table" and this, together with the vegetation composition, is a requirement for peat to accumulate (Moore 1989).

Vegetation in upland catchments is sensitive to changes in climate and palaeoecological data from peat cores has indeed been used to reconstruct past changes in climate. A rise in summer temperatures and prevalence of prolonged droughts, followed by intense rain, may be expected to bring about changes in biomass, peat accumulation and nutrient cycling associated with a lowering of the water table and increased desiccation, humification and erosion in summer (Heathwaite 1993, Tallis 1998). Warmer, wetter winters with more frequent storms may also arise and may cause chemical and physical changes to soil structure which

Table 2.2: Summary of Research Related to Water Colour and DOC in the UK

Location	Research	Reference
Moor House NNR, County Durham	Relationship between water colour, moorland gripping and drainage	Robinson (1985)
south Pennines	Relationship between water colour and runoff – increased water colour and drainage	Edwards *et al* (1987)
Upper Nidderdale, North Yorkshire	Relationship between water colour and DOC from peat-covered catchments	McDonald and Naden (1987)
south Pennines	Relationship between water colour and microbial activity	Tipping (1989)
Coom Rigg Moss NNR	Relationship between water colour and drainage of organic soils	Chapman and Rose (1987)
Derwent catchment, south Pennines	Relationship between water colour and pH	Norton (1988)
Elan valley, Wales	Relationship between water colour and moorland gripping/drainage	Kay *et al* (1989)
Upper Nidderdale catchments, North Yorkshire	Relationship between water colour and time-lag of rainfall, lowering of water table levels and moisture patterns	Naden and McDonald (1989)
Upper Nidderdale, North Yorkshire	Relationship between water colour, pH, conductivity and heavy metals (Fe, Mn, Al)	Naden and McDonald (1989)
Upper Nidderdale, North Yorkshire	Relationship between water colour and burning, moorland gripping and grazing	Mitchell (1991)
Upper Nidderdale, North Yorkshire	Relationship between water colour, Winter Hill peat on slopes less than 5° and microbial activity	Mitchell (1991)
Upper Nidderdale, North Yorkshire	Relationship between water colour, soil respiration and microbial activity	McDonald *et al* (1991)
Upper Nidderdale, North Yorkshire	Relationship between water colour and soil moisture status and drought	Mitchell and McDonald (1992)
Thornton Moor, West Yorkshire	Relationship between water colour, peat depth and topography	Pattinson *et al* (1994)
River Burn catchment, North Yorkshire	Relationship between water colour, pH, conductivity	Mitchell and McDonald (1995)
Penniines, UK	Relationship between rainfall and decomposition of organic matter and flushing out of DOC/water colour	Tipping and Smith (2000)
Upland catchments across UK	Relationship between Water colour/DOC and water table depth and temperature	Freeman *et al* (2001a)
Moor House NNR, County Durham	Relationship between carbon and burning and grazing	Garnett *et al* (2001)
South Pennines	Relationship between water colour, morphology and chemical water quality	Blackmore and Labadz (2000)
Ashop catchment, South Pennines	Relationship between water colour, morphology and pedology	Walker 2001
Upland catchments across UK	Relationship between DOC and soil enzymes	Freeman *et al* (2001b)
Moor House NNR, County Durham	Relationship between DOC and conductivity	Worrall *et al* (2002)
Moor House NNR, County Durham	Water colour/DOC associated with water table depth and temperature	Worrall *et al* (2003)
Yorkshire and Cumbria	Increases in water colour associated with rise in prescribed burning	White *et al* (2003)
Mid Wales	Relationship between DOC and drought	Freeman *et al* (2004)
Plynlimon, mid-Wales	Relationship between DOC, deforestation and runoff	Neal *et al* (2001, 2005)
Across UK	Relationship between DOC with acidification and temperature	Evans *et al* (2005a)
Derwent, south Pennines	Relationship between water colour and prescribed burning	O'Brien *et al* (2005)
Oughtershaw Beck, , Northern Pennines	Increased DOC associated with drainage	Wallage *et al* 2006
Trout Beck catchments, North Pennines	Relationship between DOC, grazing and burning	Worrall *et al* (2007c)
Moor House NNR, County Durham	Relationship between decline in SO_4^{2-} and increase in DOC	Chapman *et al* (2005)
Moor House NNR, County Durham	DOC associated with hydrological flowpaths	Clark *et al* (2007)

could in turn affect erosional processes, increasing the loss of biomass, vegetation and species (Tallis, 1995, 1997, Milne and Hartley 2001).

Bog bursts and the transport of carbon flux (DOC and POC in water, CO_2 in water and air) may also contribute to greenhouse gases and escalate climate change (Evans *et al* 2002, Worrall *et al* 2004, Belyea and Malmer 2004). In addition, climate change may increase the number of wildfires by creating dry conditions more vulnerable to intense, high temperature and deep burns (Tucker 2003, Cosgrove 2004). Such fires may cause a serious loss of soils through erosion; generate intense episodes of water discolouration and the loss of an important habitat which may only be restored through costly and lengthy restoration.

Climate change is therefore seen as being a fundamental influence upon changes in upland catchment areas both historically and in the future, and it may have a significant effect on the success of attempts at restoration of hydrological function and re-vegetation of bog plant species associated with this land type. Escalating rates of erosional processes and consequent degradation of blanket bog (largely upland catchments located on deep peat) are widely cited, along with the possible contribution to climate change (as bogs change from sinks to sources of carbon). Furthermore, climate change is considered by many stakeholders to be the over-riding threat to the continued existence of blanket bog found in these upland catchments within the UK and there are additional concerns that some restoration projects might be in vain if the forecast changes in climate occurs (O'Brien *et al* 2007).

Many authors (e.g. Dobbs and Watts 1987, Goldsmith *et al* 1997, Evans *et al* 1999, Watts *et al* 2001, Worrall and Burt 2004) have confirmed water colour levels have escalated since the 1970s and suggest there is a relationship between the increase in colour and severe droughts and storm events. The colour output may be related to the time moisture is deficient in the acrotelm (upper soil layer) and Naden and McDonald's study (1989) found a significant negative relationship between mean monthly colour and moisture deficit at time lags of 3 and 14 months, i.e. autumn colour is high following a dry spring and a dry previous summer. These findings were similar to Mitchell and McDonald (1992) who identified that the rate of colour accumulation increased when drought conditions exceeded 120 days. They concluded this may be the point when a particular soil pore size becomes de-watered allowing decomposition processes to add to the colour store.

More recently however, Freeman *et al* (2004) conducted a catchment based experiment by manipulating rainfall and creating drought conditions on a number of catchments in mid-Wales by simulating a series of summer droughts to investigate whether the effects of drought would increase DOC levels. The experiments took place during two periods (1992-94 and 1999-2000) between late spring and early autumn. The results showed that the levels of peat DOC concentrations were substantially lower on the manipulated (drought) catchment than on the control (unmanipulated) catchment ($p<0.01$). During such aerobic conditions associated with drought, gaseous CO_2 rather than dissolved aqueous CO_2 were likely to prevail. However, they found there was no evidence of DOC release increasing above that of the control following the five simulations of drought-like hydrological changes. They concluded that the hypotheses of reduced summer precipitation generating a rise in DOC trends could therefore be rejected.

Researchers have also concluded that abnormally high temperatures and prolonged periods of little or no precipitation would lower water table levels and increase soil moisture deficit, thereby raising aerobic conditions in the upper acrotelm layer and accelerate microbial activity and humification processes (Mulholland *et al* 1999, Glatzel *et al* 2003, Worrall and Burt 2005). Researchers identified intense rainfall events may exacerbate the recharge process and raise DOC and water colour release (Worrall *et al* 2002, Worrall and Burt 2005). These increases are likely to be more frequent in view of current predictions regarding climate change (Fowler *et al* 2007) and therefore are a priority to water companies to find an acceptable solution to combat increases in water colour predicted from climate change.

Controversially, a review by Kalbitz *et al* (2000) of the effects of temperature on DOM in soils found that although laboratory experiments suggested a trend of increasing DOM concentrations with increasing temperature, this was less obvious in field experiments. They concluded that the release of DOM (and DOM fluxes) under field conditions would not depend entirely on temperature. Soil properties, hydrological processes and other climatic conditions such as precipitation would all have an affect on water discolouration and DOC flux and their contributions are discussed in the following sections.

The low temperatures also affect the length of the vegetation growing season, which is conventionally described as a period when the mean temperature exceeds 5.6 °C. In the south Pennines the growing season has been estimated at 160 days at an altitude of 610 m (Phillips *et al* 1981). The instability of a blanket bog surface and the considerable temperature fluctuations experienced, however, may provide an inhospitable environment for establishment of plant propagules (Tallis and Yalden 1983) and for revegetation of bare peat areas.

During the summer, when the temperatures are generally higher, areas of bare peat previously eroded by wind and frost action may be subject to desiccation and wind-blow (Tallis and Yalden 1983). The low albedo of bare peat raises surface soil temperatures as the radiation is readily absorbed into the dark surface, causing the temperature in the upper layers of peat to rise (Watts *et al* 2001). Areas particularly vulnerable to desiccation are steep-sided gullies located within deep peat with a slope < 5° (Pattinson *et al* 1994), where it is difficult to re-establish vegetation because of the soil instability. Gully walls with a southerly aspect are more susceptible to fluctuations in temperature and may erode at a greater rate than north-facing slopes due to their exposure to wind, radiation and the forces of gravity (Mitchell and McDonald 1995). This combination of climatic, topographic and geomorphic conditions have been linked to the production of water colour, DOC, and increased sediment flux associated with peat desiccation on blanket bogs (Labadz *et al* 1991, Evans and Warburton 2001, Worrall *et al* 2002, Warburton 2003, Holden *et al* 2004).

2.3.2 Edaphic Factors

The fixation and storage of organic matter in terrestrial ecosystems have attracted increasing attention in the light of recent concerns regarding climate change and global warming (Moore 2002, Belyea and Malmer 2004, Fowler *et al* 2007). The accumulation of peat and development of humic soil horizons are an example of such storage, but can only occur when organic productivity exceeds decay. Such areas are sometimes referred to as a carbon 'sink' as they contain a high proportion of partially decomposed organic matter of which approximately 50% is organic carbon (Garnett *et al* 2001, Holden *et al* 2006a). These organic soils are typically black to dark brown in colour due to the high organic matter content.

Humification of peat involves the breakdown of plant debris and the synthesis of those products into the more stable, but complex humic substances (HS) of high molecular weight (Jolly and Chapman 1987, Scott *et al* 2001). These products are found in the upper layers of the soil (acrotelm). Humification is generally restricted when peat soils are water logged and anaerobic conditions prevail, but the process increases in peat catchments during the summer when changes, such as lowering of the water table and subsequent moisture deficit allow humification to proceed (Tipping *et al* 1989). If these changes are followed by rain, partially humified and therefore lower molecular weight materials will be flushed from the peat into the surface waters as the water table rises and the soils recharge. These materials are generally released in autumn and winter in the form of dissolved organic carbon (DOC) together with a noticeable rise in water discolouration (Smart *et al* 2001, Dawson *et al* 2002, Worrall *et al* 2002).

Many authors have found that areas of peat soil, and in particular the Winter Hill Association (1011b) series (Tipping *et al* 1989, Mitchell and McDonald 1995) are connected with surface waters containing highly coloured compounds, (Butcher *et al* 1995, Clark *et al* 2007). This soil is defined as a "raw oligo-fibrous peat soil" (Tallis and Switsur 1973, Jarvis *et al* 1984). McDonald and Mitchell (1990) found water colour was significantly correlated to percentage cover of Winter Hill soil series (1011b). Hope *et al* (1997) studied 11 sub-catchments of the River Dee, NE Scotland and also found a strong positive correlation between the annual fluxes of DOC and POC with the cover of hill peat in the catchment area, suggesting that hill peat is a major source of organic matter to the river. Pattinson *et al* (1994) established a positive correlation between high water discolouration and peat depth. They observed soil moisture varied more significantly in areas of greater peat depth during dry summers followed by higher colour being washed out in an autumn flush. These processes are discussed further in Section 2.3.4.

2.3.3 Physico-Chemical Factors

McDonald and Naden (1988) reported that humic acids produced during warm, dry conditions may alter the chemical and biochemical processes, producing humic acids that are significantly higher in average molecular weight yielding yellow to brown melanin type pigments on further photo-oxidation. Such changes indicate DOM production is dynamic with a complex interaction of different processes which may constantly change its production (McDonald and Naden 1988, Mitchell 1990, Scott *et al* 2001). These humic and fulvic acids increase in solution, raising colour levels as water passes through the peat when hydrogen bonds begin to break down (Hayes 1987). These less aromatic humic substances are more soluble and therefore their prevalence in soil water during the autumn flush is greater relative to the more aromatic and possibly aggregated materials (Scott *et al* 2001).

Increased oxidation in the acrotelm raises microbial activity, approximately trebling the decomposition rate of organic material due to the increased surface area of soil exposed to air (Mitchell 1991). The products of this oxidative degradation form the basis of water colour consisting of a series of natural organic compounds (primarily humic and fulvic acids) (McDonald *et al* 1987, Tipping *et al* 1989).

Many researchers have found temperature and soil moisture are linked to microbial activity and the production of water colour (e.g. McDowell and Likens 1988, Mitchell and McDonald 1992, Evans *et al* 1999). Anderson (1973) and Kirschbaum (2004) found microbial activity increased when temperatures were raised and Sommers *et al* (1981) found a similar increase in colour production when soil moisture was low. Grieve (1984) established that the level of biological activity and soil moisture was directly related to rainfall patterns and Christ and David (1996) confirmed a strong exponential relationship between temperature, moisture content and DOC.

Grieve (1984) determined seasonal variations in DOC with summer and autumn maxima positively correlated to soil temperature, whilst Scott *et al* (1998, 2001) examined the processes and found DOC and colour production was dependent on the adsorption rate of soil particles and soil water flow. They confirmed that during intense drought conditions, the production of DOC was low, caused by an overall decrease in microbial activity or a possible diversion of the decomposition pathway to full mineralisation i.e. production of CO_2.

Kalbitz *et al* (2000) concluded that reduced rates of decomposition in dry soils (during drought conditions) could cause microbial products to accumulate and could contribute to high DOC concentrations in the soil leachate once the soils began to rewet. Lundquist *et al* (1999) suggested that the increase in DOC concentrations during such rewetting cycles could be caused by a combination of reduced microbial utilisation of DOC during dry periods, enhanced turnover of microbial biomass and condensation of microbial products by rewetting and disrupted soil structure allowing previously sequestered carbon to be more available as DOC. Christ and David (1996) provided evidence to support this and suggested that a disruption of microbial biomass after soil drying could allow high proportions of hydrophilic neutrals and bases to accumulate whilst the wetter conditions favoured the release of hydrophobic acids (see Section 2.2.1). Whilst temperature was not found to be highly correlated with DOC release (see Section 2.3.2), the pattern of low soil moisture followed by changes in water fluxes are positively related to the amount of DOC released after a dry period (Yeakley *et al* 1998, Tipping *et al* 1999, Evans *et al* 2002).

The microbial extracellular enzyme phenol oxidase has been associated with the storage capacity of carbon in peat soils (Freeman *et al* 2001b). The enzyme's activity is low in an active wet bog where anaerobic conditions prevail and cannot promote organic carbon from decomposing and escaping into the air as CO_2. The phenolic compounds the enzyme would naturally destroy under aerobic conditions are allowed to build up under the anaerobic conditions (that is, beneath the water table), thereby preventing bacteria from decomposing the organic material. However, as the bog dries out, the influx of bimolecular oxygen boosts the enzyme's activity and destroys the phenolic compounds, thereby increasing the decomposition rate. Freeman *et al* (2001b) found that enzyme activities increased seven-fold in oxygen saturated conditions when compared with oxygen-free conditions thereby raising the humification rate and potential dissolvable carbon store. Freeman *et al* (2001b) refer to the enzyme as "a fragile latch mechanism holding in place a vast carbon store of 435 gigatonnes (worldwide carbon capacity)". Freeman *et al* (1993) had previously found that lower water tables which are associated with increased aeration also a caused of a sharp decline in phenolic concentrations. They found that CO_2 flux reached a maximum of 146%, but rapidly declined when the water table was recharged and returned to control levels in laboratory conditions.

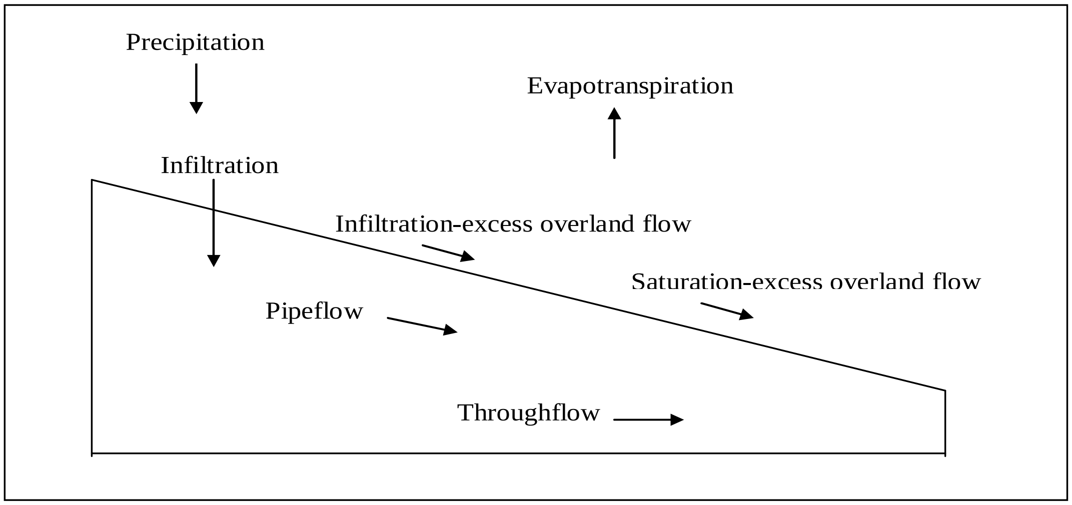
Worrall *et al* (2004) advocated that the 'enzymic latch' mechanism may also be responsible for an increase in DOC and water colour, that is, hydrolase enzymes present in peat bogs are inhibited by the presence of phenolic compounds which build up in peat during anoxic conditions when phenol oxidase is restricted (beneath the water table) (Freeman *et al* 2001b). Therefore, if the water table falls, it may result in a decrease in phenol oxidase activity and as oxygen levels increase, they destroy the phenolic compounds that repress hydrolase activity. Worrall *et al* (2004) argued that the loss of phenolic compounds meant that decomposition could continue even after the water table rises again and therefore the enzyme-latch production does not cease once the water tables have been restored and so allows the additional DOC production to continue. This suggests that droughts are a major driver for increased DOC which may then be exacerbated by local factors such as land management.

2.3.4 Hydrological Processes

Water flowpaths and water fluxes in organic soils may be altered by environmental change, whether directly by for example, drainage or restoration strategies, or indirectly by climate change and chemical deposition (Scott *et al* 1998, Clark *et al* 2007, Worrall *et al* 2007b). Such changes may affect the soluble and particulate carbon removed from such systems. In order to predict the consequences of these changes it is important to understand the temporal and spatial variability of hydrological processes in these upland catchments.

Peatlands form in regions of high precipitation excess where a positive water balance presides with the major inputs of water and nutrients coming from either precipitation or groundwater influx. Peat is very sensitive to the degree of soil saturation and changes in hydrology, and is capable of storing large quantities of water. Saturated peat is 90-98% water by mass (Heathwaite and Gottlich 1993, Charman 2002). The relative position of the water table controls the balance between peat accumulation and deposition and therefore its stability (Holden *et al* 2004) and is affected by six basic processes that form the hydrological cycle in a catchment system shown in Figure 2.2. These processes are precipitation, infiltration of water through peat, flow in pipes and fissures which are not directly open to the atmosphere, diffuse surface flow, unconfined flow in directed channels and evapotranspiration (Ingram 1983).

Figure 2.2: Schematic diagram to illustrate water pathways in a blanket bog



Peat hydrology is often described using a diplotelmic model. The upper layer is known as the acrotelm, which is periodically aerated and contains decomposing plant material, and the lower, anaerobic, permanently water logged layer known as the catotelm (Ingram 1983). The water table always lies within the acrotelm and is temporally variable generally being found within 5 cm of the mire surface during the autumn and winter, but capable of falling to generally 20-25 cm, but up to 40 cm in the spring and summer (Evans *et al* 1999 Holden *et al* 2006b) This water level is a control factor for infiltration and surface runoff with a high incidence of saturation-excess overland flow dominating runoff production from peatlands during periods of high water table level due to the low hydraulic gradient and near-saturated state (Burt *et al* 1990, 2001, Holden *et al* 2001, Clymo 2004).

The hydrological regime of many upland catchments in the UK generally show that streamflows are dominated by high peak flows and discontinuous summer flow (e.g. Burt *et al* 1990, Evans *et al* 1999, Worrall *et al* 2007a). The discharge often responds quickly to precipitation events, typically peaking within one hour of maximum precipitation and subsiding to baseflow within 7 to 12 hours of the cessation of rainfall (Crisp and Robson 1979, Robinson and Newson 1986, Labadz *et al* 1991). The runoff regime of blanket peat catchments can therefore best be described as "flashy" and a typical hydrograph shows the rapid response to rainfall with a steep recessional curve and minimal baseflow. Many small tributaries in the headwaters of such catchments may completely dry up after a relatively short period without rain and the poor maintenance of baseflow may be a problem for water companies who rely on stream flow to supply their reservoirs (e.g. Severn Trent Water, Yorkshire Water, and United Utilities), despite high water table levels being maintained within 40 cm of the surface for 80% of the year (Holden *et al* 2006b).

Streamflow is the end-product of a number of runoff production processes which control the speed of water movement, residence time of contact with soils and the nature of nutrient and sediment fluxes (Fraser *et al* 2001, Holden 2005a). A number of factors affect streamflow such as climate, soil type, vegetation cover and landuse and are further affected by antecedent soil moisture and precipitation intensity and duration (Scott *et al* 1998, Emmerich and Heitschmidt, 2002, Worrall *et al* 2006, 2007b).

The main types of runoff occurring on upland catchments with organic peat soils are infiltration excess overland flow, saturation excess overland flow, throughflow and pipe or macropore flow and each is discussed briefly below.

2.3.4.1 Infiltration-excess Overland Flow

Any given soil will have an infiltration capacity, a maximum rate at which the soil can absorb falling rain when it is in a specified condition. As soil becomes saturated, with continued precipitation input, infiltration capacity falls asymptotically to a final, minimum, constant level (Ward and Robinson 2000). Where precipitation is of greater intensity than the infiltration capacity of the soil, "infiltration-excess overland flow" will occur. Where rainfall is particularly intense or soil is particularly fine textured, this situation can occur long before the soil is actually saturated with water.

2.3.4.2 Saturation-excess Overland Flow

Saturation-excess overland flow occurs when the soil profile is completely saturated, excess water (added from above by precipitation, or laterally by overland or subsurface flow) cannot be accommodated. Hewlett and Hibbert (1967) first put forward the hypothesis that in many catchments the precipitation entering the soil by infiltration moves both vertically and laterally through the soil, and that as a result of the lateral movement the areas immediately around the stream channels become saturated. With time the 'saturated wedge' moves upslope and any rain falling onto this surface runs off as saturation-excess overland flow. Burt *et al* (1990) described the frequent occurrence of saturation-excess overland flow in peatlands, explaining how expansion of the saturated zone during precipitation leads in turn to expansion of the area experiencing overland flow.

2.3.4.3 Subsurface flow through the Peat Matrix

Most soil matrices are permeable to water to some extent, giving rise to both lateral and vertical flows within the ground. The term 'throughflow' is widely used for shallow subsurface flow, particularly downslope flow through soil profiles and is therefore analogous to lateral shallow flow through the peat matrix. The rate of flow in any rigid medium is controlled by three factors according to Darcy's law (Darcy 1856):

$Q = kIA$ where :

Q = groundwater discharge ($m^3 s^{-1}$)

k = hydraulic conductivity ($m s^{-1}$)

I = hydraulic gradient (dimensionless - "head" per unit distance)

A = cross-sectional area across which flow occurs (m^2)

The hydraulic conductivity of a material, k, reaches a maximum when all available pore spaces are already filled with water. This is known as the saturated hydraulic conductivity, sometimes abbreviated to k_{sat}.

Baird (1997) pointed out however that the hydraulic conductivity of a given volume of peat is unlikely to be uniform in all directions, which will affect the direction and quantity of flow, and that entrapped gas bubbles may retard flow in peat pores even below the water table (Baird *et al* 2004). This is likely to cause a spatial variation in flow across a catchment irrespective of differences in topography.

2.3.4.4 Macropore flow and Pipeflow

Macropore flow occurs in pores above capillary size which allow water to move by gravity, bypassing the soil matrix and providing rapid recharge or drainage of the water table. Macropore flow may be almost as rapid as surface flow and is most commonly observed in structured soils such as cracked clays where it has been shown to increase stormflow volumes and peak discharge (e.g. Robinson 1985). The same phenomenon could occur where peat becomes cracked as a result of frost or desiccation. Thresholds with regard to macropore flow are thought to exist with regard to rainfall intensity and antecedent soil moisture: if the soil is too dry, or rainfall too light, then any flow which finds its way into macropores is rapidly absorbed into the soil peds (see, for example, Anderson and Burt 1990). Baird (1997) stated that macropores are commonly assumed to exert 3 cm suction, which means that they are more than 1 mm in diameter. He found that they accounted for over 50% of flow even in a highly humified fen peat. Holden *et al* (2001) investigated macropore flow in blanket peat in the northern Pennines, England, and found that macropores accounted for an average of 36% of flow through the peat, with 51% in *Sphagnum*-covered peat. They also reported a change with depth in bare, *Calluna* and *Eriophorum*-covered peats, such that macropores were most significant in the 5 cm zone, accounting for 47-53% of flow, and had reached a minimum (13-22%) by 20 cm below the surface.

Rapid subsurface flow also occurs in larger features known as "pipes" in many blanket peat-covered catchments. Jones and Crane (1984) for example, found that almost half of the 'stormflow' from a blanket peat catchment in mid-Wales originated in discrete pipes. These pipes can be up to hundreds of metres in length and vary greatly in diameter from a few centimetres to more than a metre, but typically form branching subsurface networks which undulate throughout the peat profile (Jones 1981, Holden and Burt 2002b, Holden 2005b). The precise boundary between pipes and macropores is difficult to define, but pipes may exhibit a greater degree of connectivity in the downslope direction. The role of pipes as sites for gully extension and stream channel initiation also remains unclear, but they can play a significant role in the hydrology of some peat-covered catchments by providing linkage from distant source areas to the stream network (Holden 2005b).

2.3.4.5 Peat Hydrology, Water Discolouration and DOC Flux

The dynamics of precipitation and water fluxes through changes in hydrological processes are also greatly responsible for seasonal changes in the concentrations and fluxes of DOC in soils (Christ and David 1996, Kalbitz *et al* 2000, Evans *et al* 2002). In catchments where there is a relatively high hydrological turnover, temporal and spatial variability are closely related to DOC distribution. Water colour and DOC concentrations are typically positively correlated with discharge and usually show a clockwise hysteresis (higher concentrations at equivalent water discharge during the rising stage compared to the falling stage) (Grieve 1984, Labadz *et al* 1991, Hope *et al* 1997). The inverse relationship between DOC concentration and water flux suggests that leaching of carbon from the top layers of the soil and the dilution of DOC during high precipitation could be responsible for the temporal change in DOC concentrations (McDowell and Likens 1988, Mitchell and McDonald 1992, Worrall *et al* 2002, 2004, Evans *et al* 2005a, Cooper *et al* 2007). The amount of contact time between the soil and soil solution is a deciding factor in the generation of humic substances and subsequent discharge of DOC and water colour (Boyer *et al* 1996). For example, in the northern hemisphere, more water generally passes through the upper soil horizons through surface and sub-surface overland flow in the spring, and DOC is generally low, whilst in summer, low soil water content and longer contact time may lead to higher DOC concentrations during episodic events. The DOC and water colour levels reach a peak during the autumn, when soils recharge and the soil solution having been in contact for the longest period during the summer (and therefore of the highest colour) is flushed out creating the autumn flush. The DOC then diminishes during the winter due to the short residence time of water in contact with soil horizons high in organic matter as surface flow predominates (Fraser *et al* 2001, Worrall and Burt 2005, Worrall *et al* 2006).

A study by Boyer *et al* (1996) in Deer Creek, Montezuma, Colorado examined the main factors controlling DOC variation, that is, the hydrological catchment responses which include flow paths through and residence times of water in the catchment in order to create a suitable model. The model was used to test the hypothesis that

DOC in riparian and hillslope soils is “flushed out” by the formation of a ground-water ridge during periods of snowmelt, suggesting that DOC builds up in the vadose zone (zone between the water table and ground water level – unsaturated zone) during periods of low flow (through leaching of overlying organic matter and through microbial activity). They concluded that DOC from the unsaturated zone may be pushed out into the stream during periods of high flow.

Hongve (1999) believed the water pathways in organic soils were important in determining DOC concentrations in streams and that when soil solution percolated through a deep soil DOC was selectively reduced. He found the B-horizon (the layer of sub-soil containing leached and decomposed organic matter) effectively controlled DOC and water colour concentrations which increased during the summer irrespective of the source whilst during the autumn, live moss (*Sphagnum*) gave percolates with approximately the same colour intensities and higher DOC concentrations than peat from 10-15 cm depth from the same mire. Following incubation of the samples for a two-month period, he found peat samples at a depth of 20-25 cm depth produced the same DOC concentration as previously, but DOC and colour in the surface layer were 6-8 times higher than found originally and concluded that the B-horizon effectively controlled DOC concentrations. These findings are supported by Schiff *et al* (1998) and Chasar *et al* (2000) through the measurement of radiocarbon which confirmed DOC from peatland soils occurs in the uppermost peat and vegetation horizons.

Tipping *et al* (1999) also observed the highest DOC and water colour concentration during the autumn and concluded they were caused by the degree of soil humification and hydrological processes. They argued that during the summer microbial activity produced “potential dissolved organic carbon”, but water percolated into the deeper soils where DOC absorption maintained low soil solution concentrations. However, as the soil rewetted during the autumn, they concluded lateral flow became more significant and DOC mobilised as the proportion of drainage water passing through the surface horizons would increase and flush out the DOC-rich compound.

Mitchell and McDonald (1992) found macropore flow could also contribute to an increase in water colour. They hypothesised that the degree to which water may access the pore spaces and rewet the peat may determine the extent of colour release and found the degree of discolouration through throughflow was directly proportional to the extent of near surface rewetting of peat. The upper layers of peat were found to be extremely hydrophobic and resistant to rewetting due to the collapse of macropores following drying, and the high suction pressures found in micropores. They also concluded that drying caused humic macromolecules to shrink, binding the lower weight molecular fractions responsible for colour. On initial rewetting the peat shed water, preventing the removal of organic matter, but continued wetting eventually allowed water access to all pore spaces, eventual saturation and removal of colour.

Despite other findings relating highly coloured water to peat soils (e.g. McDonald and Mitchell 1990, Hope *et al* 1997), Hongve (1999) found the influence of mires on the level of organic substances in water to be insignificant and therefore the occurrence of mires was not the primary source of water colour. He found that the influence of water pathways in water-logged mires may affect DOC concentrations more than the leaching of DOC from the peat. He concluded that the deep layers of peat (up to 25 cm depth) appeared quite impermeable and the dominant flow passed laterally through the less decomposed superficial layer.

Scott *et al* (1998) also found that the maximum flux of DOC occurred some time after the maximum rate of dissolvable DOC (usually occurring during the summer). They believed this was caused by the lack of soil water flow during the height of summer and the number and type of rain events which tended to be smaller and less frequent. During such periods the soil moisture deficit was higher so that rainfall recharged the deficit rather than went to runoff from the catchment. They claimed that the DOM produced in summer was therefore stored in the soil until the larger and more frequent rain events occurred in late summer/early autumn, flushing the soils and causing a sharp rise in flux. They believed that the timing of the efflux of DOC and water colour depended on rainfall patterns during this time. By winter the summer "store" of DOC was much depleted, especially the hydrophilic fraction, and the DOM in drainage water was therefore more hydrophobic and potentially more difficult to treat by traditional processes.

Tranvik and Jansson (2002) suggested that the relationship between climate change (temperature) and the increased flux of DOC from the release of hydrolase enzymes put forward by Freeman *et al* (2001b) is too simplistic (see section 2.3.2 and 2.3.3). They argued that hydrological function is one of the key considerations accounting for changes in DOC concentration and variations in and between sites can be accounted for by differences in hydrological variables. Evans *et al* (2002) also considered the temporal and spatial variation between sites caused by changes in hydrological conditions. They agreed that hydrology is an important contributor to DOC export, but that it should be seen as a two-stage process. DOC is first produced in the soil (through biological activity) and then transported from the soil to the drainage network by hydrological processes. The transport of DOC is then controlled by discharge so hydrology will influence the short-term fluctuations in riverine DOC production whilst the long-term changes in discharge (unless accompanied by changes in DOC production) cannot generate a sustained trend in DOC flux.

2.3.5 Atmospheric Factors

Atmospheric pollution has been recognised by many authors as a major threat and cause of degradation of soils (e.g. Tallis 1965, Phillips *et al* 1981, MacKay and Tallis 1996, Proctor and Maltby 1998). The impacts of sulphur and nitrogen deposition have been identified of particular relevance in changing the acidity of the soil with the deposition in particular of SO_2, NO_3, NH_4 ions originating from acidifiers emitted by industrial and vehicular emissions (Proctor 1992, Yesmin *et al* 1996, Monteith and Evans 2000, Neal *et al* 2003). Other acidifiers include toxic substances such as ozone, volatile organic compounds (VOCs), heavy metals and fertilising substances such as ammonium and nitrogen oxides.

Some upland catchments have been subject to increased atmospheric deposition over the past 250 years since the commencement of the Industrial Revolution; for example, the south Pennine moorlands located between the major conurbations of Manchester and Sheffield (Ferguson and Lee 1983, Moore 2002). The effects of such an increase in localised acidification on these sensitive upland environments are multitude, affecting chemical, physical and biological processes as well as species particularly sensitive to changes in acidity such as *Sphagnum* (Hogg *et al* 1995, Mitchell *et al* 2002). Such acidification can increase soil acidification, change decomposition rates and nutrient recycling, and saturation of nitrogen (Holden *et al* 2006a). Although little research has been conducted on the relationship between measurements of soil pH and acidification, particularly in peat soils, Skiba *et al* (1989) did find a strong correlation between deposition of acidity and low pH and concluded that acid deposition had caused further acidification of peat soils in Scotland. Schindler *et al* (1992, 1997) found a rapid decline in DOC concentration in bog pools of an experimentally acidified wetland and Cronan and Aiken (1985) found a strong negative correlation between DOC concentrations and pH between 3.5 and 4.8 of the O/A horizon leacheates in the top layers of the soil.

2.3.5.1 Impacts of Atmospheric Deposition and Water Quality

Although the ecological health of moorlands such as the south Pennines may have been impoverished by such acidification, water quality in terms of water discolouration and DOC loss may have actually been limited due to the chemical reaction between carbon and sulphur, particularly during the peak of sulphur deposition in the 1980s (Davies *et al* 2005, Evans *et al* 2005a, Clark *et al* 2007). The chemical reaction of acidic deposition increases the leaching of base cations such as calcium (Ca) and magnesium (Mn) from soils and so reduces the number of cation exchange sites occupied by base cations. In so doing it increases the proportion of exchange sites occupied by aluminium (Al) and H+ ions. In the long-term this process causes an increase in soil acidification and enhances the solubility of heavy metals such as aluminium, manganese and lead whilst binding the organic pollutants through absorption (Tipping and Smith 2000, Evans *et al* 2004, Reynolds *et al* 2004, Sharp *et al* 2006).

Since the 1950s however, legislation and regulation has tried to reduce the polluting emissions through a set of coordinated abatement strategies. Examples of legislation having a profound affect include the Clean Air Act (1956, 1968), and more recently the 1999 Gothenburg Protocol which has set emission ceilings for 2010 for sulphur, NOx, VOCs and ammonia, and the Aarhus Protocol (1998) which committed the UK to reducing heavy metal deposition levels to below 1990 levels (McNish 1997, Defra 2008, Europa 2008).

Since the imposition of the legislation and restrictions on emissions there has been a 60% decrease in sulphur (S) deposition in the UK during the last 20 years (Fowler *et al* 2005). The Acid Water Monitoring Network (AWMN) have monitored the response of surface waters to this decline at 22 sites across the UK which include sites on peat and peaty podzol and peaty gley soils and found that there has been a decrease in non-marine SO_4 (Davies *et al* 2005). During this same period of study (1988-2002) there was a significant rise in the DOC at all sites with an increase on average of 91% relative to 1988-1993 means (Evans *et al* 2005a). Although the AWMN found a variation in the temporal pattern of DOC across the sites that may suggest that local factors could contribute to observed DOC variations, the fact that all sites showed a significant increase indicated that there may have been one or more underlying drivers of change operating in a uniform and unidirectional manner (within the limited period of monitoring) across the whole of the acid-sensitive area of the UK (Evans *et al* 2005a). These findings suggest that changes in atmospheric deposition may have affected all the sites because of its ability to deposit spatially and temporally over wide areas during a relatively short period.

2.3.6 Topographic Factors

Hillslope discharge, topography and sediment lithology interact to influence water table fluctuations, riparian groundwater flow patterns and fluxes entering the riparian zone. Vidon and Hill (2004) found that landscape topography influenced riparian subsurface flow patterns, particularly where the slope gradient is steeper than 5%.

McDonald and Mitchell (1990) found that drainage intensity was positively correlated with mean water colour. They reported that intense drainage networks may promote high colour 'flushes' by having a marginally lower water table which in deep peat would result in a significantly greater zone of aerobic decomposition and so a larger colour source. The high drainage intensity could also increase runoff and export of organic solutes.

Pattinson *et al* (1994) found water colour and the topographic index Ln(*a*/tanβ) to be positively correlated. This index represents the contributory area above a point (*a*) and local slope (β); as the contributory area increases, the slope angle lowers, and colour at that point increases. Mitchell (1990) reported that areas of low slope angle had a correspondingly slow rate of water movement, giving water the maximum potential to dissolve organic matter and become more discoloured.

2.4 Impact of Land Use and Changes in Land Use on Water Quality and Quantity

Although the natural processes of erosion have obviously shaped upland catchments used for gathering grounds, the anthropogenic pressures on these areas have undoubtedly increased over the last 200 years (Tallis 1998). This section considers those factors related to land use and management which may have accelerated the rate of erosion and degradation of soils and the release of water discolouration and DOC.

The recent JNCC Common Standards Monitoring (CSM) report of the first six year cycle of monitoring (1999-2005) of the SSSIs in England identified grazing, burning, and drainage as the main causes of blanket bog degradation on SSSIs (Williams 2006). Table 2.3 shows the percentage of the unit area not meeting the PSA target and shows that moor burning is the factor accounting for the highest percentage area not meeting favourable condition, followed very closely by overgrazing, and then to a lesser extent drainage.

Table 2.3: Reasons for Adverse Conditions and Percentage of Unit Area of SSSIs not meeting Favourable Condition (Adapted from English Nature 2006b)

Moor burning	32.45%
Overgrazing	31.24%
Drainage	12.21%
Air pollution	7.07%
Water pollution - agriculture/run off	7.03%
Inappropriate scrub control	6.05%
Undergrazing	5.98%
Forestry and woodland management	5.78%
Inappropriate ditch management	5.41%
Inappropriate water levels	2.12%
Agriculture - other	1.82%
Public access/disturbance	1.78%
Fire - other	1.26%

The hydrological, biological and chemical processes responsible for raising levels of water discolouration discussed in Section 2.3 may be exacerbated by changes in landuse and drainage which increase runoff and minimise the residence time of water in peat, so potentially increasing water discolouration when the soil is recharged (Shaw *et al* 1996, Evans *et al* 1999, Holden and Burt 2003).

Generally, loss of vegetation resulting from anthropogenic factors such as burning, grazing or increased gully erosion is likely to reduce interception of precipitation, increase wind exposure (and therefore evaporation) and desiccation and erosion associated with increased humification and thus water colour (Evans *et al* 1999, Warburton 2003, Worrall *et al* 2003). Removal of vegetation cover through grazing or burning can also affect the local microclimate; increase the likelihood of freeze/thaw action and therefore erosion, DOC and water discolouration (Hope *et al* 1997, Freeman *et al* 2001a).

Increases in stocking densities and erratic burning regimes have created unfavourable and degenerated upland catchments, some severely eroded and lacking in diversity of flora and fauna (Anderson *et al* 1997, Evans 1997, 1998, 2005 Tallis 1998, Pakeman *et al* 2003). Table 2.4 summarises the main factors affected by land management and drainage identified by researchers. The effects are discussed in more detail in the following sections.

Table 2.4: Impacts on Blanket Bogs associated with Land Use and Management

Threat	Impact on Blanket Bog	Impact on Wider Environment	Ongoing or Ameliorated	References
Land use and Management Controlled burning	Changes in soil structure, increased erosion, desiccation, humification. Change in species composition – loss of diversity - monocrop of heather or grass	Carbon release Changes in biomass and peat accumulation and nutrient cycling with lowering of water table, increased desiccation, humification and erosion. Chemical & physical changes to soil structure – amplify desiccation & erosion processes, loss of biomass, vegetation & species.	Ongoing, rise in controlled burning during 1980s-90s due to govt subsidies. Still widely practiced due to economic gain from grouse shooting.	Shaw *et al* (1996), Tucker (2003), Yallop *et al* (2005), Glaves *et al* (2005) Section 2.4.1
Grazing	Changes in soil structure, increased compaction & runoff, increased erosion. Raise nutrient level in concentrated areas. Frequent & concentrated removal of vegetation	Flood risk, deterioration of water quality, health risks	Possible amelioration due to change in govt subsidies to area payments. More prescriptive farm plans for stocking densities. Legacy of over-grazing is severe degradation in some areas and long-term recovery.	Shaw *et al* (1996), Section 2.4.2
Drainage (Natural and Anthropogenic)	Soil erosion, reduction in water table, desiccation and change in vegetation composition to “dry heath” or grass species.	Increased runoff & flooding; loss of carbon. Increased siltation of lotic (flowing water) systems and decrease in reservoir storage capacity through deposition.	Very few drains (grips) cut, but active erosion increasing gully-network, some grips still active. Programme of grip/gully blocking initiated.	Holden & Burt (2003), Holden 2006b), Evans & Warburton (2001) Section 2.4.3

2.4.1 Prescribed (Controlled) Burning

Several literature reviews have collated information on the effects of burning (and grazing) on particular land types and soils. These include the ENNR 172, "*Literature review of the historical effects of burning and grazing of blanket bog and upland wet heath*" (Shaw *et al* 1996) and ENRR 550 "*Review of the impacts of heather and grassland burning in the uplands on soils, hydrology and biodiversity*" (Tucker 2003). Following the publication of ENRR 550, Defra commissioned a further review to assess the effects of burning on biodiversity, soils and hydrology. This resulted in the "*Science Panel Assessment of the Effects of Burning on Biodiversity, Soils and Hydrology*" (Glaves *et al* 2005). The Science Panel define prescribed (controlled) burning as:

> *"Controlled fires sometimes called 'prescribed' or 'management' burns, are planned and carried out for land management purposes as they are controlled by the current Heather and Grassland Regulations and Code (though they do not always necessarily follow their requirements)" (Glaves et al 2005 p.18).*

Literature of direct relevance to the specific impacts of prescribed (controlled) burning on water discolouration and DOC is scarce. The main approach has often been concerned with the effects on agriculture from soil loss rather than specifically on water quality, conservation or restoration of upland catchments which often include areas of blanket bog (Stewart *et al* 2004). However, in terms of food production from agriculture (mainly grazing) and sport (mainly grouse), the principal aims of burning are to prevent establishment of woody species, to reduce litter and release nutrients. The effect is to stimulate earlier growth of grasses and *Calluna* and so temporarily increase the accessibility, palatability and nutrient content of forage for grouse and livestock (Gimmingham 1972, Lawton 1990, Tucker 2003).

Burning on grouse moors is generally through prescribed burning of strips approximately 30m wide and 0.5 ha in total area. The normal aim is to burn the heather when it reaches a height of 20-30 cm (late building/mature stage) which generally results in a fire return of 10-15 years, whereby a tenth to fifteenth of the land would be burnt on average each year (Tucker, 2003). The practice of rotational burning is aimed at maximising the grouse populations by creating and maintaining a mosaic of different growth stages of heather across a site (pioneer [young], building, mature and degenerate [old and collapsing]) (Andrews and Rebane 1994). This is intended to provide the optimum conditions required by the grouse for nesting, feeding and breeding (Lawton 1990).

The method of burning dwarf shrub vegetation has undergone a revolutionary change in the last 20 years. Traditionally fire kettles (paraffin containers with a wick) were used to light the vegetation which had to be relatively dry and was therefore burnt after a period of dry weather, or at the end of a day with the potential to create a relatively hot and intense fire and result in possible damage to soils and destruction of vegetation and seed banks (Glaves *et al* 2005). The 'cool burn' technique was introduced by Geoff Eyre (private landowner/farmer in the Peak District) which uses diesel or gas pressure burners and has now largely replaced the traditional burning methods and allows burning of damper vegetation and therefore cooler burns (G Eyre 2006, *pers comm*).

At present, the recently updated Heather and Grass etc Burning Regulations (2007) regulate the burning of moorlands and grasslands in England and stipulate legal prescribed burning is only permitted from 1st November to 31st March in lowland areas and from 1st October to 15th April in the uplands (Defra 2007). The timing restrictions are in place to minimise the effects of burning on any land type so that burning takes place while the ground and vegetation are still relatively wet and have not dried out and so ensure a "cool burn" that reduces the damage to the vegetation and underlying organic soils. The Burning Regulations are also supplemented by a voluntary Code (The Heather and Grass Burning Code updated in 2007 (HMSO 2007).

A review of the Burning Regulations and also the Code was conducted in 2005 by Defra in collaboration with Natural England, conservationists, farmers, gamekeepers, and moorland managers to assess whether they were "fit for purpose" or required some revision in the light of new evidence on burning since the Regulations were first published in 1994. The aim of the review was largely to determine the best means for ensuring that burning practices are sustainable and to the advantage of wildlife conservation and biodiversity, game management and to agriculture throughout a range of English landscapes and habitats (including upland catchments used for water supply) (Defra 2005). The main driver for the Defra review resulted from the publication of the interim Sites of Special Scientific Interest (SSSIs) Condition assessment and the main causes of unfavourable condition which threatened the achievement of Public Service Agreement (PSA) Target 3 (Objective 1, ii):

> *"Care for our natural heritage, make the countryside attractive and enjoyable for all and preserve biological diversity by: Bringing into favourable condition by 2010, 95 per cent of all nationally important wildlife sites" (Defra 2004 p 33).*

In addition, a Science Panel was set up by Defra to address the new "evidence" relating to controlled burning, particularly summarised in the "*Review of the Impacts of Heather and Grassland Burning in the Uplands on Soils, Hydrology and Biodiversity*" (Tucker 2003) which also addressed the contribution that sustainable burning practices made to the protection of soils, water and air (Glaves *et al* 2005). Their findings are discussed in the section on impacts of burning on peat soils.

2.4.1.1 The Extent of Burning on Peat Soils

Until recently, the actual extent and use of prescribed burning as a management tool in the uplands was unclear. Yallop *et al* (2005, 2006) estimated the extent of prescribed burning in the uplands using digitised aerial photographs and acknowledged that the areas included a combination of wet heath and bog, in addition to dry heath. However, they estimated a rise from 34% burns in the 1970s to 48.6% new burns in 2000 (Yallop *et al* 2006). Although the areas of consistently managed burns indicated a rotation of between 14-25 years and fell within the recommended burning rotation of 20 years on blanket bog (Shaw and Wheeler 1995), Yallop *et al* (2006) found a general trend of pronounced burning intensification which included areas designated as SSSIs.

2.4.1.2 The Impact of Burning on Peat Soils, Water Quality and DOC Flux

Conway and Millar (1960) studied the effects of burning on paired catchments in the north Pennines and found severe burning could alter the loose-textured surface of peat, changing it into an amorphous, hydrophyllic substance affecting water infiltration. Warburton (2003) also found the ignition of peat waxes during particularly intense fires could cause skin-like tarry bitumen to be formed, creating a crust on the surface of the peat which affected water infiltration. Studies by Mallik *et al* (1984) and Maltby *et al* (1990) reported that prescribed burning may also encourage erosion by increasing surface runoff.

Although Anderson (1986) initially studied the effects of wildfires on peat and did not compare it to controlled burning, she found that they had the capacity to cause extensive damage, particularly in years of summer drought and in areas of thin peat, resulting in severe erosion and poor vegetation regeneration.

In terms of water quality Mitchell and McDonald (1992) found that moorland burning could increase the colour store by lowering infiltration capacities and enhancing drying of the sub-surface soil, producing extreme colour when it eventually rewets. Hydrophobic compounds may also be deposited within the soil following burning through a process of distillation during prolonged smouldering burns (Garnett *et al* 2000). Garnett *et al* (2000) believed that this could then create layers of soil that interfered with water and root penetration to create structural weaknesses that may be more prone to erosion.

Maltby (1997) also found that temperature ranges in the upper soil may increase diurnally and seasonally following a controlled burn, with the formation of needle-ice encouraging erosion of bare peat and soil surfaces. These factors may raise peat desiccation and humification and provide a potential site for water colour generation and storage.

Tallis (1998) reported the immediate impact of a prescribed fire as the removal of vegetation, leaving blackened ash-covered exposed soil or humus. This top layer may be subject to greater fluctuations in soil surface temperature and moisture regimes, with higher temperatures and desiccation rates particularly during summer.

Imeson (1971) reported that burning *Calluna* eliminated interception and transpiration of precipitation and moisture, causing an increase in the volume and intensity of throughflow, which accelerated the formation, and growth of shallow gully networks and seepage faces. He found a relationship between gully development and moor burning, which could exacerbate peat desiccation and humification processes.

A review by Stewart *et al* (2004) questioned whether prescribed burning degraded blanket bog, but was inconclusive in its findings. They reported that the available evidence suggested that burning either degrades blanket bog or is contradictory in effect, with only one article reporting the effects of rotational burning. They recommended the precautionary principle of avoiding burning on blanket bog if favourable condition is to be achieved or maintained.

Yallop *et al* (2005) also reported that the immediate effect of burning bog vegetation is to destroy the above-ground woody tissues of the shrubs, the bog-moss surface, and any species sensitive to fire. Perhaps more importantly in terms of blanket bog conservation, Kuhry (1994) reported that prescribed burning may reduce or halt peat accumulation with a direct loss of *Sphagnum* moss, which is the main peat-building species (Ferguson and Lee 1983). Such losses will inevitably lead to exposure of soil and the acceleration of hydrological, biological and chemical processes such as humification, desiccation, runoff and erosion which are intricately linked to water colour production.

Glaves *et al* (2005) noted the lack of science based evidence of the effects of burning on blanket bog, but some research has recently been completed or is on-going to investigate the effects of prescribed burning on blanket bog. The research has tended to focus on water quality issues e.g. water companies interested in improving surface water quality draining from upland catchments through sustainable land management and has resulted in several water companies with upland catchment areas recently investing in research to determine the effects of land management practices (including prescribed burning) on water quality e.g. Severn Trent Water, United Utilities, Yorkshire Water, North West Water. For example, O'Brien *et al* (2005) have made a spatial study of water discolouration in the south Pennines (funded by Severn Trent Water) and investigated the effects of prescribed burning on a catchment scale.

White *et al* (2003) completed a scoping study for Yorkshire Water on the control of water quality and suggested that there was a significant relationship between the area of prescribed burn and the spatial variation of water colour within the catchments studied. This study has since been repeated by Yallop *et al* (2006) and the findings support the original study, suggesting that there is a clear correlation between the prescribed area burnt on deep peat and the generation of water colour.

However, O'Brien *et al* (2006) also completed a study of water discolouration in the headwaters of the Derwent catchment, south Pennines (funded by Moors for the Future) and found there was no significant relationship between the percentage area of prescribed burn and true (filtered) water colour across the Derwent catchments. Nevertheless, they did identify a positive correlation between water colour, soil type (specifically Winter Hill peat, characteristic of blanket bogs) and high altitude.

Holden (2005b) found that the number of underground soil pipes was significantly higher under *Calluna*-covered peat than any other vegetation types, suggesting that the current burning regime practiced to increase the spread and vigour of *Calluna* plants may induce sub-surface erosion through increased macropore flow around the woody rhizomes and the development of pipes. The exit holes of soil pipes were also identified as point-sources of highly discoloured water during rainfall events.

Clement (2005) study of plot sites at Burnt Hill, Cumbria found that the runoff rates from unburnt heather were approximately 3 mm hr^{-1}, but when the site was burnt, the runoff production was increased to 11 mm hr^{-1}. She suggested that not only did the heather burning cause a loss of vegetation, but also an increase in runoff production of 8 mm hr^{-1}.

Recent evidence of the effects of burning has been presented by Worrall *et al* (2007a) who investigated the effects of prescribed burning at Trout Beck catchment, located in the headwaters of the River Tees within the Moor House NNR. They utilized the experimental plots set up on Hard Hill in 1954, which included some plots not burnt since then and some burnt regularly on 10 and 20 year rotations. Results indicated that rotational burning (with grazing) was associated with decreased relative depth of the water table (20 year cycle by 8% and 10 year cycle by 26%). The deepest water tables were found on ungrazed and unburnt plots. It was suggested that this may be explained by a change in vegetation, with shrubby species such as *Calluna* dominating on the "unmanaged" plots and increasing evapotranspiration. Worrall *et al* (2007a) also noted that the presence of burning decreased the soil water pH and electrical conductivity was also found to be lower on burnt plots. On plots not burnt the soil water compositions were pH 4.11-6.93, whilst on burnt plots they were reduced to pH 4.09-5.43. The lowest dissolved organic carbon (DOC) concentrations were observed on those grazed plots which were also burnt on a 10 year rotation. These also recorded the lowest conductivities. Several possible explanations were proposed, including changed flow paths that reduce residence time of waters, or hydrophobicity created by frequent burning resulting in water having less contact time with the soil organic matter, but the presence of burnt material (ash) was suggested as the most likely explanation. Worrall *et al* (2007a) concluded that regular burning and grazing had certainly limited development of vegetation on the plots, and noted that short burning cycles may bring water tables nearer the surface and have some benefits for loss of DOC, but they also stated that conditions may be very different shortly after a burn and that it is important to consider the whole cycle of burning when considering whether it is a beneficial management practice.

2.4.2 Grazing

JNCC Common Standards Monitoring (CSM) (JNCC 2006) guidance states that overgrazing is the second cause for blanket bog degradation on SSSIs in England with 31.24% of SSSI units being found in unfavourable condition due to over-grazing (see Figure 2.1) (English Nature 2006). The term “over grazing” has been included in the statutory definition of the Good Farming Practice Guide for the England Rural Development Programme and is defined as:

> *“Grazing land with livestock in such numbers as adversely to affect the growth, quality or species composition of vegetation (other than vegetation normally grazed to destruction) on that land to a significant degree” (Defra 2006 p. 11)*

Small herbivores such as voles, grouse and hares are a natural feature of blanket mire and are not considered harmful, but the large herbivores associated with upland catchments with peat soils > 0.5 m (defined as blanket bog) are predominantly domesticated sheep (cattle, ponies and deer also graze in some areas) and have been associated with its degradation (Hulme and Birnie 1997, Reid and Grice 2001). Grazing or herbivory are frequently thought of as having negative impacts upon the maintenance of blanket bog ecosystems and may be considered completely unnecessary as a management tool where active blanket bog conditions prevail and the climax vegetation is maintained through a functioning hydrological system (English Nature 2005). However, these conditions do not persist across most of the UK blanket bogs moors and it has been suggested that grazing by wild and domestic herbivores is crucial in preventing colonisation of the bog surface by trees (Thompson *et al* 1995, Welch 1998). In fact, the most recent advice from agencies such as Natural England (previously English Nature) is to not graze at all on wet blanket bog (English Nature 2005, Reid and Grice 2001).

There is a vast amount of literature available on the effects of grazing on various land types, the first study of which was in 1977 which examined the effect of grazing on the hills in the Peak District (Evans 1977), followed by a number of studies and reviews (e.g. Yalden 1981, Shaw *et al* 1996, Evans 1997, 1998, 2005, Backshall *et al* 2001). However, Shaw *et al* (1996) pointed out that much of the literature on the impacts of grazing has focused on dry heath and that very few studies have included blanket bog. The Defra literature review of hill farming in the uplands: "*An assessment of the impacts of hill farming in England on the economic, environmental and social sustainability of the uplands and more widely*" (IEEP 2004) also found that there was little empirical research to indicate a causal relationship between grazing and ecological or landscape changes on blanket bog or wet heath. Indeed, the commissioned research on overgrazing in the uplands funded by Defra has primarily focused on the maintenance and enhancement of heather moorland, making it difficult to identify effective management prescriptions for achieving favourable condition on other forms of moor such as blanket bog. This may be considered an area for specific research focus in the future.

Many mire species have a marked seasonal pattern of growth, but only *Calluna vulgaris*, *Eriophorum vaginatum* and *Vaccinium myrtillus* provide winter grazing of relevance for areas of upland which are grazed throughout the year. Fresh plant growth normally commences in April, but only *Molinia caerulea*, *Scirpus cespitosus* and *Rubus chamaemorus* provide summer grazing for sheep and cattle, whilst *Eriophorum angustifolium* is utilised in later summer and autumn, for example Rawes and Hobbs (1979) found bare ground could be created around areas of *Sphagna* and large lichens which attracted grazers. Several authors have observed that if the soil surface is continually disturbed by animals during the growing season, seedling germination and invasion by plants will be inhibited (Anderson and Radford 1994, Mackay and Tallis 1996, Bragg and Tallis 2001, Evans 2005). Climatic conditions occurring in the uplands in winter, such as frost-heave, heavy rainfall and strong winds may then prepare the soil for further erosion and result in the expansion of bare areas of soil (Evans 1997, 1998, 2005). Although some of these areas may be readily colonised by bryophytes, peat in particular may become so unstable and erodible when exposed that vegetation cannot easily take hold (Evans 1997, 2005). The effects of grazing can be long-lasting and there is a lack of quantified science-based research to suggest how long it may take before a degraded moorland may recover from the effects of over-grazing. A review of impacts and their recovery with regard to soils, water quality and DOC flux is discussed in Section 2.4.2.1.

2.4.2.1 *Impact of Grazing on Peat Soils and Water Quality and DOC Flux*

McHugh *et al* (2002) investigated the spatial distribution of erosion in the uplands through repeated visits to National Soil Inventory sites. They identified overstocking as a significant threat to the environment and found bare areas of soil were limited to discrete features such as sheep scars or gullies in areas of degraded peat. Evans (1977, 1997, 2005) found bare soil was created by sheep when the grazing intensity was 0.5-0.6 ha per sheep/lamb, rising to 0.15-0.3 ha/sheep summer grazing levels where scars were widespread. He found that most bare soil was created by sheep at small breaks of slope where they initiated scars by rubbing against the vegetation. He also found poorly drained peat soils on flat or gentle slopes were particularly sensitive to sheep grazing and may be liable to sheet and gully erosion. Such disruption in the physical structure of the peat may result in wastage and soil oxidation, increasing erosion and potential water discolouration (Garnett *et al* 2000).

The grazing behaviour and preferences of herbivores have been well reviewed by Shaw *et al* 1996 and Backshall *et al* (2001) and these highlight the problems of determining the level of impact of the grazing livestock on blanket bog. The response to stocking densities will not only be affected by the type of grazer (due to its feeding preferences and grazing techniques), but a range of other environmental variables that may be site specific. The main components of the grazing process are defoliation when vegetation is eaten and/or trampled by sheep and exposure of bare organic soil which is susceptible to erosion through weathering processes, particularly by wind and water in the uplands. The effects of trampling are likely to be more evident on wet ground such as blanket bog, where hoof prints can cut through the vegetation into the underlying peat (Evans 2005) or disturb the upper layers of exposed peat soils and disrupt the physical structure of peat, again making localised areas more vulnerable to soil losses through erosional weathering processes and oxidation (McDonald and Naden 1998, Warburton 2003). However, the intensity and extent of damage will vary according to the factors such as husbandry techniques, stocking densities and breed of livestock (RSPB 1995, Backshall *et al* 2001, Stewart and Eno 1998):

Variation in husbandry techniques across England and Wales may also be of relevance for the condition of upland catchments as this will affect the grazing preferences of sheep at different times of the year and the vulnerability of peat soils to increased erosion. For example, in the Peak District the normal practice is to leave most of the hill sheep out on the upland grazing throughout the winter (set-stocking) whereas at Moor House (northern Pennines) sheep generally graze only from April to October. Issues associated with increased stocking densities and lack of shepherding have included loss of vegetation structure; creation of short swards; heavy trampling and poaching contributing to increased run-off and flooding incidents downstream; erosion of peat soils through trampling and sheltering by sheep; and contamination of watercourses with run-off from these areas (Evans 1997, 2005, Reid and Grice 2001). These effects may be exacerbated by set-stocking and over-wintering of stock on the blanket bog when the water table is high and when wet areas are more susceptible to trampling and poaching damage (Shaw *et al* 1996). In addition, Evans (1997) reported that where the vegetation is weakened or disrupted at small breaks of slope, sheep can form hollows or scars in which to rest or take shade. He observed that where these scars penetrate into unstable soils, such as peats, the area of bare soil can rapidly expand and lead to expansion of other bare areas downslope where the disturbed soil buries vegetation. He also noted that sheep scars may form "knickpoints" in valley floors which may initiate up-valley gully incision (Evans 1998).

Although many researchers have found that livestock may cause soil compaction and increase runoff from upland catchments, few quantitative studies have been completed to determine the link between livestock densities and erosion rates. However, a study at Blelham Tarn, Cumbria by van der Post *et al* (1997) of two frozen sediment cores showed an exponential increase in sedimentation rates for the past 40 years which could be attributed to erosion within the catchment. The predominant sediment source was identified as surface soil and could be closely linked with the increase in sheep stocking density in the catchment during the same period. Monitoring studies in Wales found an 11% loss of organic matter in soil from permanent pasture between 1980 and 1997 with the worst effects found on peaty soils and over-grazing identified as one of the major contributors of erosion (Reynolds *et al* 2002). Further studies have examined the effect of stocking densities on soil structure and function, including water movement in upland soils. Sansom (1999) found that annual water yield increased on the north Derwent catchment where sheep numbers were doubled from 1944-75. Carroll *et al* (2004) completed a study at the ADAS Pwllperian research farm, mid Wales and found the infiltration rates, that is, the rate of water movement into the soil, doubled on pastures grazed by sheep over a 15 year period. During this time, the sheep numbers were reduced from 3.7 sheep.ha^{-1} to 1.9 sheep.ha^{-1} and the results suggest that even at quite low stocking rates, the soil may be compacted and result in a lowering of the infiltration rate. The study concluded that the relationship between peat soils and stocking densities was complex and that further studies were required on peat soils using a number of replicate plots on differing soil textures in order to further the understanding of the relationship between stocking densities and the affects on soil. Clement (2005) found runoff was higher where sheep grazed compared to an exclosure where sheep had been excluded at Burnt Hill, Cumbria and concluded that grazing pressure affected the vegetation cover and runoff production, but had little impact on increasing sediment production. She found that grazing on unburnt heather vegetation increased runoff production by 4.4 mm hr^{-1}, on burnt heather by 1.5 mm hr^{-1} and on moorland grass by 0.8 mm hr^{-1}.

2.4.3 Naturally Eroding Gullies

The general definition of a gully has been given by Brice (1966) as a "recently extended drainage channel that transmits ephemeral flow, has steep sides, a steeply-sloping or vertical head scarp, a width greater than 0.3m and a depth greater than 0.6m". These naturally-eroding systems occur extensively throughout upland catchments associated with deep peat soils and differ from the man-made moorland grips. The grips are generally more uniform in width and depth, having been dug with a plough for the sole purpose of draining the land more effectively.

Gully systems that are particularly characteristic of an eroding blanket bog are produced by water erosion (Warburton 2003, Evans *et al* 2005b) and can be observed on the interfluves of blanket bog, particularly in the south Pennines where this type of erosion is thought to be most obvious and widespread (Conway and Millar 1960, Bower 1962, Tallis 1965, Tallis 1998, Evans *et al* 2005b). Figure 2.3 shows an example of a large gully in the headwaters of a deep peat catchment in the south Pennines, UK.

Figure 2.3: Gully formation in deep peat, south Pennines, UK (O'Brien 2003)

Gully systems are considered to be relatively permanent water courses, but are associated with landscape instability and accelerated erosion (Evans and Warburton 2001). However, there has been relatively little research on the development of gully networks in peatland systems (Labadz *et al* 1991, Evans *et al* 2005b). It is generally agreed that most of these networks originate from 400-600 AD (Tallis and Switsur 1973, Labadz *et al* 1991), although more recent gully erosion within the last 200 years (Tallis 1973) are likely to relate to the continuing long-term development of these gully systems and increased human activity particularly prescribed burning and intensive grazing (see 2.4.1 and 2.4.2) which may have accelerated the erosion processes (Tallis 1998)..

2.4.3.1 Impact of Gully Erosion on Water Quality and DOC Flux

The rate of gully network development on blanket peat in the last 150 years is of concern, having been estimated at around 6mm.yr^{-1} (Tallis 1998). Labadz *et al* (1991) found evidence that much of a gully network in the Peak District would have eroded within 200 years at current rates, with sediment yield estimated at ~ 50 t.km^{-2}.yr^{-1}. Evans *et al* (2006) compared a gully system in the north Pennines (Rough Sike) with one in the southern Pennines (Upper North Grain). They obtained organic sediment yields of 31 t.km^{-2}.yr^{-1} in the former, where revegetation seems to be occurring naturally, but ~ 195 t.km^{-2}.yr^{-1} in the latter where active erosion represents a significant loss of particulate carbon. Gully erosion and its contribution to peat desiccation and accelerated decomposition has also been associated with the release of carbon into water courses (POC, DIC, DOC and water discolouration), and CO_2 into the atmosphere (Evans and Warburton 2001).

Whilst overland flow and water erosion has been recognised as the major factor contributing to gully formation, workers such as Sansom (1999), Jones (1981) and Bower (1960) recognised that some gullies started as underground water courses (soil pipes) with their floor on the peat base and originated with the collapse of subsurface pipes. These soil pipes have initially been attributed to a number of factors such as climate, faunal activity (burrowing) and live or decaying roots (e.g. *Calluna*), and occur preferentially in soils of a certain chemical and pedological quality such as peat soils, particularly those subject to some form of degradation leading to shrinkage and cracking (Jones 1981, Jones *et al* 1997, Holden and Burt 2002b, Holden 2005a). These pipes can be up to hundreds of metres in length and vary greatly in diameter from a few centimetres to more than a metre, but typically form branching subsurface networks which undulate throughout the peat profile (Jones 1981, Holden and Burt 2002b). Such a dense network of underground drainage coupled with surface drainage will obviously contribute to the volume of sediment, DOC and water colour being discharged from a catchment in terms of overland and subsurface runoff. Table 2.5 summarises the main hydrological and hydrochemcial effects on blanket bog arising from natural and man-made drainage systems.

Table 2.5: Hydrological and Hydrochemical Effects on Peatlands from Natural and Artificial Drainage

Process	Response	Effect	Reference
Carbon sequestration	Change from sink to a source	Drainage and lowering of water table with the resultant increase in aerobic peat layers can change bog from a carbon sink to a carbon source.	Holden (2006), Holden *et al* (2006a)
Direct drainage	Alters flow patterns	The presence of dense gully/grip networks creates rapid runoff. Results in increased sensitivity of runoff to storm events with higher peak flows occurring earlier. Contradictory evidence of deep water table and slower runoff from drained bog due to underground flow rather than surface flow Drainage and rainfall-runoff relationship will vary between peat types due to different hydraulic conductivity properties of peat soils Drainage density – spacing of <4m required, if exceeds distance may not drain peat due to very low hydraulic conductivity Flood peaks increased due to increase peak flows. Changes observed at hillslope and catchment scale	Conway and Millar (1960) Evans *et al* (1999), Holden and Burt (2002b) Burke (1967) McDonald (1973) Stewart and Lance (1991) Robinson (1985)
	Dewaters peat body	Drained peatlands tend to increase low flows as the peat slowly "de-waters" and temporarily increases the storage capacity as water table is lowered	Robinson (1985), Holden *et al* (2004)
	Lowers average water table	Although the main aim of ditching is to reduce the water table, contradictory evidence of the effectiveness of the drains in doing so. Ditches may have a localised effect on the water table and may increase the runoff of surface storm water without altering the storage capacity of the catchment.	Conway and Millar (1960) Stewart and Lance (1991), Holden *et al* (2004).
Desiccation & oxidation	Increases microbial activity and peat humification	Bacterial aerobic activity increased in desiccated layers which decomposes and humifies upper layers of soil.	Christ & David (1996), Clymo (1983), Worrall & Burt (2004)
Loss of soil structure	Increase in bulk density, compression & cracking	Severe shrinkage and decomposition caused by a lowering of the water table, bulk density of peat in upper layers increases. Physical breakdown and consolidation of peat	Egglesmann *et al* (1993)
	Slumping, hydrophobicity and cracking	Subsidence associated with collapse of drainable macropores. A rise in capillary action results in an increase in water removal from sub-surface layers leading to an acceleration of peat shrinkage and cracking. Once the peat dries out and becomes hydrophobic, it cannot be readily re-wet to re-gain its original moisture content.	Holden *et al* (2004),
	Change in vegetation composition	Loss of diversity and restriction in the full range of bog species, elimination of water-tolerant species e.g. Sphagna and increase in graminoid species.	Fisher *et al* (1996), Coulson *et al* (1990)
Mineralisation	Increased mineralisation of peat and release of nutrients	Oxygenation of the peat enhances the mineralisation of nutrients, particularly Carbon-bound N and S, and organically bound P. The rate of mineralisation is effected by environmental factors such as pH, temperature, redox potential in addition to substrate factors e.g. decomposition, organic matter, nutrient content, inhibitors (chemical & biological) to microbial activity.	Scott *et al* (2001) Scott *et al* (1998)
	Change in nutrient composition	Increase in N and P and decrease in K of peat after drainage caused by an increase in the retention of N by microbial immobilisation as plant residues decompose and total N per volume of peat is increased and lowers C:N ratio.	Sundstrom *et al* (2000), Proctor (1992, 1994)
	Changes in water chemistry	Large increases in NH_4 concentrations from ditching and lowering of water table, but small increases in nitrification. Contradictory evidence of increases and decreases in Ca, Mg and K from drainage.	Scott *et al* (2001) Crisp (1966)

Little investigation of associated floristic changes that result from natural drainage of the land has been completed as most work has concentrated on the effects of anthropogenic drainage systems (grips). Consequently the inter-relationships between vegetation growth and hydrological conditions in wetlands are not very well understood (Yazaki *et al* 2005). Stewart and Lance (1983) reviewed the studies available at that time and concluded that moor grips generally had a minimal impact on the hydrology and vegetation of peatlands. They generally accepted that the immediate effect of drainage was to lower the overall water table in the adjacent mass, and to increase the amplitude of short-term and seasonal fluctuations in the water table. However, various research has reported that this effect rarely extended beyond 0.5-2 m (Stewart and Lance 1983, Robinson 1985) and therefore had little overall impact on the blanket bog. Coulson *et al* (1990) concluded from their study at Moor House NNR, North Pennines and Waskerly, County Durham, that the greatest effect of drainage and therefore desiccation would occur immediately downslope of each ditch. However, they found that there was no significant change beyond 5 m in the composition of flora relative to the position of the ditch and that the effects of upland drainage were negligible. Conversely, other researchers have found that following drainage, the vegetation in a narrow strip adjacent to the ditch edge is modified as a result of the lowering of the water table and the deposition of excavated peat. Studies have generally found that the prominence of dwarf shrubs such as *Calluna, Empetrum nigrum, Erica tetralix* and *Vaccinium myrtillus* increased following the installation of drainage (Tallis 1965, Anderson *et al* 1995, Tallis 1998).

2.4.4 Gully-blocking

Gully blocking in deep peat is still a very recent approach to moorland restoration and erosion control. The main aims of this technique are to:

i) Control further gully erosion;

ii) Reduce sediment loss from peatlands;

iii) Promote revegetation;

iv) Reduce water discolouration in streams;

v) Raise local water table levels to saturate peat (Evans *et al* (2005b).

This technique has been pioneered by the National Trust in a number of areas in the Peak District, and by Natural England (e.g. Saddleworth Moor, Yorkshire) (Trotter *et al* 2005). Although the National Trust has used gully blocking as a restoration technique since 1992, this has generally been on a small-scale where specific gullies have been targeted for blocking (e.g. Kinder Scout, Bleaklow, North Grain on the High Peak Estate, south Pennines). There is currently only one example of large-scale restoration using gully-blocking on a catchment-scale and this has been implemented by the High Peak Partnership Project on the Within Clough catchment, south Pennines and forms part of this research. This site was also used by the University of Manchester to determine the extent of revegetation of blocked gullies with those that had re-vegetated through natural blockage in the gully system.

The lack of experience of techniques and of empirical science-based evidence to support on-going gully blocking strategies resulted in the Moors for the Future (MFtF) commissioning the Universities of Manchester and Leeds to identify strategic locations for gully blocking in deep peat and review methods and techniques for gully blocking (Evans *et al* 2005b, Trotter *et al* 2005). The research objectives were to assess and predict the hydrological and geomorphological impacts of existing and planned blocks within the Dark Peak; to determine feasible locations for gully blocking in deep peat and to develop a decision making process for prioritising sites and materials that could lead to the successful revegetation and control of moorland erosion (Evans *et al* 2005b). This resulted in the publication of a comprehensive report: "*Understanding Gully Blocking in Deep Peat*" (Evans *et al* 2005b), that was necessary due to the planned extensive and potentially costly use of gully blocking in the Bleaklow Restoration Project.

2.4.4.1 Impact of Gully-blocking on Water Quality, Hydrology and DOC Flux

Historically ditch blocking has taken place on peat (both raised and blanket bog) that has been severely degraded by peat harvesting and extraction, resulting in a change in soil structure, loss of hydrological function and change in vegetation. Although the effects of restoration through ditch blocking have been monitored at sites in North America, northern Europe and the UK, the results may not be directly comparable or perhaps even relevant to the effects that may occur from ditch blocking on degraded peat soils. Conditions and therefore responses may vary greatly. Research on the different techniques of grip blocking in the UK has been limited due to a dearth of prioritisation of funding for monitoring by land managers and agencies and therefore a lack of science-based evidence exists. Despite this there seems to be a programme of restoration by grip (and gully) blocking that is going ahead unabated, reflecting the perceived urgency of the situation as a result of the recognition of these sites as important stores of carbon, water and wildlife which need to be protected from further degradation. However, the lack of funding for sustained scientific monitoring means there are a number of unresolved issues regarding the short- and longer-term effects of such management practices.

The rationale used for many ditch/gully blocking restoration projects is to "raise the water table level" in an attempt to increase the wetness of the peat and so facilitate conditions for mire plant vegetation and the continued sequestration of carbon. Where monitoring has taken place, there is a general indication that water table recovery following ditch blocking is quite rapid (Grosvenier *et al* 1997, Price 1997, Veli-matti *et al* 1999, Holden 2005a). However, Wheeler *et al* (2002) considered that it was still unclear whether full hydrological and hydrochemical recovery is possible, together with the recovery of an accepted vegetation composition desired to enhance peatland biodiversity (Bragg and Tallis 2001).

Nevertheless, some recent research has indicated positive changes associated with ditch blocking. A limited amount of research has been completed as to the effectiveness of ditch blocking in terms of hydrology, sediment production, and carbon release (water colour and DOC) and this has largely been supported by water companies such as Severn Trent Water, Yorkshire Water, United Utilities and Northumbrian Water who have a vested interest in the upland catchments which provide an important source of potable water. A study of the hydrologic status of an intact, drained and blocked area of the Geltdale and Glendue SSSI by Holden (2005c) found that there was evidence of hydrological recovery on the blocked site. There was less tendency for the water table to penetrate the deep peat (catotelm) and less fluctuation in response to climatic conditions. Overall discharge of the monitored grip showed a reduction in the discharge in year 2 compared with year 1 (under similar climatic conditions) and low flows were maintained in the blocked grip during the second summer.

The Whitendale Trial (Armstrong *et al* 2005, Worrall *et al* 2007a) showed that grip-blocking reduced runoff in the grip by up to 90% with an average effect of a 70% decrease in flow, and water tables increased significantly during that period. However, the study also indicated that grip-blocking increased water colour concentration within the grip when compared with unblocked (control) grips and this was maintained throughout the study period. The runoff from the blocked grip was higher in water colour and there was no significant benefit on the water colour of the blocked grips within the limited period of the study (Armstrong *et al* 2005, Worrall *et al* 2007a). Grove (2005) also studied the Whitendale site and observed that erosion occurred around the edge of some of the plastic piling blocks where the peat had been exposed at the surface, causing desiccation and shrinkage of the peat soil resulting in a crack being created between the pile and the peat. Such cracks are susceptible to further erosion, particularly by water and at such points the water may find a preferential path around the grip, scouring out the peat and so reducing the effectiveness of the grip block (Grove 2005). Figure 2.4 shows a crack formed at the grip blockage at the Whitendale site.

Figure 2.4: Soil Shrinkage by Grip Block (Plastic Piling) (Grove 2005)

Another concern for the hydrology of blanket bog is that there is a potential for drainage to cause major and irreversible damage to peat soils, particularly through accelerated runoff and sub-surface pipeflow (Jones and Crane 1984, Jones *et al* 1997). Holden (2005a) suggested that many of the restoration programmes which place small dams into ditch (grip) networks in order to block them up and rewet the peat soils should also consider the changes in peat structure and hydrological routing that may have taken place since the drains were installed. This re-routing of water through a dense network of soil pipes may need careful consideration when planning future restoration work in order for such projects to achieve their aims of rewetting the blanket bog and reducing the volume of sediment and particulate carbon from the catchment via a dense pipe work mechanism.

Holden *et al* (2006b) found blocked ditches produced approximately the same sediment load as undrained peat and that partially blocked drains (for example, naturally in-filled drains partially blocked by slumping peat) had a mean flow velocity of two orders of magnitude lower than that in clear drains and three orders of magnitude less sediment than clear drains.

Wallage *et al* (2006) examined the effect of drain blocking for reducing dissolved organic carbon (DOC) and water discolouration from Oughtershaw Beck, a headwater tributary of the River Wharfe, northern England. The ditches in this area were blocked using peat blocks in 1999 under the Upper Wharfedale Best Practice Project. They found that the artificially drained areas of peat produced higher levels of water colour and DOC compared to intact areas of peat, although the blocked drains produced lower rates of water colour and DOC (average 62% and 69%) when compared with the drained site. The *Carbon:Colour* ratio showed that for every carbon unit, the

DOC at the blocked site contained significantly more colour than per unit of carbon at the intact or drained sites. This suggests that the DOC at the blocked site was obtained from a more humified source than at the intact site and implies some form of disturbance to the DOC production and/or transportation process (drainage installation creating water table fluctuations and increased oxygenation and enhanced microbial activity). They concluded that most of the additional colour and DOC came from peat deeper than 0.1 m, but shallower than 0.4 m, with an almost 40% increase at 0.2m depth and recommended ditch blocking as a suitable technique to ameliorate the enhanced water colour and DOC associated with peatland drainage.

Monitoring of ditch blockages on peatland catchments thus appears to indicate that there is a beneficial effect in terms of hydrological function by rewetting the peatland and reducing the discharge from the catchments, and there is at least one study showing evidence of decreased water colour on blocked sites, but early indications show that the ditch drainage and subsequent blocking can cause an increase in the release of water colour and DOC.

The research on effects of grip blocking has generally been completed within the last five years and started after the commencement of this reported research. There is a need for further research and the collation of spatial and temporal data to determine if initial changes observed are a result of variability in catchment conditions or are a result of changes in land use and the re-blocking of gullies or grips.

2.5 Predictive Models of Water Colour and DOC

Models are invaluable tools for resource management as they help managers to develop a shared conceptual understanding of complex natural systems and allow testing of management strategies to predict outcomes of high-cost environmental manipulations and so set priorities (Caminiti 2004). Natural systems are however, extremely complex and even a detailed simulation model may be considered simple in comparison and prevents the ability to predict accurately within reasonable error levels when sufficient detail is lacking (Reckhow 1985). Uncertainties in the output from models often arise from conceptualisation of the processes modelled, the quality and quantity of data, constraints on the modelling technology and assumptions used in the scenario tested (Caminiti 2004).

Researchers have developed models which may be more successful in hindcast than forecast mode and their application to other catchments from the one on which they were developed may not be reliable (Ward and Robinson 2000). As a result there are numerous models which have been developed initially for water colour (e.g. Jolly and Chapman 1987, Naden and McDonald 1989, Mitchell and McDonald 1991) and more recently for predicting DOC concentration (e.g. Boyer *et al* 1996, Worrall and Burt 2005, Quinton *et al* 2006, Johnston *et al* 2007, Worrall *et al* 2007a).

The models for prediction of water colour and DOC incorporate aspects of integrated catchment management at a number of levels from micro and macro-scale using deterministic to broad-brush models which creates difficulties in choosing the most appropriate to meet a resource managers needs (Caminiti 2004).

The two basic models used in terms of catchment scale are firstly the lumped model which involves a single value being applied to each parameter representing the whole catchment (Kirkby 1988) and therefore do not account for the spatial variability within a catchment. Secondly, the distributed model by contrast, separates the catchment typically into grid cells where values for each parameter are represented in each grid cell. This therefore accounts for the spatial variability within the catchment and allows the calculation of fluxes from the catchment and subsequently almost all models are now distributed (Kirkby 1988).

A third and widely used approach to modelling water colour and DOC concentrations is the empirical model which is based on observation rather than theory and define a mathematical/statistical relationship (usually through regression analysis) between the dependent variable being modelled (in this case water colour or DOC) and factors perceived to influence the dependent variable (e.g. rainfall, discharge, or pH). Although such models have been found to be good predictors, they often are not able to explain the processes involved because of the long lags in the system.

To overcome this, process-based models have been developed to encompass the actual processes and factors involved in the generation and output. The model parameters have a direct physical interpretation of the process being modelled. Section 2.5.1 discusses the use of such models in the prediction of water colour and DOC.

2.5.1 A Review of Predictive Models of Water Colour and Dissolved Organic Carbon from Catchment and Meteorological Variables

Whilst there are numerous water quality models, the fundamental concepts on which they are based are relatively few and quite simple. The three basic concepts are concerned with generation, delivery and transport. Most of the techniques used to model water quality have been based on averaging across time (e.g. daily vs long term), spatial range (e.g. sub-catchment to whole catchment) and processes (e.g. hillslope or gully erosion). Examples of European models used to model changes in water quality include CHESS (Climate, Hydrochemistry and Economics of Surface Water Systems), SWAT (Soil Water Assessment Tool) and CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) (Boorman 2003).

The environmental factors known or that can be hypothesised to affect water discolouration and DOC concentrations have been discussed in the literature review; for example, changes in atmospheric pollution, factors associated with climate change which affect soil productivity, degradation and mobilisation within the catchment and soil and land cover characteristics. Clearly there are a large number of processes that need to be considered and in addition, the interaction of such processes requires an understanding in order to successfully comprehend the variation in water colour and DOC concentrations on a temporal and spatial scale.

Previous researchers (for example Jolly and Chapman 1987, Naden and McDonald 1989) have used stepwise multiple regression techniques to generate a predictive model from independent variables in order to predict true colour (°H). Whilst meeting with some success, Jolly and Chapman (1987) found their model worked well on catchments with a seasonality flush, but was poor on those catchments with a steep rise in colour. This form of empirical modelling of water colour was used to develop a lumped model of colour response as the calculations are based on processes operating uniformly over the catchment.

Naden and McDonald (1989) developed three models to predict water colour in the Upper Nidderdale catchments, North Yorkshire from data collected at the nearby Chellow Heights Water Treatment Works (WTW). The first model was a time series model to predict changes in the level of water colour discharged from the catchment. A Box-Jenkins approach to modelling seasonal time series was applied to the water colour data and an autoregressive moving average ARIMA model applied to find the best fit of a time series to past values of the tme series in order to make forecasts. They found that although the seasonal influence and overall pattern of water colour was reasonably modelled, the extremes in the data were underestimated.

To overcome this problem, Naden and McDonald (1989) developed two transfer function models which attempted to predict water colour using two other explanatory variables – rainfall and soil moisture deficit. However, as the two variables are related (soil moisture deficit is in part a product of cumulative rainfall), they provided two methods of examining the same underlying mechanisms. They found water colour was negatively correlated to rainfall in the previous 7, 8, 15 and 16 months. In terms of the autumn flush of colour, this implied that high autumn colour was related to a dry spring and in the previous year, a dry summer. The transfer function model for rainfall explained 58.7% of the variance in water colour.

They also found soil moisture deficit was highly correlated to water colour in the current and previous two months as well as in the same season in the previous year (i.e. 13, 14, and 15 months previously). The transfer function model explained 68.8% variance in water colour data which was an improvement on the seasonal time series model for predicting water colour.

Pattinson *et al* 1994 found water discolouration was associated with high values of the topographic index Ln (a/tanβ), peat depth and aspect of the local slope and developed a predictive model to identify potential areas of high water colour and so allow land managers to manage water resources more effectively.

Boyer *et al* (1996) used TOPMODEL (which incorporates the topographic index Ln (a/tanβ) to simulate the hydrological response from a catchment and then routed the predicted flows through a simple model that accounted for the temporal changes in DOC. The conceptual model represented the terrestrial (soil) reservoir in which DOC built up during low flow periods and was subsequently flushed out when infiltrating meltwaters caused the water table to rise into the reservoir.

Several researchers have developed the use of TOPMODEL and the topographic effect on soil moisture and hydrology and applied the model at a catchment scale (e.g. Mackay and Band 1997, Naden *et al* 2000) improving on the individual hillslope representation identified by workers such as Pattinson *et al* (1994) and Boyer *et al* (1996).

As computing power and GIS capabilities have improved, spatially distributed models have been developed to simulate the runoff and erosion dynamics of larger and more complex catchments (Tong and Chen 2002, McCabe *et al* 2005). This has the advantage of identifying source areas likely to generate water colour and DOC and be proactive in minimising or preventing the occurrence. The disadvantage of such models are that they are often not capable of simulating change over long periods, particularly seasonal change occurring in the natural environment such as plant growth and development, soil moisture deficit and evapotranspiration and is clearly a disadvantage when considering the impacts of climate change. An alternative approach to the identification and prediction of change in water colour and DOC concentrations is the use of paired catchment studies and this method of analysis is discussed in Section 2.5.2.

2.5.2 A Review of Paired Catchment Studies to Predict Changes in Water Discolouration and Dissolved Organic Carbon

Paired catchment studies have been used widely as a means of determining the magnitude of water yield changes resulting from large scale changes in land management (e.g. Elliott *et al* 1999, Evans and Warburton 2001, Burt and Swank 2002, Best *et al* 2003). Blackie and Robinson (2007 p 31) advocate that "*Despite their limitations, catchment studies are the only way to demonstrate the effect of a change in land use at the catchment scale in the way that plot studies and mathematical models fail to do*".

These studies involve the use of two catchments with similar characteristics in terms of topography, pedology, area, vegetation and management. Following a calibration period, where both catchments are monitored, one of the catchments is then subjected to treatment and the other remains as a control (Best *et al* 2003). This allows the climatic variability to be accounted for in the analysis. Any change in water yield can then be attributed to changes caused by the treatment process.

A number of methods of analysis of data at various time scales have been used, but the most commonly accepted method is to produce a linear regression between the control and the treated catchment for data collected during the calibration period (Best *et al* 2003, Brown *et al* 2005). The regression equation is then used to predict the variable (e.g. water colour or discharge) that would have occurred in the treated catchments if the treatment had not taken place. The difference in the observed and predicted variable is then assumed to be caused by the changes in landuse as this method provides a control over climatic variability (Bari *et al* 1996).

Many previous studies have used annual analysis to assess changes between treatment and control catchments. However, increasingly seasonal or monthly analysis of paired catchments has been used to overcome the problem of insufficient data being available during the pre-treatment period by which relationships could be developed (Lane and MacKay 2001). It has been argued by some researchers that monthly data with an explicit seasonal component such as the autumn flush of colour should be used to account for observed changes post-treatment (e.g. Watson *et al* 2001).

A number of studies have focussed on the same site/catchment both before and after changes in land management practice, but this requires forward planning and a longer-term approach than that necessary for paired catchments. The first paired catchment studies concentrated on the effects of afforestation/deforestation, e.g. the Coweeta Long Term Ecological Research Project in North America providing valuable long-term information on changes in the hydrological processes (Hibbert 1969, Webster *et al* 1992, Elliott *et al* 1999, Swank *et al* 2001). A similar paired study, the Plynlimon experiment, was set up in mid-Wales to investigate the effects of land use on water yield in upland catchments (Kirby *et al* 1991). Due to its longevity the experiment has been used to test afforestation and deforestation impacts on catchment-scale hydrological processes (Mount *et al* 2005, Archer 2007).

Paired catchment experiments and research have been adopted at several sites in the UK, particularly on blanket bog upland catchments where blocking of grips or gullies is occurring. Changes in the hydrological processes are perhaps easier to observe as these precipitation-fed catchments rely on one principal source of water only (e.g. Mitchell 1991, Mitchell and McDonald 1995, Worrall and Burt 1999, Evans and Warburton 2001, Holden *et al* 2004, O'Brien *et al* 2005). Of particular importance to blanket bog management and restoration are the long-term studies completed at the Moor House Reserve, Upper Teesdale with its extensive blanket peatlands (e.g. Conway and Millar 1967, Garnett *et al* 2000, Burt 2003, Worrall *et al* 2006, Clark *et al* 2007) and upland sites monitored by the Acid Waters Monitoring Network, providing long-term data on several upland areas of blanket bog (Evans *et al* 2005a, Monteith and Evans 2000). It should be noted, however, that long-term studies can only identify effects of changing land management if other factors remain constant. Given current predictions of climate change, paired catchment studies have an advantage here.

Other small-scale upland catchment studies on soils high in organic matter are limited, but examples include a study by Burt and Gardiner (1983) at Shiny Brook, south Pennines which examined the differences in runoff and erosion by comparing an eroded and uneroded catchment. Gustard and Wesselink (1993) modelled landuse change (pasture, conifer and heather) on interception, soil and channel water storage at Balquidder, Wales by examining flow duration curves, baseflow and storage-yield relationships. Robinson and Newson (1986) compared forest and moorland hydrology of upland peat sites at Plynlimon, Wales, whilst Worrall and Burt (2004) examined the DOC of two catchments over a period of approximately 40 years to determine if there was any significant increase in carbon loss from peat catchments. They concluded that climate was the main driver of DOC increase, particularly following severe droughts.

2.6 Summary

This chapter has reviewed the existing literature on water discolouration and DOC concentrations from upland catchments used by water companies as a source of water supply for potable water. The main areas of discussion have identified the properties of water colour, the processes involved in the generation of colour and DOC and the potential factors causing a rise in levels of water colour and DOC on a temporal and spatial scale. The properties of water colour and DOC have been extensively researched and a number of authors have recognised the main components as humic substances made up of humin, humic and fulvic acid. More recently these substances have been further separated into hydrophyllic and hydrophobic components and the difficulty of their treatment and removal by traditional processes at the treatment works has raised interest in alternative solutions such as sustainable catchment management to support traditional processes to reduce or ameliorate the production of these compounds.

The factors generating water colour and DOC concentrations are derived from autochthonous and allochthonous processes. These include the complex internal processes such as the chemical, physical and biological factors which are largely affected by the soil and its properties; and the interaction with water, affected by climate and external factors such as anthropogenic atmospheric pollution and land use.

Since the commencement of the study, further investigations have tried to identify the processes involved in the generation and amelioration of water colour and DOC. Research has focussed on upland catchments to identify techniques to reduce or ameliorate discoloured water high in DOC concentrations draining from the catchments used to supply upland reservoirs. The effects of prescribed burning, grazing and drainage (natural gullies and grips) on water colour have been researched (largely funded by water companies). These have tended to examine the trend in colour/DOC over time by identifying changes in land management practices which may correspond to changes in water colour rises. Alternatively, small field experiments within enclosures or set areas and controlled laboratory experiments have tried to identify changes from the manipulation of certain factors such as burning or grazing. These experiments have at best been short-term, usually lasting for not more than two years, and some for only a few months. Conclusions have been drawn and extrapolated to apply to longer time periods or other areas of the UK by their incorporation into water quality and hydrology models. Less is known about the longer-term effects of landuse and their manipulation, particularly at a catchment scale at which land managers operate. This study is therefore timely in its investigation of the role of blanket peat moorland management in the generation and amelioration of discolouration of surface waters.

3 THE GEOGRAPHICAL DISTRIBUTION OF WATER COLOUR AND DOC AND INTRODUCTION TO THE STUDY SITE

3.1 Introduction

This chapter presents details of the geographical extent of water discolouration and DOC (Section 3.2) in terms of its global distribution (Section 3.2.1), UK uplands (3.2.2), and the Peak District (3.2.3). The study site is described (Section 3.3) including a general description of the area, the geology and pedology, topography and landform, vegetation, landuse and management, and climate.

3.2 The Geographical Extent of Water Discolouration and DOC

3.2.1 The Global Distribution of Water Discolouration and DOC

Freshwaters exhibiting a yellow-brown or even black colour are found in many parts of the world and this discolouration occurs naturally through the release of dissolved organic material and leaf litter into drainage basins (Mitchell 1990). On a global scale, however, most discoloured water seems to be associated with areas from 40ºN-65ºN and 40ºS-60ºS (Mitchell 1991). These area are generally of a cool, temperate climate with a mean precipitation ranging from 600-4000 mm and are located in the Nordic countries, parts of Central Europe, northern UK, north-eastern US, with some occurrences in New Zeland and Tasmania (Moore 2002, Nordtest 2004, Holden *et al* 2007).

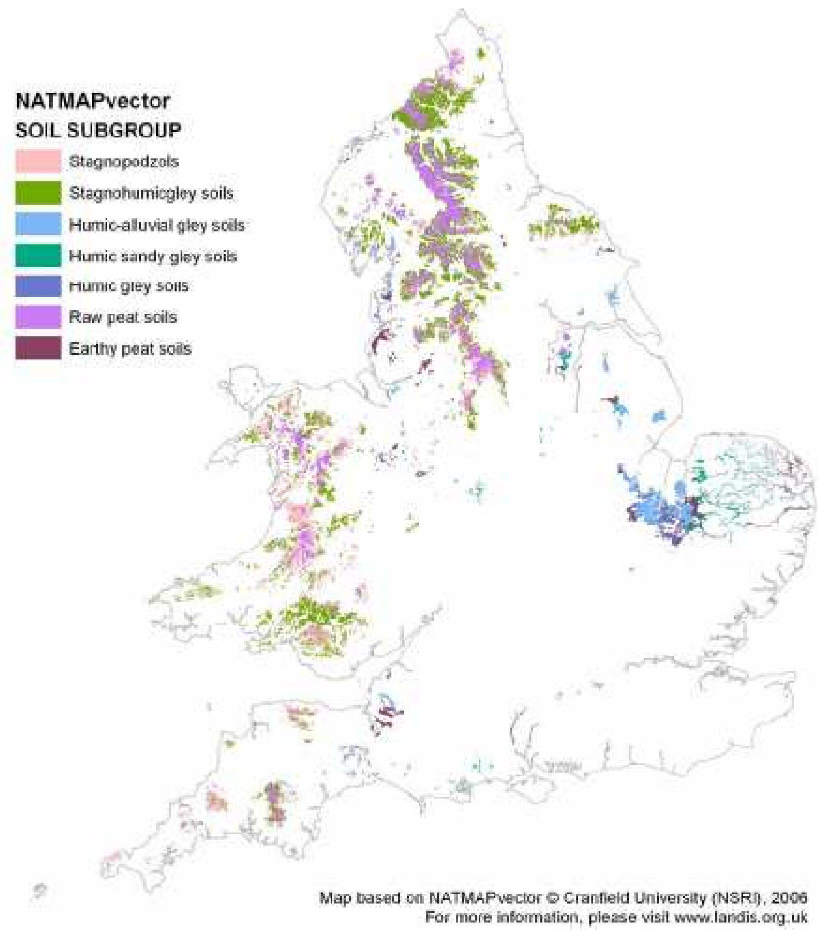
Monitoring of European and US surface waters has been undertaken by the UNECE ICP Waters programme and suggests that DOC concentrations have increased widely across the Nordic Countries and UK, the foothills of central Europe and in North eastern US (Löfgren *et al*. 1999, Liltved and Gjessing 2003 Grunewald *et al*, 2003, Skjelkvåle *et al* 2000). Hejzlar *et al* (2003) reported increases in DOC in the surface waters of rivers in the Czech Republic since the mid-1980s and an increase in DOC concentrations in Finnish streams during this time period.

Similarly to the UK, 80% of the drinking water in Norway and 70% and 50% of drinking water in Sweden and Finland respectively is provided by surface waters which are vulnerable to increases in discolouration and increased costs of treatment (Nordtest 2004). Such increases are thought to be a result of several factors including climate, anthropogenic deposition, hydrological processes and landuse.

3.2.2 Water Discolouration and DOC in the UK Uplands

The British Uplands (areas above 250 mAOD) occupy approximately a third of the UK land area and are mainly concentrated in Scotland, Wales, northern England and the west country (Fielding and Howarth 1999). The areas are characterised by high rainfall, low temperatures and acidic soils high in organic matter (Mitchell 1991, Tallis 1998, Holden *et al* 2006a). Figure 3.1 shows these areas classified as "raw peat soils". Such areas are a nationally important asset due to their provision for gathering and storing of water, but water draining from these upland catchments with organic-rich soils are also associated with coloured water of similar appearance to weak tea (Mitchell 1991).

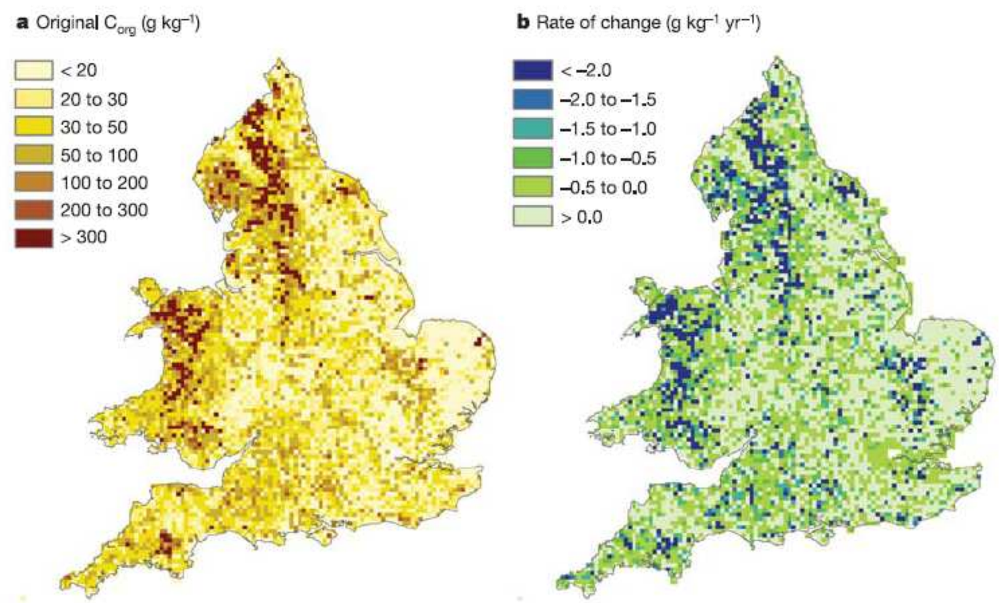
Figure 3.1: Distribution of Organic Soils in England and Wales (Holden *et al* 2006a)



Bellamy *et al* (2005) found that the relative rate of carbon loss increased with soil carbon content. Figure 3.2a shows that the mapped areas of high carbon content corresponded to those areas of raw peat soils presented in Figure 3.1. Figure 3.2b shows that the areas are also those with the greatest carbon loss estimated at over 2 $gCkg^{-1}yr^{-1}$. They acknowledged that some of the loss has been to drainage waters and this is consistent with the observed increases in water colour and DOC in surface waters reported at specific sites by other researchers (Bellamy *et al* 2005, Garnett *et al* 2001, Evans *et al* 1999, Holden 2005a).

Evans and Monteith (2004) reported that DOC levels in UK upland waters have almost doubled since the late 1980s and so represent the largest change in upland water quality over this period. The impacts of such changes are likely to be significant, particularly increased carbon export from terrestrial stores to freshwater and increased water treatment costs in peaty areas such as the Pennines which provide valuable sources of water for the major conurbations of Lancashire, Yorkshire and the Midlands.

Figure 3.2: Changes in Soil Organic Carbon Loss 1978-2003 (Bellamy *et al* 2005)



3.2.3 Trends in Water Discolouration in the Peak District, Derbyshire

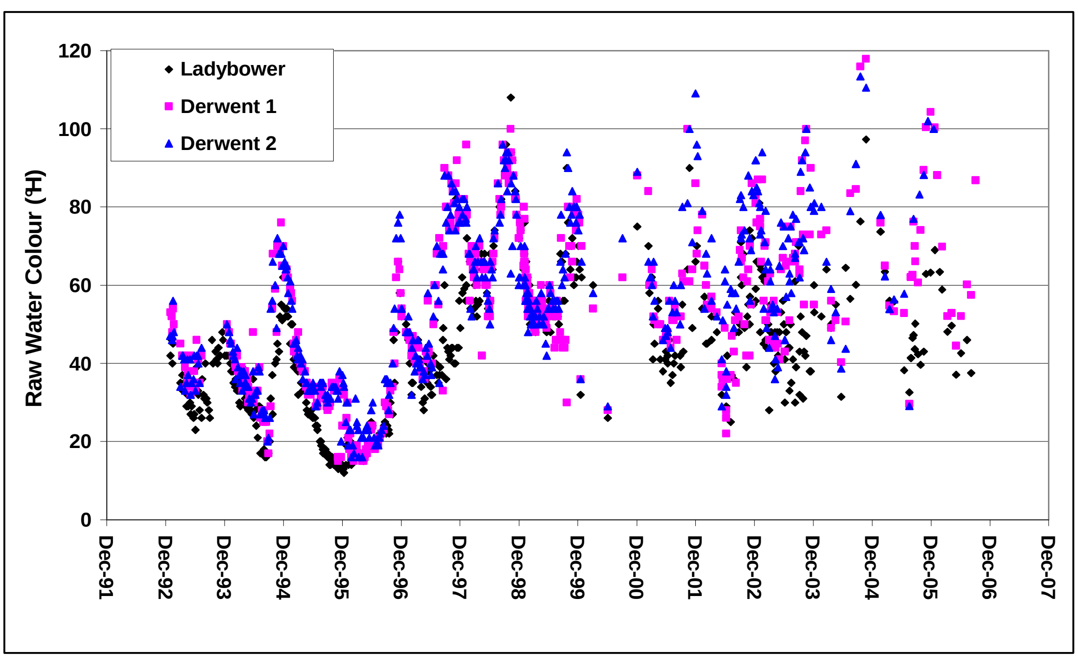
The uplands of the Dark Peak area of the Peak District, Derbyshire form the southern limit of the Pennines and provide a major source of water for several water companies. Water draining to the north supplies water to the reservoirs owned by Yorkshire Water and United Utilities whilst water draining to the south supplies water to Severn Trent Water. The River Ashop catchment, together with the Derwent and Westend catchments drains into three large reservoirs (Ladybower, Howden and Derwent repectively) with a total holding capacity of 46345 Ml of water (Severn Trent Water 2007).

Bamford Water Treatment Works (WTW) is fed from the three main reservoirs. It is responsible for treating water which is then distributed to the major conurbations in south Yorkshire, Derbyshire, Nottinghamshire and Leicestershire. However, there had been a noticeable deterioration in the influent water quality to the water treatment works over the fifteen years leading to the start of this project. Hazen units (°H) are the traditional standard measurement of water colour used by most water companies (Hongve and Akesson 1996) and the colour from the reservoirs had risen year on year to a recorded maximum of 116 °H in 2004 (Figure 3.3). The data represent water drawn from Ladybower reservoir and two abstraction points from the Derwent reservoir.

The Bamford WTW underwent a major refurbishment of the rapid gravity filters approximately eight years ago to ensure compliance with current drinking water legislation both at the final treatment stage and within the distribution system (Drinking Water Directive EC98/83). The first stage of treatment being used was clarification, which is not at present being updated. However, there was some concern that if the influent water quality continued to deteriorate, the present configuration of the works would not provide an adequate process stream to ensure Bamford WTW achieved all the water quality standards.

The data shown in Figure 3.3 were obtained from Severn Trent Water for Bamford WTW and were usually collected at least on a weekly basis. Figure 3.4 shows these data aggregated to monthly means, in order to allow further graphical and statistical analysis. Figure 3.4 shows a number of events in which discolouration rose significantly and these peaks are listed in Table 3.1. The peaks in colour demonstrate a clear seasonal effect, in which water colour was elevated in late autumn to a peak in November or December and then declined to a much lower value towards March and April. This rise is often termed the 'autumn flush' of water colour (Butcher *et al*, 1992; Pattinson *et al*, 1995; Naden and McDonald, 1989). Figures 3.3 and 3.4 also indicate a doubling in maximum water colour levels from around 50 °H in 1993 to over 100 °H in 2005.

Figure 3.3 Raw water colour (°H) at Bamford WTW Jan 1993-Sept 2006



The responses of Derwent inlets 2 and 3 were similar and showed the highest levels of water colour to September 2006 although Ladybower consistently produced lower colour than the two abstractions at Derwent. Note that the sampling protocol changed from weekly to fortnightly/monthly sampling in 2005 and the high water colour levels may therefore have been representative of raw colour for one day only during each month, but this does allow direct comparison as sampling took place on the same day at each site.

Figure 3.4 Bamford WTW average monthly water colour Jan 1993 – Sept 2006

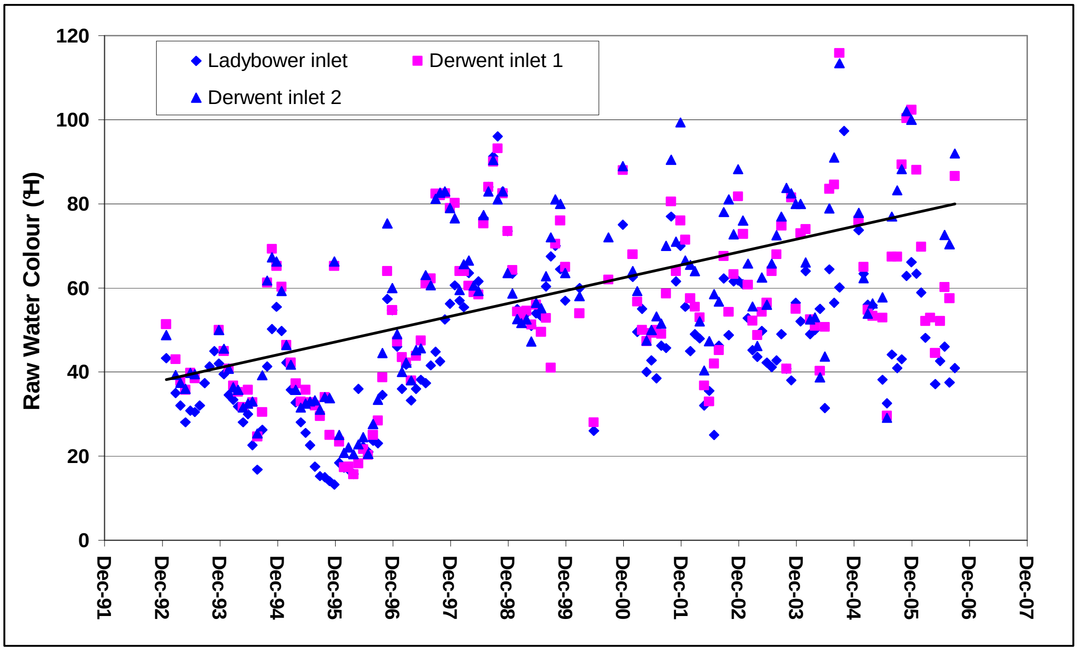


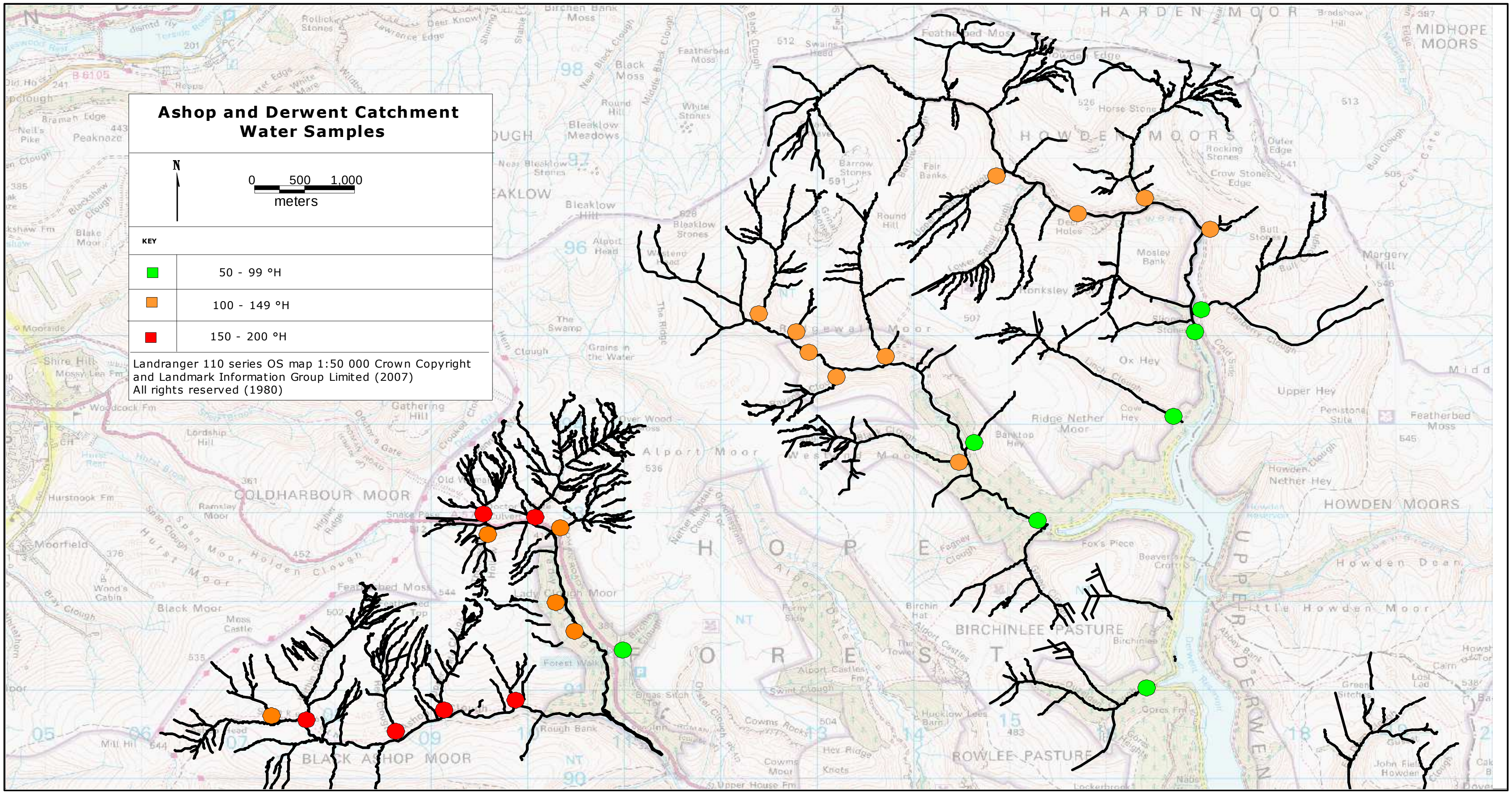
Table 3.1 Major peaks in discolouration at Bamford WTW 1994-2006 (Raw 2 and 3 inlets)

Colour Peak	Peak (°H)	Supply
December 1994	69	RAW 2
November 1996	75.3	RAW 3
November/December 1997	83	RAW 2
October 1998	92	RAW 2
October 1999	81.6	RAW 3
December 2000/January 2001	73.5	RAW 2
November 2001	92.3	RAW 3
September 2004	116	RAW 2
November 2005	104.3	RAW 2
September 2006	86.8	RAW 2

3.2.4 Water Discolouration in the Ashop Catchment, Derbyshire

Water discolouration on the Ashop was originally identified as a concern in 1999 by the National Trust (landowner) and Severn Trent Water. Preliminary studies of the wider Derwent and Ashop catchments (Blackmore and Labadz 2000, Walker 2001) identified those catchments contributing high true colour and "true colour load" (a conceptual quantity of colour, derived as the product of discharge and true colour). This is important in terms of costs of water treatment concerning increased costs associated with intensive treatment processes, the addition of flocculants, and improvements to plant infra-structure to meet the regulated water quality standards (Packman 1990, Maitailainen *et al* 2002). Figure 3.5 shows the location of samples collected and analysed by Blackmore and Labadz in February/March 2000 (Blackmore and Labadz 2000). The samples have been separated into values of high, medium and low colour (°H) and the figure indicates that high colour samples (shown in red) were concentrated in the Ashop catchment.

Figure 3.5: Ashop and Derwent Catchments Spatial Colour Feb-Mar 2000 (Blackmore and Labadz 2000)



3.3 Site Selection

On commencement of this research, further spatial sampling (May-Sept 2002), confirmed those catchments identified by Blackmore and Labadz (2000) to have high true colour and these were subsequently selected to be in the study area. Selection of appropriate field catchments was based on the following criteria:

i) The catchments were part of the wider catchment network contributing to raw water supplies at Bamford Treatment Works;

ii) Catchments had high levels of water colour;

iii) Catchments had broadly similar geology, topography, rainfall and landuse;

iv) Catchments had the potential to be manipulated by changing landuse and management (drainage, burning and grazing) and to maintain the chosen management for a period of years;

v) Catchments were accessible but sufficiently remote from public areas to prevent disturbance to any equipment installed;

vi) Catchments had suitable streams on which to locate monitoring equipment which were accessible for installation and maintenance of equipment to maximise data collection.

Following a detailed study of secondary data (including maps of topography, geology, soil, vegetation, landuse) and pilot primary field data (spatial water sampling and colour analysis, vegetation and condition assessment), six catchments of the River Ashop, Derbyshire were selected as being most appropriate for the study. The catchments were Doctors Gate Clough, Upper North Grain, Nether Gate Clough, Upper Gate Clough, Red Clough and Within Clough which are described collectively in the following sections.

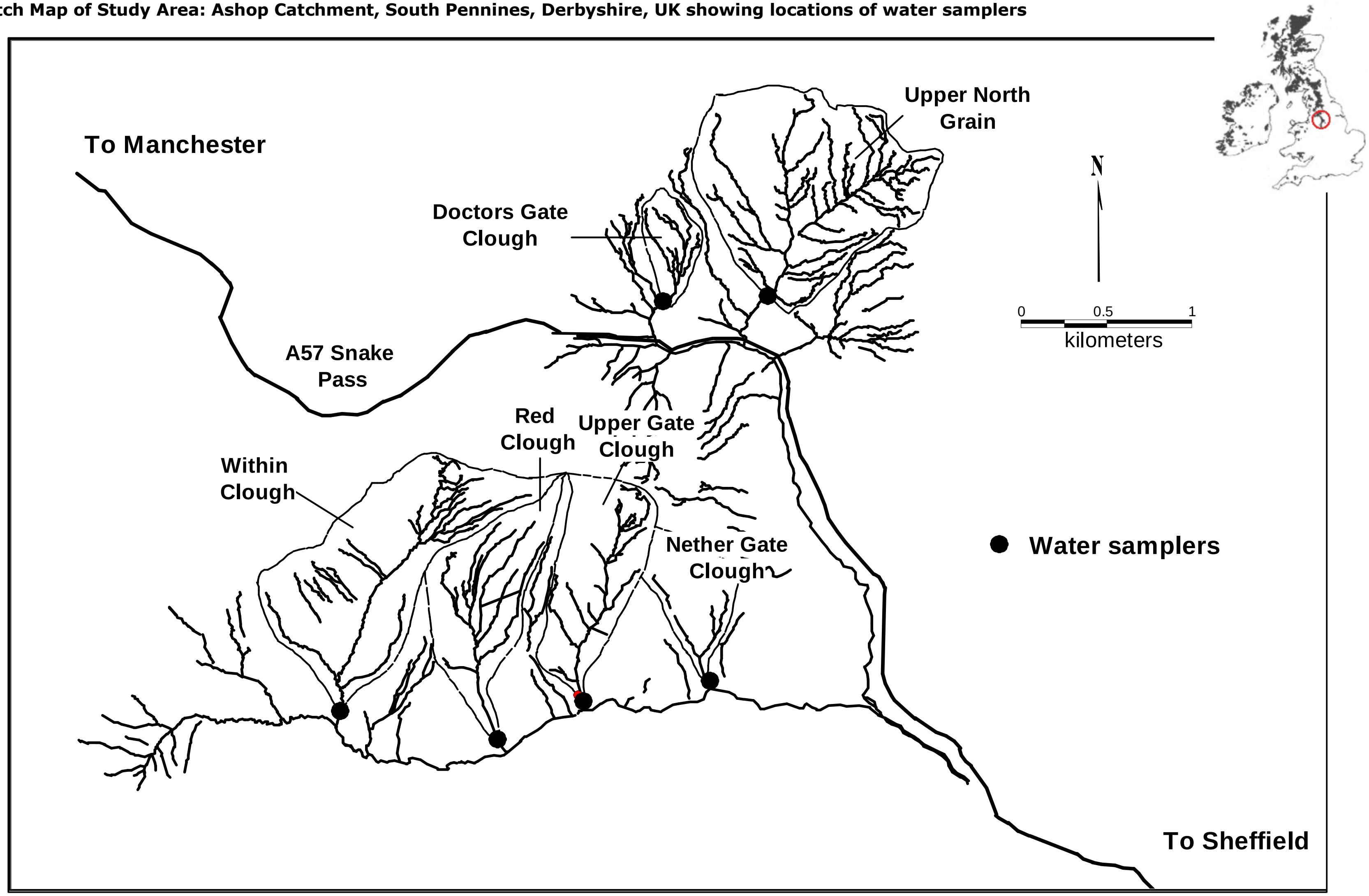
3.4 The Ashop Catchment

The River Ashop is approximately 11 km in length and is one of the major rivers in the Dark Peak area of Derbyshire. The river drains a catchment area of 45 km^2, exhibiting a high drainage density. It forms one of the major inflows to Ladybower Reservoir, and therefore provides a major source of potable water to large populations in the Midlands. Figure 3.6 shows the study area comprising the six experimental catchments and Table 3.2 gives locations of the downstream limit of monitoring in each case.

Table 3.2: Locations of the Downstream Limit of Monitoring at each Experimental Catchment

Site	Grid Reference	Site	Grid Reference
Doctors Gate Clough	SK 09607 93119	Upper Gate Clough	SK 09141 90732
Upper North Grain	SK 10220 93149	Red Clough	SK 08636 90505
Nether Gate Clough	SK 09883 90857	Within Clough	SK 07719 90674

Figure 3.6: Sketch Map of Study Area: Ashop Catchment, South Pennines, Derbyshire, UK showing locations of water samplers



3.4.1 Geology and Pedology

The experimental catchments are underlain by a mix of shales, siltstones and sandstones of late Carboniferous Millstone Grit age (Wolverson-Cope 1998). These Namurian rocks were formed approximately 300 Ma (million years ago) and are overlain with a range of acidic soils. Deep blanket bog peat soils (Winter Hill Association (1011b) peat) are found in the headwaters of the Ashop catchments; whilst acid loamy upland soils with a shallow wet peaty surface are located in the lower tributaries of the sub-catchments and adjacent to the main River Ashop (Jarvis *et al* 1984). Figure 3.7 and 3.8 show the geology and soil types within the study area.

Figure 3.7: Geology Map of Ashop Catchment (supplied by British Geological Survey/Edina Service)

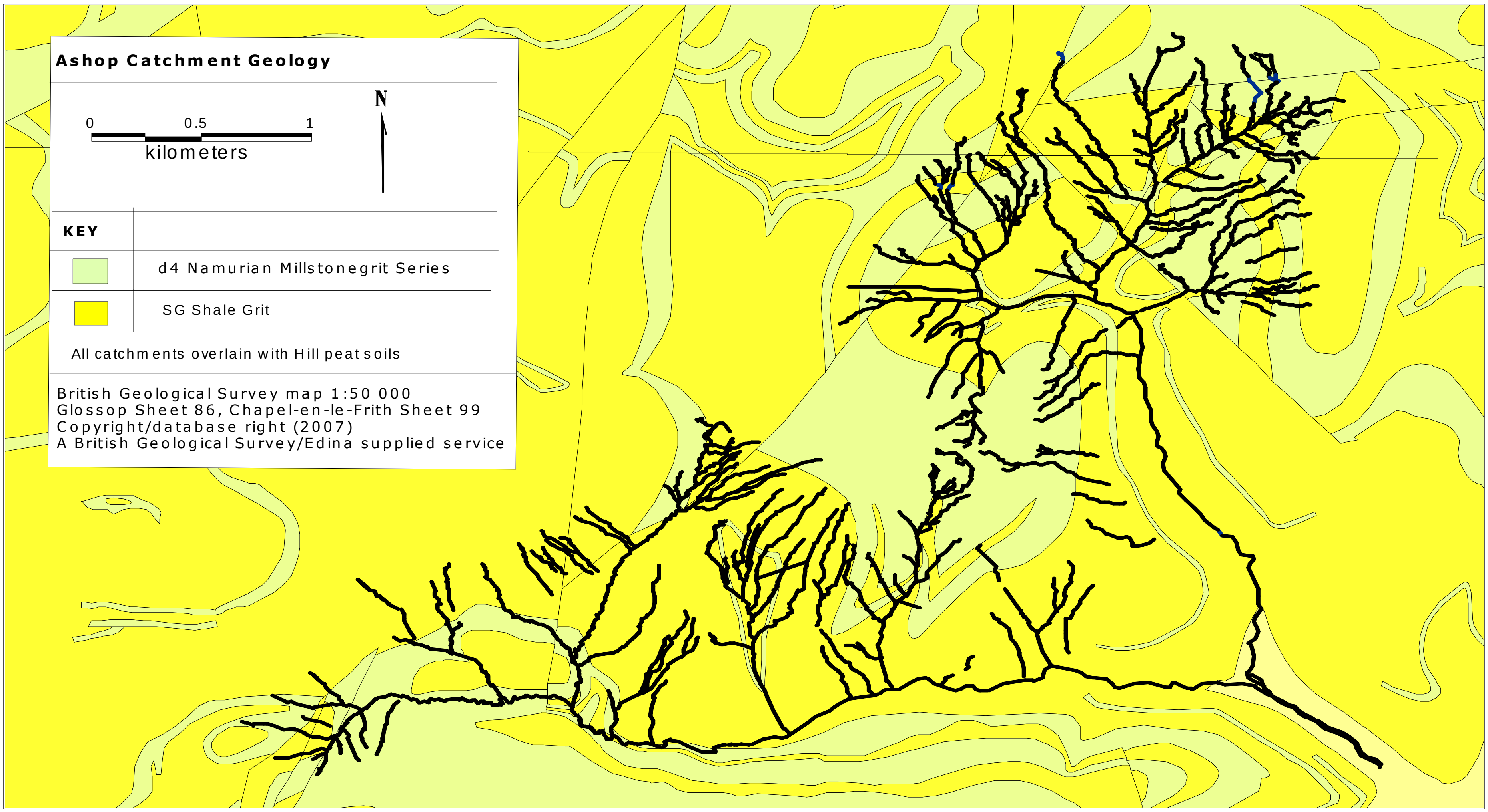


Figure 3.8: Peat Soil Map of Ashop Catchment (supplied by Natural England/Edina Service)

3.4.2 Topography and Landforms

The Ashop catchment lies within the designated Dark Peak Character Area which is defined by its distinctive landscape character features. The Ashop valley is adjacent to the Kinder plateau with its long rocky ridges and edges formed by the harder Millstone Grit sandstone (see Figure 3.9). Within the Ashop catchment itself, there are several areas of gritstone outcrops which dominate the landscape of the open moor. The hard gritstone is interspersed with softer shales which have slowly eroded to create the broad Ashop valley (altitude ~ 400m) and numerous rocky "cloughs" including Nether Gate, Upper Gate, Red and Within Cloughs (see Figure 3.10).

Figure 3.9: Ashop Valley Adjacent to Kinder Plateau Formed from Millstone Grit Sandstone

Figure 3.10: Red Clough with Exposed Millstone Grit

The watersheds (altitude ~ 530m) of the cloughs provide the distinctive landscape of the "high moors" with its open rolling landscape, blanketed in peat soils of varying depth and a mosaic of micro-topographic features such as pools and hummocks (see Figure 3.11), and erosion features such as bare earth, small landslide scars and groughs. The plateaux tops are heavily dissected by natural drainage channels which drain down into the Ashop catchment and provide a source for the River Ashop (see Figure 3.12).

Figure 3.11: Watershed of Upper North Grain with Microtopography of Pools and Hummocks

Figure 3.12: Plateau and Slope Dissected by Naturally Eroded Gullies with *Calluna*-dominated vegetation at Within Clough

3.4.3 Vegetation

The study area forms part of the extensive Dark Peak Site of Special Scientific Interest (SSSI) having been designated for its unique landform, geological and pedological structures, together with its composition of species associated with this particular upland environment (Natural England 2007). Cotton grass moorland dominates the highest plateaux, and heather (*Calluna vulgaris*), together with other dwarf-shrub species such as bilberry and crowberry (*Vaccinium myrtillus* and *Empetrum nigrum*) dominate the drier bog (see Figures 3.12). A number of acid flushes have developed adjacent to the stream channels and are typified by common rush, *Juncus effusus*, and *Sphagnum sp*. (Rodwell *et al* 1991) illustrated in Figure 3.13. Figure 3.14 shows the main vegetation types identified by Natural England on the experimental catchments.

Figure 3.13: Stream Channel with Acid Flush Vegetation

Figure 3.14 Ashop Experimental Catchment Vegetation Types (Adapted from Digitised maps provided by Natural England)

3.4.4 Land Use - Burning and Grazing

Precise land management varies between the experimental catchments, but is primarily for sheep grazing and the rearing of grouse. Table 3.3 shows the land management at the commencement of the research in 2002 on the Ashop catchments. Heather burning was used as the main management tool to maintain a diverse age structure of heather from pioneer to mature, aimed at providing a nutritional food source and cover to maximise grouse populations and species associated with the moorland habitat (Lawton 1990, Backshall *et al* 2001). The prescribed (controlled) burning was carried out on a rotation (approximately 8-10 years) by gamekeepers in agreement with Natural England (previously English Nature) under a shooting tenancy leased from the National Trust.

Table 3.3: Ashop Catchments Locations and Land Management

Site	Central Grid Reference	Maximum Altitude (m)	Land Management
Doctors Gate Clough	SK 09568 937795	520	Grazing, no burning
Upper North Grain	SK 10840 94102	520	Grazing, no burning
Nether Gate Clough	SK 10021 91501	490	Grazing and burning
Upper Gate Clough	SK 09500 91779	520	Grazing and burning
Red Clough	SK 08646 91791	520	Grazing and burning
Within Clough	SK 08419 92059	515	Grazing and burning

The study area was entirely within the Tier 2 North Peak ESA agreement negotiated between Defra and the National Trust. Grazing densities were set at 0.6 $LU.ha^{-1}$ (livestock units/ha) (*pers comm* Steve Trotter, former National Trust manager High Peak Estate 2002). The hill breeds of sheep grazed on the Ashop catchments are Swaledale and Herdwicks which are capable of thriving in difficult, unfertile terrain, whilst maintaining production of young and wool for sales (Backshall *et al* 2001).

3.5 Climate

Relevant climatic data for the Dark Peak, particularly at high altitudes are not easily obtainable. The data often relate to weather stations at lower altitudes in urban/semi rural areas which are more densely populated where data can be collected and equipment monitored more readily, for example, Buxton weather station. Whilst these stations provide important long-term data sets, they may not be directly relevant to the area under study. The following sections therefore give an overview of the climatic conditions prevailing on the upland moorlands of the Peak District. Primary data collected during the monitoring period were recorded on equipment installed at the study site to enable more accurate and relevant data to be recorded (see Chapter 4).

3.5.1 Precipitation

Rainfall is generally correlated to altitude with high and more intense rainfall falling on the higher slopes (450–650 m) (Burt 1980). Orographic and convectional rainfall dominate the region with low pressure fronts generally moving eastwards from the Atlantic, together with high snowfall/rainfall mainly during January and February from the cold, wet polar maritime air in winter (Edwards 1973, Burt 1980).

The average annual rainfall is approximately 1350 mm with the average monthly rainfall between October and January estimated at 100 mm (Burt 1980) and an average of 160–200 wet days (rainfall recorded at 0.025 cm) each year.

3.5.2 Temperature and Sunshine Hours

The mean monthly temperatures range from 2.27 °C in January to 14.2 °C in July, although the temperature for the summer months (June, July, August) only averages 10 °C and frosts have been recorded above 300 mAOD throughout the year except for July and August (Edwards 1973).

Low cloud, fog and mist combine to reduce sunshine, particularly in winter with the average annual daily sunshine recorded at only 3.3 hours, reducing to 0.7 hours per day in winter and rising to a mean of 5 hours per day during the summer at the experimental catchments.

3.6 Summary

This chapter has presented information on the global distribution of discoloured waters and DOC, and has identified key areas of rising colour and DOC concentrations in the UK uplands before focussing on water colour and DOC in the Peak District and Ashop catchment. This area of the south Pennines is an important provider of raw water for potable water supplies to several water companies, but has a rising trend in water colour and DOC concentrations for the last 20-30 years making it an ideal area on which to focus research.

The rising trend in water colour has been described at Bamford WTW, which treats water from the Ladybower reservoir into which the River Ashop flows. Preliminary studies found that the Ashop catchment tributaries were highly coloured and provided the rationale for selecting this catchment as a suitable site on which to conduct the research.

4 EXPERIMENTAL METHODOLOGY

4.1 Introduction

In order to investigate the significance of traditional management practices and eroding natural drainage systems on discoloured runoff, a number of options were considered which included replicate plots and simulated laboratory experiments. A paired catchment approach was chosen however, to evaluate the impact of landuse at a catchment scale. This was because the partnership with landowner and tenants meant manipulation of management at a catchment scale was possible. This differed from many previous studies where co-operation between land managers at such a large scale was difficult. In addition, the ability to extend the work to a larger scale meant studying the small-scale effects were not considered as relevant to the practitioners such as the National Trust and Severn Trent Water plc. An integrated framework of field and laboratory research was therefore used to determine the changes in water discolouration, runoff and DOC flux on a temporal and spatial scale. This combined fieldwork (survey and sampling), laboratory analysis (colorimetric analysis) and secondary data analysis (digitised maps including aerial photograph and satellite imagery).

Identical sets of hydrological and water quality instruments were installed on each of the sub-catchments in October 2002 and were maintained throughout the monitoring period until September 2006 (see Figure 3.1 equipment location). It should be noted that the study area was located within one of the harshest environments in England and equipment was subjected to extremes in temperature, rainfall and discharge with a resultant loss of data on occasions. Data loss is discussed in the appropriate sections.

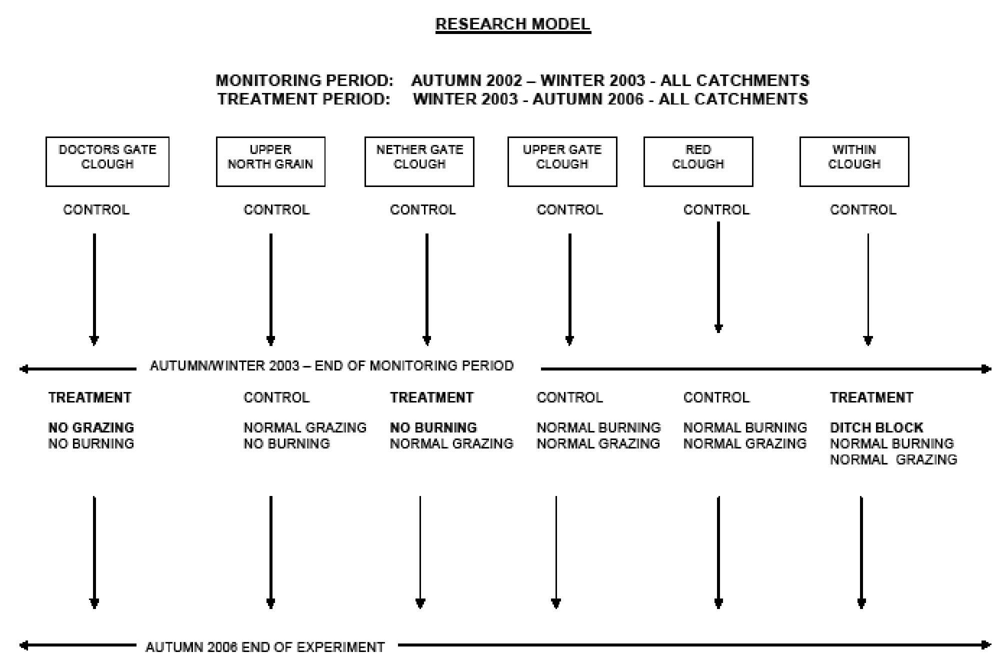
4.2 Experimental Design

4.2.1 Paired Catchment Study

The paired catchment approach overcomes the problem of climate variability and non-stationarity of water colour (see Section 2.5.2). Whilst other workers have considered management manipulation for water colour amelioration at laboratory and plot scale (for example Garnett *et al* 2000, Benavides-Solario *et al* 2001, Holden and Burt, 2002a, Aguilar and Thibodeaux 2005), no previous study has evaluated the impact of these approaches at a catchment scale where a sufficient degree of experimental control has been maintained.

An experimental approach was therefore adopted in which pairs of catchments were monitored for a control period to establish their degree of similarity. One catchment was then treated to a management practice, such as the removal of grazing, whilst the other was not affected. The impact of management on the treated catchment could therefore be considered in comparison with the untreated or control catchment. The study sought to consider the impact of a number of factors on the runoff of discoloured water. These included blocking of eroding gullies, the management of controlled burning, and grazing exclusion. Figure 4.1 shows the programme of implementation.

Figure 4.1: Research Model - Programme of Implementation Ashop Study Sites Autumn 2002-Autumn 2006



4.2.2 Management Manipulation

The research was partly funded by Severn Trent Water plc and the National Trust (landowners), but prior to the commencement of monitoring, agreements had to be reached with all parties who had an interest in the proposed study sites. This was vital as the investigation of management practices such as grazing and prescribed burning was and still is politically sensitive. For example, grazing regimes had recently undergone change in 2001 following an adjustment in the Rural Development Programme Regulation which resulted in area payments replacing the previous headage payments for livestock and livelihoods of tenant farmers were considered under threat (Holden *et al* 2007). The use of prescribed burning as a management tool to control grouse populations was already under question by conservation organisations such as English Nature and the National Trust, particularly as grouse numbers had been in decline since the 1970s despite the continued burning (Davies 2005). An investigation into the effects of prescribed burning on water quality and the co-operation of shooting tenants and gamekeepers to comply with changes in burning agreements was fraught with difficulty. Prolonged negotiation was required between land managers (National Trust), enforcers (Natural England), the investigators (Nottingham Trent University) and the practitioners (shooting tenants and game keepers) before agreement could be reached. The following sections describe the rationale which led to the selection of treatment and control catchments appropriate to the study. See Figure 3.1 for catchment locations.

4.2.2.1 Within Clough (Treatment Site – Gullies Blocked)

In December 2002 the Environment Agency (contracted by the National Trust) secured digital terrain data for the High Peak Estate, Derbyshire using a LiDAR system, that is, an airborne laser scanner capable of measuring the elevation of land surface laterally at 2 m intervals with a vertical accuracy of 0.1 m (Haycock 2003). The survey focused on key areas of land where upland peat soils were heavily eroded to enable the Trust to map accurately the area and extent of intact peat blocks and gully networks, and identify potential areas suitable for restoration.

Following initial analysis of the LiDAR data (Haycock 2003) and field surveys (Nottingham Trent University) Within Clough was identified as being suitable for blocking gullies located in the headwaters of the catchment. Analysis of the LiDAR data enabled gullies to be categorised 1-7 (Category 1 = indention of soil surface; Category 7 = severely eroded gully to bedrock). Following field observations, Category 4 gullies were identified as suitable for blocking. These natural gullies were identified as actively eroding and cutting into areas of relatively intact peat, but were not considered to be so degraded to be beyond restoration. The National Trust received funding from English Nature to install the blocks, and having sought advice on the materials and positioning of the dams, approximately 1000 small dams of heavy-duty plastic piling, spaced at 3 – 8 m intervals, were installed in the headwaters of the catchment during the autumn/winter 2003 (Trotter *et al* 2005). Figure 4.2 shows the location of each dam in the catchment surveyed with a dGPS by Moors for the Future and Figure 4.3 shows a typical section of gully blocked at Within Clough with the plastic piling.

Figure 4.2: Map of gully-block sites at Within Clough, south Pennines (data plotted by Moors for the Future)

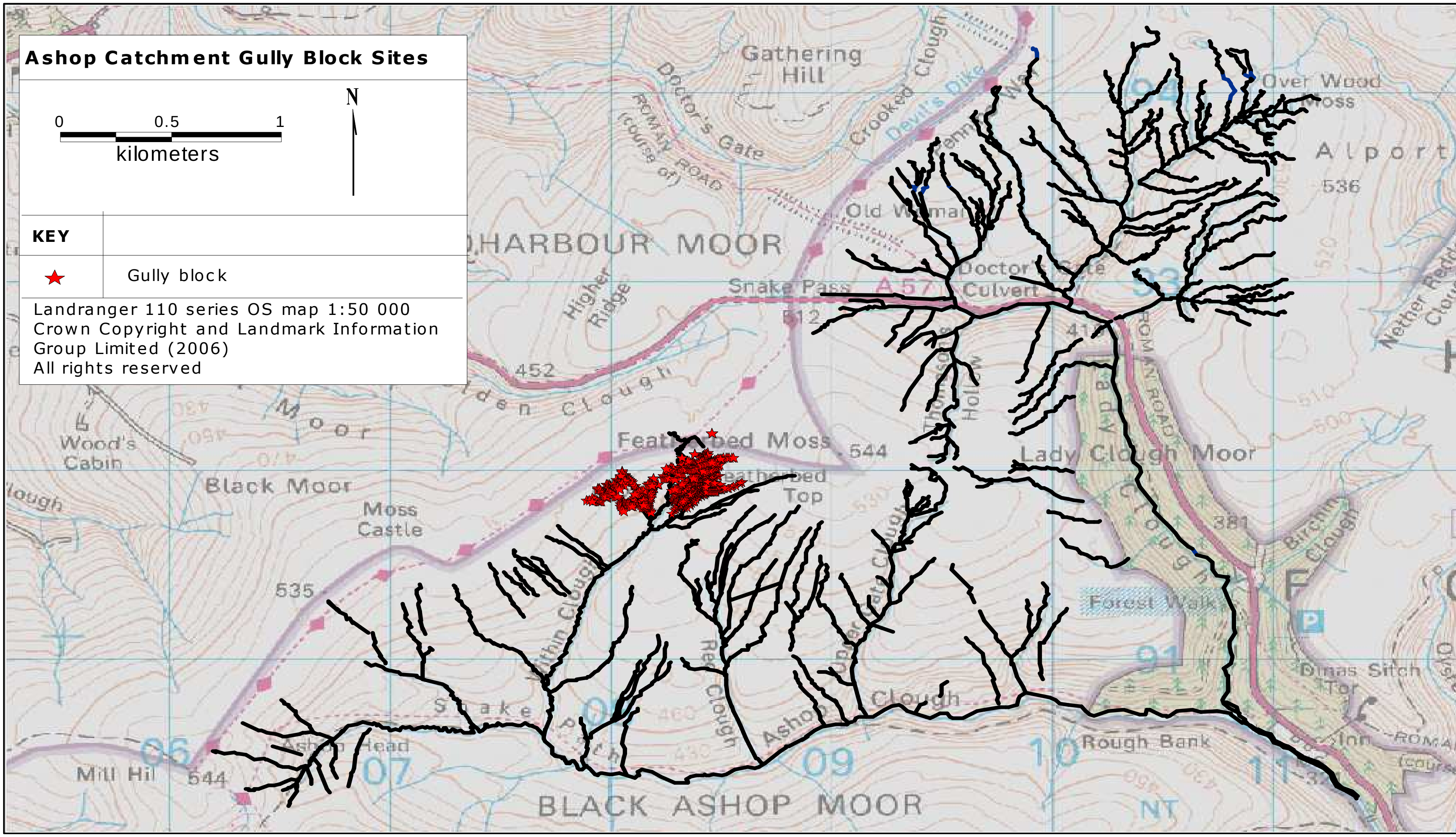


Figure 4.3: Gully blocking with plastic piling at Within Clough, south Pennines

4.2.2.2 Nether Gate Clough (Treatment Site – Cessation of Burning)

Nether Gate Clough is located on the Ashop in an area primarily used for grouse-shooting. The main management tool used to maintain the mosaic of heather is one of prescribed (controlled) burning – a practice also shared on other Ashop catchments, that is, Upper Gate Clough, Red Clough and Within Clough.

Taking into account the environmental and financial concerns of the shooting tenant and game keepers on the Ashop, an agreement was reached with interested parties whereby prescribed burning would not take place within the Nether Gate Clough catchment for a period of three years, commencing 2003-04 and ending in 2006-07. This action was enforced by English Nature (and continued by Natural England) in the form of an agreed burning plan. The catchment falls within the Dark Peak SSSI and management practices had to be agreed by English Nature (Natural England) before being implemented.

Nether Gate Clough was the second smallest catchment studied on the Ashop (doctors Gate Clough being the smallest), and is located to the east of the remaining catchments (see Figure 3.1). Its geographical position and size were a deciding factor in selecting it for the cessation of the burning regime as this would enable moorland burning to be continued on the remainder of the Ashop catchments with little effect on Nether Gate or organised grouse shooting.

4.2.2.3 Doctors Gate Clough (Treatment Site – Removal of Grazing)

English Nature, Defra, the National Trust and private landowners in the North Peak, Derbyshire reached an agreement in 2001-02 to exclude sheep from 2500 hectares of moorland by erecting 14 miles (22 km) of post and wire fencing (English Nature 2005). The aim of the project was to remove sheep for a limited period (at least 10 years) and encourage restoration of moorland through natural re-vegetation and re-seeding of heather and cotton-grass. The fence was erected during autumn 2003 and part of the enclosed area incorporated Doctors Gate Clough and provided an ideal opportunity to study the effects of sheep removal on water discolouration.

4.2.2.4 Upper North Grain, Upper Gate Clough and Red Clough (Control Sites)

Having selected three catchments on which to manipulate management, the remaining catchments, i.e. Upper North Grain, Upper Gate Clough and Red Clough were identified as suitable control sites on which there would be no change in management.

Upper North Grain was considered as a potential alternative site to Within Clough for gully blocking due to its similar intense dendritic pattern of gullies in the headwaters. However, this catchment was already extensively used for research, particularly by the University of Manchester. It was therefore thought inappropriate to study the effects of gully blocking as this would have affected other long-term studies in the catchment.

All six catchments are influenced broadly by the same prevailing climatic conditions. The control catchments acted as a benchmark to enable the monitoring of any changes across all the catchments in terms of water quality and runoff, and so identify whether these changes were a result of management manipulation and so overcome the problem of climate variability during the period of monitoring.

4.3 Catchment Pairings

Catchments found to be similar in hydrology, pedology, geology, topography and vegetation were paired together after the calibration period (Oct 2002-Dec 2003). The strategy for management manipulation is summarised in Table 4.1 and implementation of the management manipulation and monitoring programme is shown in Figure 4.1.

Table 4.1: Ashop Catchment Management Manipulation Programme

Site	Management	Site	Management
Within Clough	Gully-blocking	Upper North Grain	CONTROL
Nether Gate Clough	Cessation of Burning	Upper Gate Clough	CONTROL
Doctors Gate Clough	Removal of Grazing	Red Clough	CONTROL

4.3.1 Cluster Analysis to Determine Similarities between Catchments

A hierarchical cluster analysis was conducted using standardised variables (hydrology, pedology, topography, vegetation, and land management) measured during the calibration period prior to any change in management. Tables 4.2 and 4.3 show the variables calculated for each catchment.

Squared Euclidian distance was calculated as the measure of similarity within the statistical software Minitab v.14 (Minitab Statistical Software 2004). This aimed to determine which catchments were most similar and enable appropriate pairing to measure differences between a control catchment (no management manipulation) and a treated catchment (management manipulation) in terms of water discolouration and water yield. Table 4.4 shows the similarity and distance level from the cluster centroids; the lower the number indicating the increased similarity between catchments. The table shows that Upper Gate Clough and Red Clough were very similar, having the smallest distance and greatest similarity level, followed by Upper Gate Clough and Within Clough, then Upper Gate Clough and Nether Gate Clough, Doctors Gate Clough and Nether Gate Clough and Doctors Gate Clough with Upper North Grain. This is illustrated as a dendrogram in Figure 4.4.

Table 4.2: Ashop Catchment Standardised Geomorphological Variables

Site location	Area (km^2)	SNL (km)	DD (km/ km^2)	ASP	Total SNL <5⁰ (m)	% TSNL <5° (m)	MSC GD (m)	Cover of Winter Hill Peat (km^2)	% cover Winter Hill peat	Altitude at conflue nce (m)	Highest altitude (m)	No. 1st order stream	No 2nd order stream	No. 3rd order stream	No. 4th order stream
Dr Gate Clough	0.19	3.3	10.4	175	3.1	91.6	0.1	0.3	83.2	450	530	13	7	1	1
Upper North Grain	1.26	12.3	8.5	132	8.3	67.3	0.1	1.4	91.7	440	530	49	11	2	1
Nether Gate Clough	0.32	1.1	5.2	153	0.0	0.0	0.2	0.2	84.4	360	475	4	2	1	
Upper Gate Clough	0.5	4.6	8.6	169	1.6	35.3	0.1	0.5	84.6	385	525	13	5	1	
Red Clough	0.55	5.5	9.2	171	4.1	74.7	0.1	0.6	86.7	410	490	12	5	1	
Within Clough	1.14	6.6	6.0	159	4.5	67.4	0.1	1.1	88.2	430	510	22	4	1	

KEY	
SNL	Stream network Length
DD	Drainage Density
ASP	Aspect
TSNL	Total Stream Network Length
MSCGD	Main Stream Channel Gradient

Table 4.3: Ashop Catchments Standardised Vegetation Type Variables

Site location	% cotton grass moorland	% Dry Bog-heather dominated	% Dry bog non-heather dominant	Land Management during 2002-03
Dr Gate Clough	29	0	61	Grazed
Upper North Grain	22	0	6	Grazed
Nether Gate Clough		97	1	Grazed & Burnt
Upper Gate Clough	25	65	6	Grazed & Burnt
Red Clough	32	62	0	Grazed & Burnt
Within Clough	40	37	19	Grazed & Burnt

Table 4.4: Similarity and Distance of Catchments in Cluster Analysis

Step	Number of Clusters	Similarity Level	Distance level	Clusters Joined	
1	5	93.6	4.97	4	5
2	4	89.9	7.8	4	6
3	3	81.1	14.6	1	4
4	2	66.46	25.97	1	3
5	1	52.62	36.7	1	2
KEY			**Cluster Number**		
Doctors Gate Clough (DGC)			1		
Upper North Grain (UNG)			2		
Nether Gate Clough (NGC)			3		
Upper Gate Clough (UGC)			4		
Red Clough (RC)			5		
Within Clough (WC)			6		

Figure 4.4: Dendrogram with Centroid Linkage and Squared Euclidean Distance for Ashop Catchments (see Table 4.4 for key to catchments)

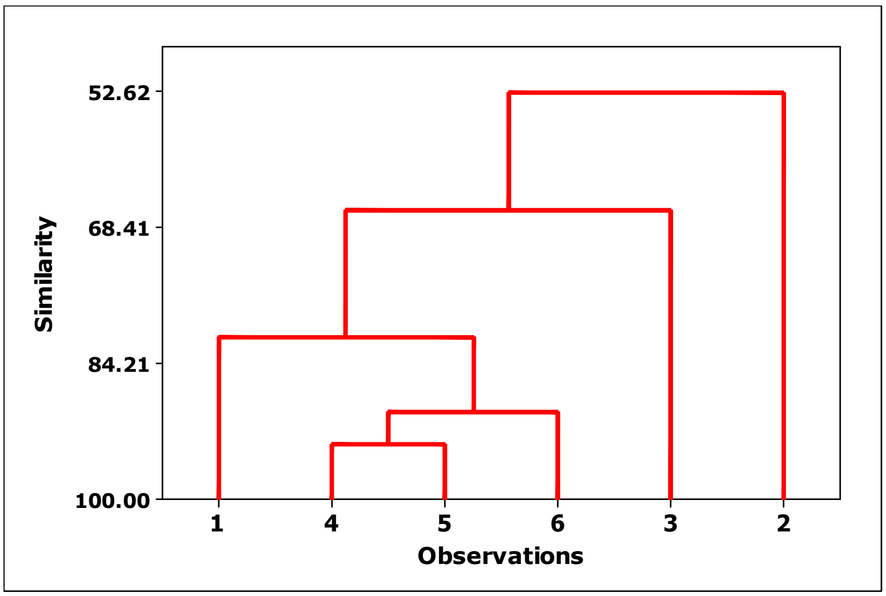


Table 4.5 shows the original catchment pairings of treatment and control catchment selected from the cluster analysis with Red Clough acting as an additional control:

Table 4.5: Original Catchment Pairings from Cluster Analysis

TREATMENT SITE	PAIRED CONTROL SITE
Within Clough	Upper Gate Clough
Nether Gate Clough	Upper Gate Clough
Doctors Gate Clough	Upper North Grain

During the study a number of observations were made which no longer made the theoretical catchment pairings appropriate:

i) In later years Doctors Gate Clough and Red Clough discharged a high volume of discoloured water associated with iron oxidation which was not observed on the remaining sites;

ii) Upper Gate Clough stage logger malfunctioned for part of the time resulting in data loss or unreliable data;

iii) The pairings were reassessed and appropriate pairings selected through correlation analysis for the calibration period (Oct 2002–Dec 2003). The paired catchment analysis to predict water colour, runoff and DOC flux is discussed in Chapter 8.

4.4 Water Sampling and Analysis

4.4.1 Water Sample Collection and Water Colour

During the initial monitoring period (May–Sept 2002) samples were collected on 15 visits from the six catchments in the study area and adjacent catchments on the River Ashop (Lady Clough, Birchin Clough, Urchin Clough, Lower Red Brook, Upper Red Brook, Sandy Hey Clough, Moss Castle Clough, River Ashop and Nether North Grain) to determine the spatial distribution and range of discoloured tributaries of the River Ashop.

In October 2002 Lange Xian 1000 automated water samplers were installed at each of the six catchments and programmed to sample hourly over a 24-hour period to provide a daily composite sample, commencing at 09.00 am GMT each day. This was necessary in order to collect a representative 500 ml sample over a 24-hour period whilst accounting for the temporal variability of water quality within the fluvial environment. This may be heavily dependent on discharge as well as changes in upstream sources of natural or anthropogenic pollution (HMSO 2000). Figure 3.1 shows the sampler locations and Table 4.6 provides the grid reference for the sampler sites on each catchment.

Table 4.6: Ashop Catchment Water Sampler Site Locations

Site	Central Grid Reference	Maximum Altitude (m)	Land Management
Doctors Gate Clough	SK 09607 93119	520	Grazing, no burning
Upper North Grain	SK 10220 93149	520	Grazing, no burning
Nether Gate Clough	SK 09883 90857	490	Grazing and burning
Upper Gate Clough	SK 09141 90732	520	Grazing and burning
Red Clough	SK 08635 90505	520	Grazing and burning
Within Clough	SK 07719 90674	515	Grazing and burning

Water samples were collected during field visits (every 10-14 days) from the samplers and also from selected tributaries immediately downstream of catchment area being monitored at Doctors Gate Clough and Upper North Grain. The raw water samples were enclosed in a bottle chamber of the water sampler in a cool, dark environment until collection during field visits. Figure 4.5 shows the bottle chamber and protective outer case of the bottle sampler. Each 500 ml sampler bottle was mixed by shaking to evenly distribute suspended sediment that may have settled to the base of the bottle following collection from the stream channel. A 50 ml bottle was rinsed with the water sample for a particular day and then a sub-sample decanted into the smaller bottle for ease of carrying back to the laboratory. The samples were then stored in a refrigerator at 4°C before being analysed (BSI 1995). All samples were analysed for water colour within three days of collection.

Figure 4.5: Lange Xian 1000 Water Sampler and Sample Chamber

On each visit, the equipment was checked, necessary maintenance carried out and batteries changed. However, approximately 30 % of data were lost from the catchments after equipment installation (refer to Tables 6.1-6.4 Ashop Summary Statistics for the number of days each year with no colour data and Appendix I – daily water analysis). The main reasons for missing data (that is, no water sample was collected over a 24-hour period) were battery failure (most common – due to harsh environment); equipment failure (tube dislodged in chamber, no vacuum, bottler index malfunction); hose out of water (hose left stranded on bank following rapid rise and fall in stage levels); or hose and/or bottles frozen.

4.4.2 Laboratory Analysis of Water Colour

The raw water samples were analysed for apparent and true colour (i.e. unfiltered and then having been filtered) in accordance with the laboratory procedures authorised by Severn Trent Laboratories (STL) (Severn Trent Laboratories 2000, 2002) and Home Office requirements (HMSO 1981, BSI 1995, HMSO 1988). Water colour was measured using a Cecil 1000 series spectrophotometer set at a wavelength of 400 nm with a path length of 40 mm (HMSO 1981, STL 2002) and converted into absorbance units per metre (aum^{-1}).

Samples for true colour were initially analysed by filtering water through a Whatman 0.45 µm cellulose acetate filter circle in accordance with Home Office and Severn Trent guidelines (Severn Trent Laboratories 2002). However, from Jan-Jul 2003 a second filtration was also conducted using Whatman 47 mm glass microfibre filter circles in addition to the cellulose acetate filters to determine the relationship between the true colour values of each type of filter circle. The repeated analysis was conducted to enable periodic analysis of samples for suspended sediment concentration and organic matter. The methodologies used for such analysis cannot be conducted with a cellulose acetate filter and therefore it was deemed preferable that water colour analysis be conducted using a glass microfibre filter only to enable direct comparison of more detailed analysis of storm events with daily composite samples. The correlation between the two filters was found to be high with an r^2 value of, for example, 0.9962 at Nether Gate Clough. Figure 4.6 shows the relationship between the microfibre filter and the cellulose acetate filter for samples collected from Nether Gate Clough and Figure 4.7 shows a time series of true colour (au^{-40mm}) at Nether Gate Clough from Jan-Jul 2003 from samples filtered from the microfibre and cellulose acetate filter.

Figure 4.6: Relationship between true colour (au^{-40mm}) cellulose acetate and glass microfibre filter at Nether Gate Clough

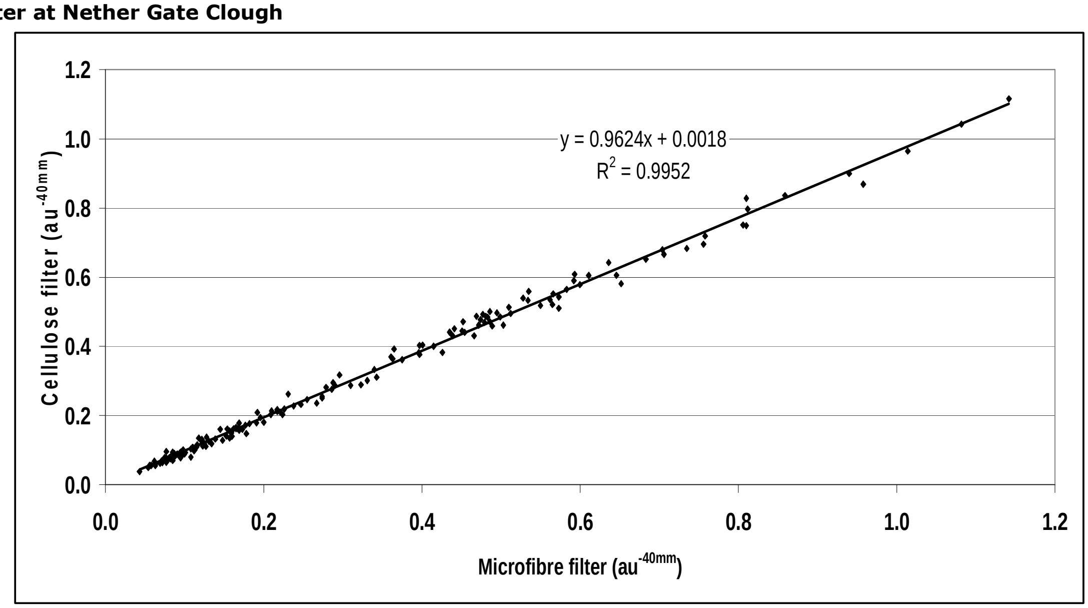
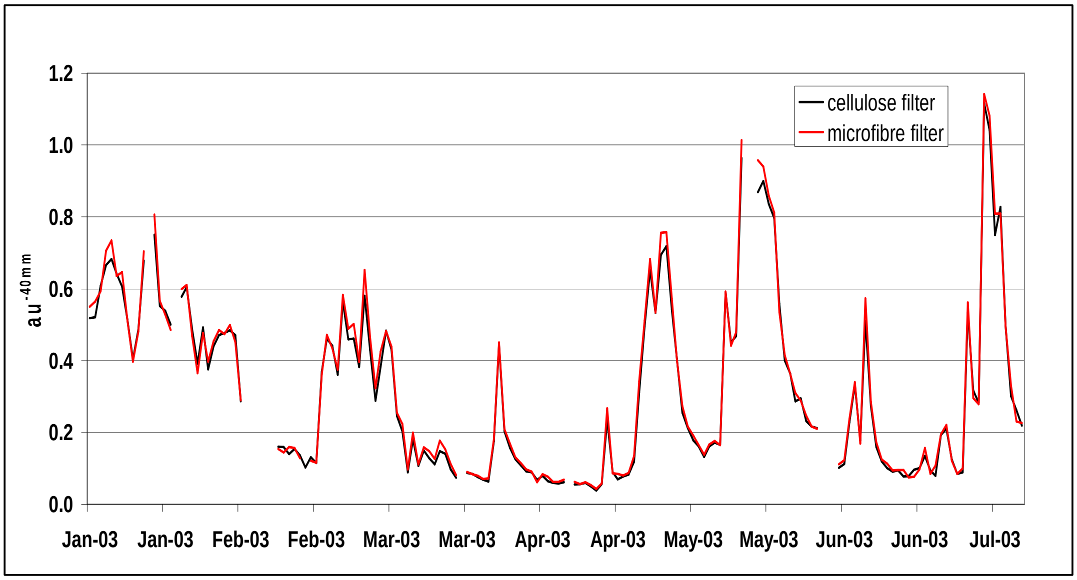


Figure 4.7: Time Series True Colour (au^{-40mm}) Nether Gate Clough (cellulose & glass microfibre filters)



From July 2003 water sample analysis was completed with the Whatman 47 mm glass micro fibre filter circles only and converted to a cellulose acetate value using a conversion equation for each catchment. Equations 4.1 to 4.6 show the predictive equation established and the r^2 value for each sub-catchment.

Doctors Gate Clough

$y = 0.8669x + 0.0328$ $\quad r^2 = 0.9513$ **Equation 4.1**

Upper North Grain

$y = 0.8529x + 0.02354$ $\quad r^2 = 0.9812$ **Equation 4.2**

Nether Gate Clough

$y = 0.9624x + 0.0018$ $\quad r^2 = 0.9952$ **Equation 4.3**

Upper Gate Clough

$y = 0.9781x - 0.002$ $\quad r^2 = 0.9801$ **Equation 4.4**

Red Clough

$y = 0.9878x - 0.0041$ $\quad r^2 = 0.9801$ **Equation 4.5**

Within Clough

$y = 0.9534x + 0.0021$ $\quad r^2 = 0.986$ **Equation 4.6**

Where y = True colour in au^{-40mm} using the cellulose acetate filter

x = True colour in au^{-40mm} using the microfibre filter

4.4.2.1 *Conversion of Water Colour (aum^{-1} to °H)*

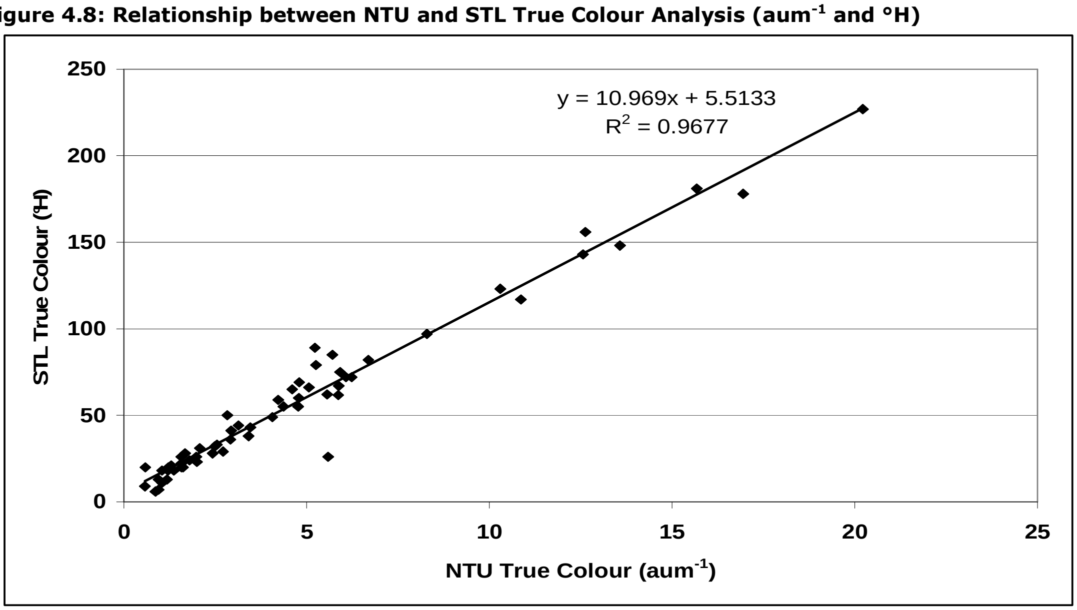
Many water companies in the UK have recorded colour measurements by two different methods. Water colour measured as absorbance at a wavelength of 400 nm has historically been the accepted unit of measurement. Following a European Community (EC) Directive (80/778/EEC), however, the standard unit of colour measurement changed to degrees Hazen (°H) and was implemented by the European Member States from January 1990. UK legislation (Water Supply (Water Quality) Regulations 1989, Water Supply (Water Quality) Regulations 2000) incorporated the standards set out in EC Directives 80/778/EEC and 98/83/EC. Watts *et al* (2001) generally accepted that colour values expressed in aum^{-1} could be converted into °H by a conversion factor of 15 (20°H = 1.5 aum^{-1}) following their studies of discoloured streams in North Yorkshire, UK.

Provision of a consistent long-term time series of water colour to enable a comparison of results from Severn Trent Laboratory (STL), meant a conversion factor from aum^{-1} to °H was required. The laboratory analyses water samples from across the Severn Trent region using a photometer and results are given directly in ºH (Severn Trent Laboratories 2002). Cross lab comparison of water collected by STW from ten streams in the Derwent and Ashop catchments, Derbyshire, were undertaken by the author and the STL laboratories for several sets of samples collected in 2003-04 (see Appendix II). Figure 4.8 shows the relationship between the two sets of analysis (r^2 0.9677) and Equation 4.7 enabled true colour in aum^{-1} to be converted into ºH.

$$y = 10.969x + 5.5133 \qquad r^2 = 0.9677 \qquad \textbf{Equation 4.7}$$

Where y = True colour in °H x = True colour in aum^{-1}

Figure 4.8: Relationship between NTU and STL True Colour Analysis (aum^{-1} and °H)



4.4.3 Laboratory Analysis of Dissolved Organic Carbon

The estimation of organic carbon in natural waters by measurement of uv absorbance has been used by many researchers over recent years (e.g. Reid *et al* 1980, Grieve 1984, Corin *et al* 1996) primarily because of the speed and precision with which measurements can be made, together with the feasibility of developing low-cost automated procedures to secure a long-term time series of data (Reid *et al* 1980). Arrangements were made with Dr Mike Billett (Centre of Ecology and Hydrology, Edinburgh) to collaborate and determine the level of DOC being discharged from each catchment. Sample sets containing a range of filtered discoloured water from high to low colour were regularly sent to Dr Billett between April 2004 and May 2005 for DOC analysis, having first been analysed for apparent and true colour. Determination of DOC was undertaken at SAC Edinburgh by digestion and uv oxidation using a Rosemount Dohrman DC-80 TOC Analyser after sample acidification and sparging with N_2. The relationship between true colour and DOC was good indicating a high correlation between the two variables. For example, Figure 4.9 shows the regression between true colour (°H) and DOC (mgl^{-1}) at Within Clough which has an r^2 value of 0.987.

Figure 4.9: Relationship between true colour (°H) and DOC (mgl^{-1}) at Within Clough

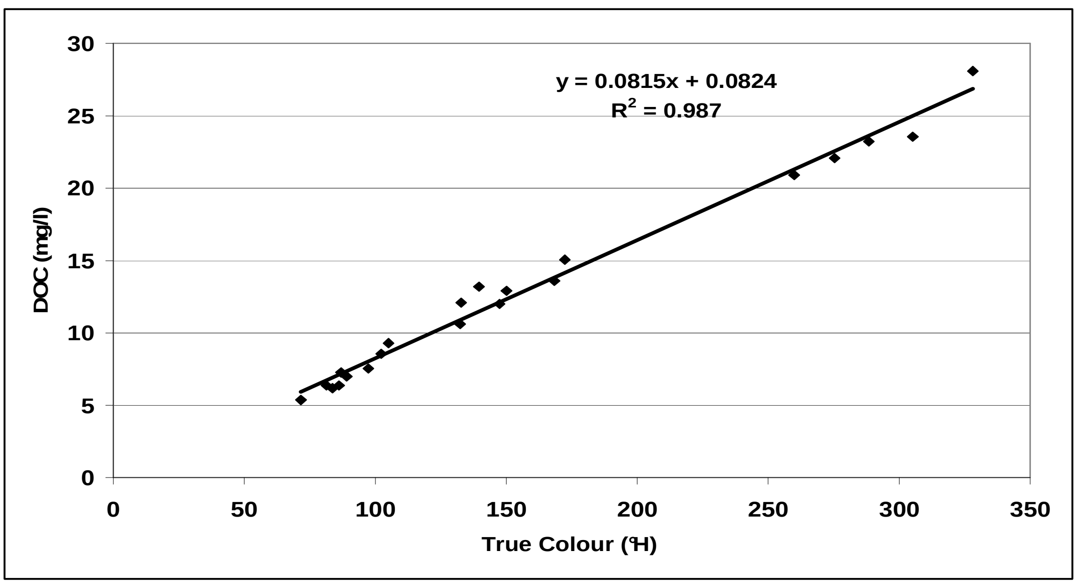
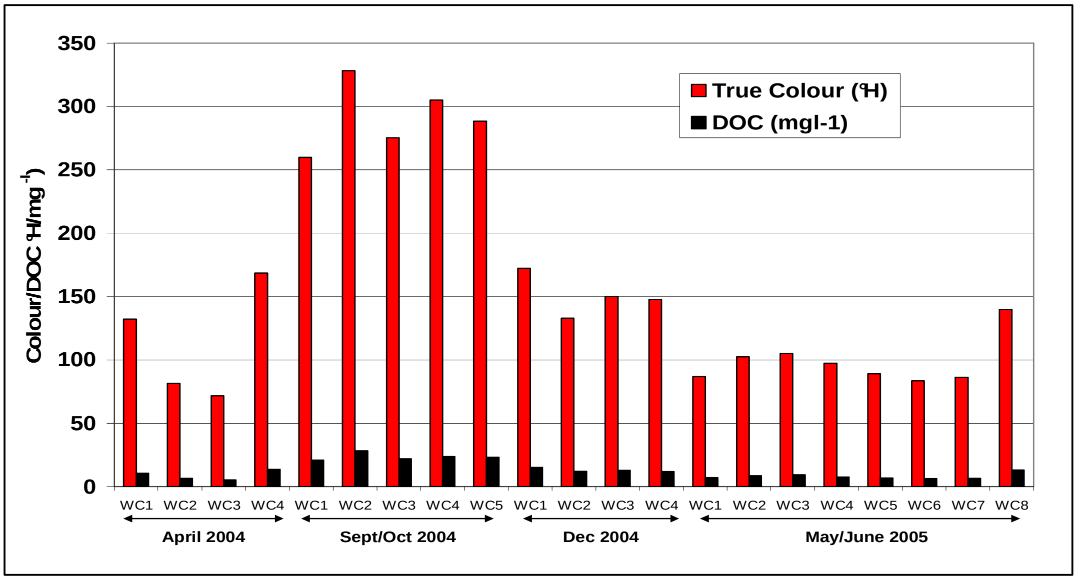


Figure 4.10 shows the numbered samples (for example WC1) which identify a water sample for a particular catchment (Within Clough) collected on a particular day. The figure illustrates the seasonal variation of samples collected and the temporal differences in true colour (°H) and DOC (mgl^{-1}). Appendix III shows the data set and sample identification for the study sites from which a predictive equation has been calculated for each sub-catchment. Equations 4.8 to 4.13 show the predictive equations and the r^2 value for each sub-catchment.

Figure 4.10: Comparison of true water colour (°H) and DOC (mgl^{-1}) at Within Clough



Doctors Gate Clough

$y = 0.0741x + 0.9055$ $r^2 = 0.8821$ **Equation 4.8**

Upper North Grain

$y = 0.0955x + 0.1262$ $r^2 = 0.9237$ **Equation 4.9**

Nether Gate Clough

$y = 0.08132x - 0.597$ $r^2 = 0.9656$ **Equation 4.10**

Upper Gate Clough

$y = 0.0697x + 1.8171$ $r^2 = 0.9726$ **Equation 4.11**

Red Clough

$y = 0.0696x + 1.0595$ $r^2 = 0.8106$ **Equation 4.12**

Within Clough

$y = 0.0815x + 0.0824$ $r^2 = 0.987$ **Equation 4.13**

Where y = Dissolved Organic Carbon (mgl^{-1}) x = True Colour (°H)

4.4.4 Laboratory Analysis of Heavy Metals

Analysis of the heavy metals iron (Fe), aluminium (Al) and manganese (Mn) was commenced in March 2006 using an Inductively Coupled Plasma Optical Emission Spectrophotometer (ICPOES). A number of filtered samples ranging in colour and turbidity were selected bi-monthly from each of the study sites and analysed. The samples represented the daily composite sample collected by the automated water sampler commencing at 9 a.m. GMT and ending at 8.00 a.m. the following day.

4.5 Air Temperature

Temperature (°C) was recorded at Upper Gate Clough from September 2003. The air temperature was recorded at 15 minute intervals with a Tinytag temperature recorder located 0.1 m from the ground surface (Grid reference SK 09110 90771 - see Figure 3.6 for location). This information was supplemented by Meteorological Office Rainfall and Evapotranspiration Calculation System (MORECS) estimates provided by the Meteorological Office and Environment Agency for the 40km x 40km square in which the study area is located (MORECS square 106). MORECS data were also provided by the Environment Agency for a 25 year period prior to the end of the study.

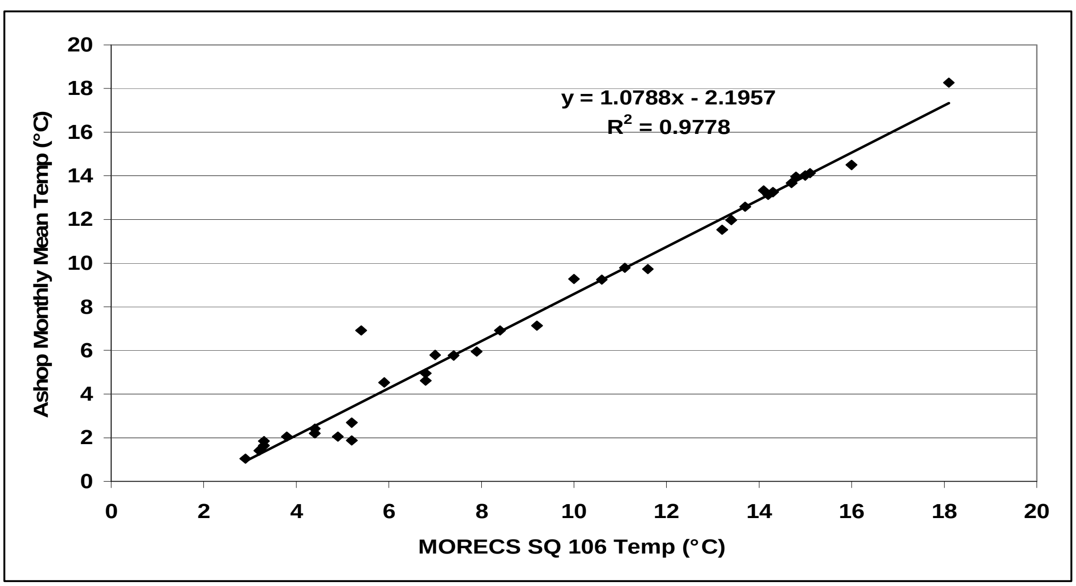
During the study the temperature gauge failed to log data for several periods: Jun-Jul 2004, 19-25 Jan 2005 and May–Jun 2006 due to problems in downloading the data logger. MORECS data for the area were used to supplement the missing monthly data. A relationship was determined by calculating the monthly temperature data at Upper Gate Clough and comparing it with the monthly MORECS temperature data from Oct 2003–Sept 2006. Figure 4.11 shows the good correlation between Upper Gate Clough temperature logger and MORECS datasets (r^2 0.9778). Equation 4.14 was used to predict the monthly temperature at Upper Gate Clough for the periods when data were not recorded.

$$y = 1.0788x - 2.1956 \qquad r^2 = 0.9778 \qquad \textbf{Equation 4.14}$$

Where y = Monthly air temperature (°C) at Upper Gate Clough

x = Monthly temperature for MORECS square 106

Figure 4.11: Monthly Temperature at Upper Gate Clough & Monthly MORECS Oct 2003-Sept 2006



4.6 Hydrometry

Hydrological processes on each catchment were investigated to collate baseline data during a calibration period (pre-management intervention) and to establish pairs of catchments with similar hydrological properties. This section details how precipitation, water stage, and water table levels were measured and discharge was calculated during this period. Those catchments found to have similar characteristics, particularly in water colour, discharge and DOC flux were considered a suitable pairing providing that other factors such as morphology, topography and land management characteristics were not too dissimilar. The following techniques have been used to study the hydrology of the catchment.

4.6.1 Rainfall Measurement

Rainfall was measured within the study site with a Casella 0.2 mm tipping bucket rain gauge located at Upper Gate Clough (grid reference SK 09110 90771 - see Figure 3.6). A Snowdon manual rain gauge was also sited next to the Casella rain gauge to validate the automatic data logged by the Casella.

The University of Manchester had sited a weather station at Upper North Grain, approximately 1.5 km from the rain gauge at Upper Gate Clough. An agreement was made with the investigator (Dr Martin Evans) to exchange rainfall data to gain more detailed information of the spatial and temporal variation in precipitation across the study site.

During the study, the Casella rain gauge failed to download data for two periods in 2003 and 2005. The periods were 23 Apr–23 Jun 2003, and 28 Jul 2005–30 Nov 2005. Data supplied by the University of Manchester and the Environment Agency (Derwent Dam rain gauge) were used to supplement missing data and so provide a composite record of rainfall during the monitoring period. A relationship was determined when rainfall was recorded at both Upper Gate Clough and Upper North Grain (during the water year Oct 2003-Sept 2004). Figure 4.12 shows the rainfall recorded at the two sites with an over-lapping period from Oct 2003-Aug 2004. Figure 4.13 illustrates the relationship between the two gauges with an r^2 0.8352. Equation 4.15 was used to predict the rainfall at Upper Gate Clough for part of the missing period in 2005 from the data at Upper North Grain.

$$y = 1.0114x + 0.5596 \qquad r^2 = 0.8352$$ **Equation 4.15**

Where y = Daily rainfall at Upper Gate Clough (mm) x = Daily rainfall at Upper North Grain (mm)

Figure 4.12: Daily rainfall (mm) at Upper Gate Clough and Upper North Grain Oct 2003-Aug 2004.

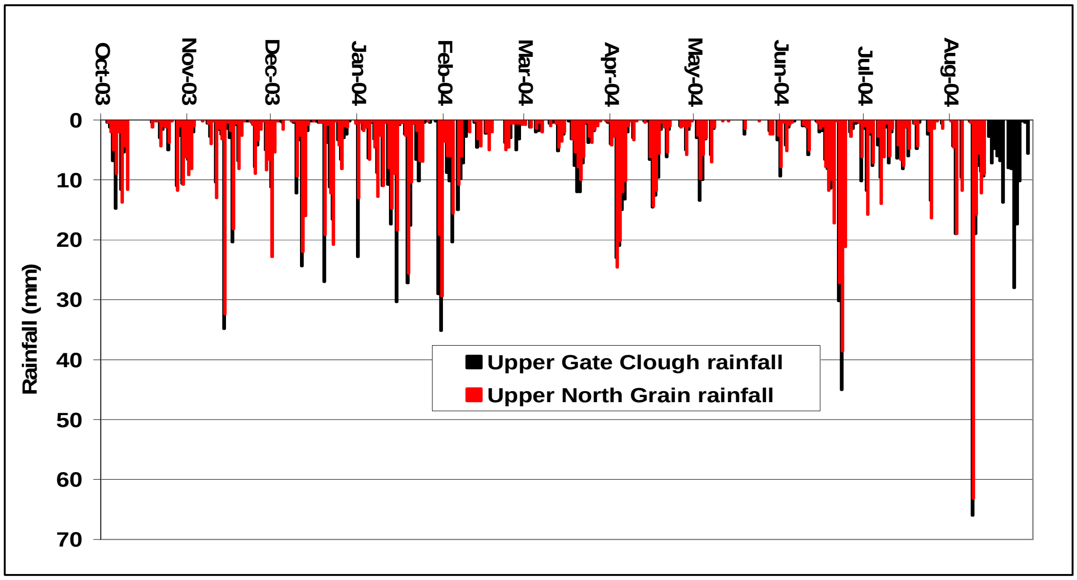
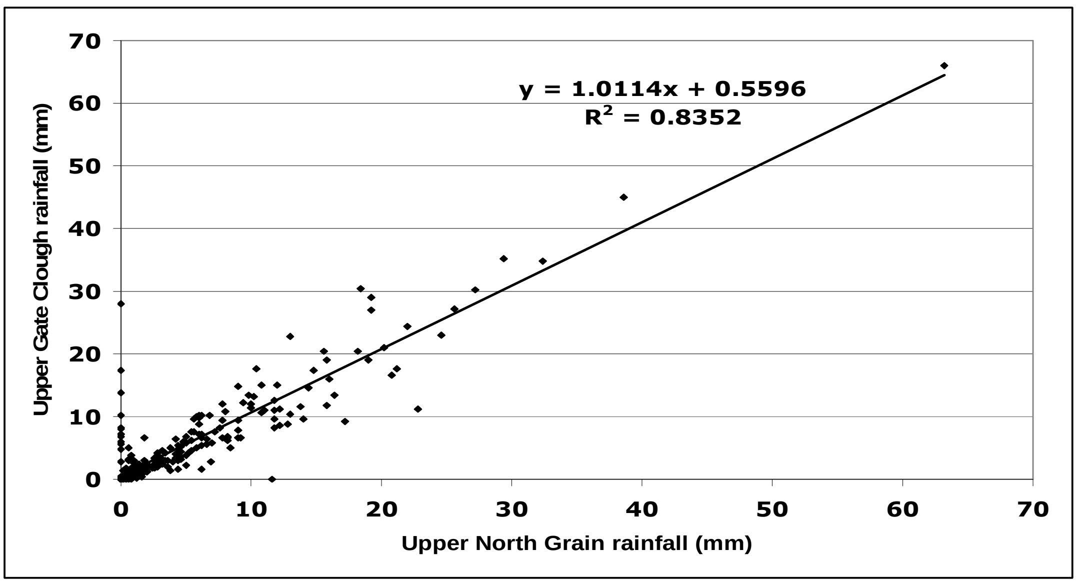


Figure 4.13: Rainfall at Upper Gate Clough and Upper North Grain Oct 2003-Aug 2004

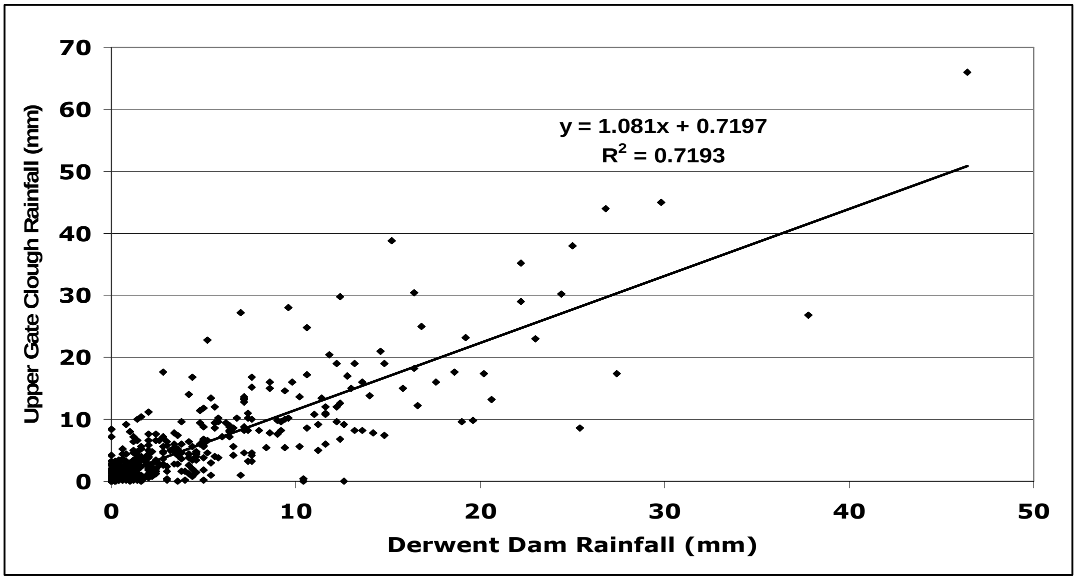


The rain gauge at Upper North Grain was also inoperable during part of this period (*pers comm*. Dr Evans 2005). The rainfall data for this missing period were calculated from a regression equation using Derwent Dam rainfall supplied by the Environment Agency to predict Upper Gate Clough rainfall. Figure 4.14 illustrates the relationship between Derwent Dam and Upper Gate Clough from 1 Jan 2004-30 Jun 2005 and shows a good relationship (r^2 0.7193) between the two data sets. A predictive equation (equation 4.16) has been used to determine the rainfall at Upper Gate Clough.

$$y = 1.081x + 0.7197 \qquad r^2 = 0.7193$$ **Equation 4.16**

Where y = Daily rainfall at Upper Gate Clough (mm) x = Daily rainfall at Derwent Dam (mm)

Figure 4.14: Relationship between Derwent Dam and Upper Gate Clough Rain Gauges Jan 2004-Jun 2005



4.6.2 Discharge Measurement

In order to monitor changes on a catchment scale, appropriate sites were selected near the outflow of each of the experimental catchments and flow was gauged at stream sections with few obstructions. Although the building of an hydraulic structure such as a weir or flume with stable and closely defined dimensions was considered, the location of the sites within SSSIs in aesthetically pleasing areas close to public footpaths placed restrictions on such constructions and permission was therefore denied by the National Trust (*pers comm.* Steve Trotter, High Peak Estate Manager, 2002).

Every effort was therefore made to maximise accuracy of water stage levels and flow velocity measurements at each site in order to identify changes between water years and between periods of pre- and post-management intervention and so determine if such changes may have occurred from land management manipulation. Fixed stage rulers remained in place throughout the project. The accepted level of accuracy for water stage level was to the nearest 0.01 m.

Stream discharge on each catchment was calculated from stage (stream surface water level) data monitored with an Ott Thalimedes shaft encoder (Figure 4.15) with a stated accuracy of +/- 2 mm (Ott Hydrometry 2001). A shaft encoder was installed at each of the six catchments in accordance with the BSI recommendations "*Measurement of Liquid Flow in Open Channels Determination of the Stage-Discharge Relationships*" (BS ISO 1100-2) (BSI 1998). The shaft encoders were encased in stilling wells and sited on a straight section of the stream channel to minimise error and data loss. Figure 3.1 show the catchments and location where equipment was installed adjacent to the water samplers at the base of the catchments.

The shaft encoders were set to record at 5 minute intervals. This frequency was selected to enable detailed analysis of storm events as the study sites were typical of upland headwaters in general in that stage can rise rapidly within a short time of a rainfall event commencing, resulting in a very flashy runoff regime (Burt *et al* 1990, Cooper *et al* 2007). The frequency of recording therefore enabled the rapid rise in stage to be captured, whilst also allowing data to be summarised into hourly, daily or monthly stage or discharge for each catchment for analytical purposes. The water samplers for each catchment were then sited adjacent to the stilling well stage logger to co-ordinate collection of automated data.

The data loggers did not operate correctly for certain periods due to failure of equipment or damage during storm events. The periods when no data or inaccurate data were recorded have been removed from the data records to allow representative data analysis. The descriptive statistics of area specific discharge (ASQ) in Section 7.2.2 show the number of days of missing data for each catchment where daily stage levels were not recorded accurately and Appendix IV shows the number of days per month when stage data were not available.

4.6.2.1 Stream Velocity

Stream flow was measured in the field using an Aqua Data Systems Sensa RC2 electromagnetic flow meter (ECM) at stable natural sections to calculate discharge (Q) at known stage levels (see Appendix V for data recorded). Rating curves were produced for each stream to enable the calculation of discharge from a stage record at any given time using a rating equation. Figure 4.16 shows the rating curves for each study site developed from the relationship between stage (measured with the Ott shaft encoder) and measured stream flow at the cross-section of each catchment Oct 2002–Sept 2006.

Equations 4.17-4.23 were established to calculate the discharge from known stage levels at each study site.

Doctors Gate Clough

$$y = 299.49x - 12.246 \qquad r^2 = 0.8974 \qquad \textbf{Equation 4.17}$$

Upper North Grain

$$y = 381.84x - 8.7081 \qquad r^2 = 0.7254 \qquad \textbf{Equation 4.18}$$

Nether Gate Clough

$$y = 199.47x - 19.102 \qquad r^2 = 0.6579 \qquad \textbf{Equation 4.19}$$

Upper Gate Clough

$$y = 268.88x - 8.9909 \qquad r^2 = 0.798 \qquad \textbf{Equation 4.20}$$

Red Clough

$$y = 244.34x - 48.562 \qquad r^2 = 0.8252 \qquad \textbf{Equation 4.21}$$

Within Clough 1

$$y = 824.45x-87.741 \qquad r^2 = 0.9914 \qquad \textbf{Equation 4.22}$$

Within Clough 2

$$y = 610.29x - 75.999 \qquad r^2 = 0.9577 \qquad \textbf{Equation 4.23}$$

Where y = Discharge (ls^{-1}) x = Stage level (m)

Figure 4.16 shows the rating curves and equations for each of the six Ashop catchments. The rating curves vary between each site due to differences in catchment size and drainage density (see Table 4.2). Upper North Grain and the two sites at Within Clough 1 and Within Clough 2 had the steepest rating curve, indicating that the discharge rate and the flow velocity at the rated section was higher than the other catchments. This was primarily because of the catchment size: Upper North Grain 1.26 km^2, Within Clough 1.138 km^2 are the two largest catchments within the study area with a greater drainage density, associated with the high number of first order streams that contribute to the run off.

Some problems were experienced with flow monitoring at Within Clough. During the monitoring period a shale bar began to form at the section of stream being monitored for stage and stream flow at Within Clough and may have affected the channel at the gauging site, particularly following a storm event in July 2003 which caused channel instability upstream. Efforts were made during site visits to maintain the channel profile, but this became increasingly difficult due to a minor slope failure just upstream from the original Within Clough site (Within Clough 1) and the increased deposition of eroded material in the channel. A second gauging site (Within Clough 2) was therefore established in May 2004 approximately 50 m upstream from the original site at Within Clough (i.e. upstream of the land slide). Flow measurements and stage were recorded at the second site whilst stage continued to be recorded at both Within Clough sites from May 2004 – Mar 2005. After this time it was no longer possible to measure the correct stage at the Within Clough 1 site due to the build-up of shale in the channel which caused an inaccurate high level of stage. Following examination of the stage records and calculation of discharge at each Within Clough site using the equations 4.21 and 4.22, the two sites were then compared and a predictive equation was calculated using regression analysis.

Figure 4.16: Rating Curves and Equations for Ashop Sub-Catchments Oct 2002-Sept 2006

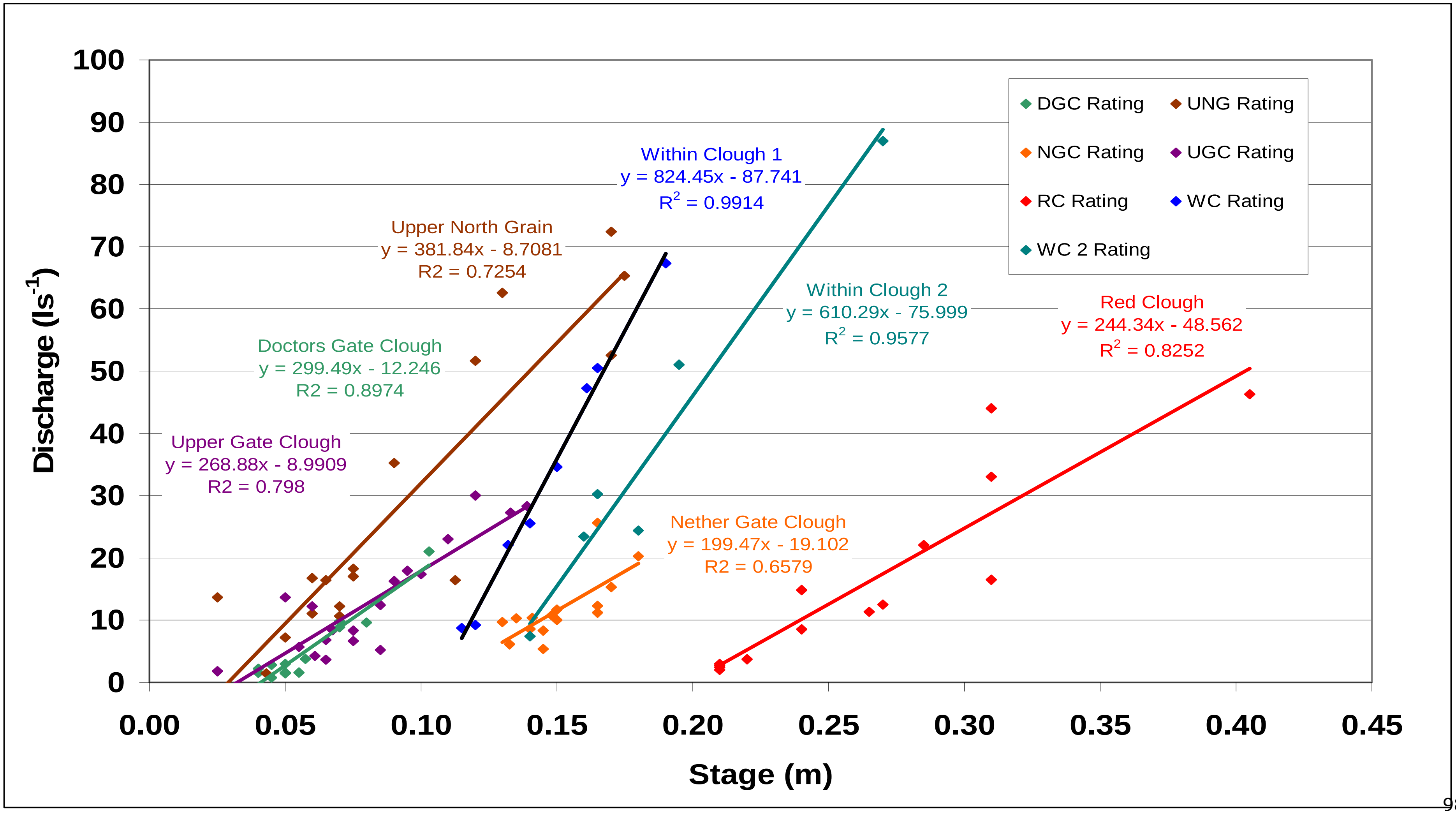
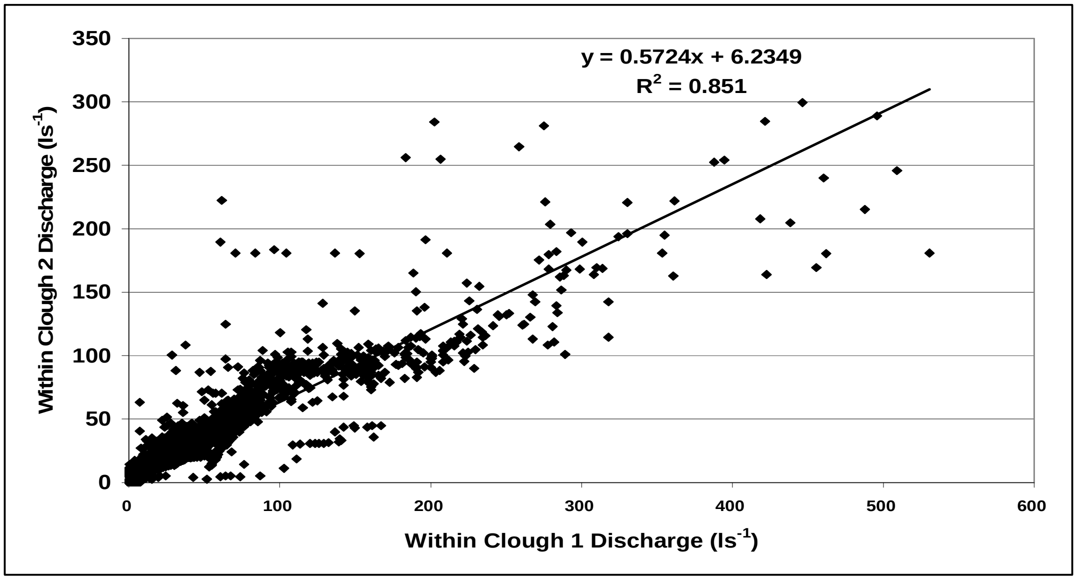


Figure 4.17 shows the relationship between both sites (r^2 0.851) and Equation 4.23 was used to predict the discharge at the Within Clough 2 site from Oct 2002 – May 2004 using the discharge data from Within Clough 1 site for this period.

$$y = 0.5724x + 6.2349 \qquad r^2 = 0.851 \qquad \textbf{Equation 4.23}$$

Where y = Discharge at Within Clough 2 (ls^{-1}) x = Discharge at Within Clough 1 (ls^{-1})

Figure 4.17: Relationship between Within Clough 1 and 2 Hourly Discharge (ls^{-1}) May 2004-Mar 2005



During the monitoring period every effort was made to obtain stream flow measurements over a range of stage levels to maximise accuracy and avoid extrapolation of discharge to higher stage levels than at those when flow was actually measured. Nevertheless, measurements at very high stage levels were not recorded for a number of reasons. The travelling distance to the site and staff arrangements for field visits reduced the degree of flexibility in visiting the site following periods of high rainfall; the quick response and rapid rise in stage following a storm event caused erratic and turbulent flow which may not have been accurately recorded by the ECM; and the high risk factor of taking measurements in a water course under such conditions had to be given due consideration. In order to determine that discharge had been recorded at representative stage levels for each catchment during the study period, a stage duration curve was calculated for each water year (Oct–Sept) and the percentage time that stage exceeded the maximum stage level at which flow measurements were recorded was noted. Figure 4.18 shows a stage duration curve at Doctors Gate Clough for the water year Oct 2004 – Sept 2005 and indicates that the stage level at which flow was recorded was only exceeded by higher stage levels for ~ 8 % of the time. Table 4.7 shows the maximum stage at which flow measurements were recorded at each catchment, with the approximate percentage time stage exceeded this level.

Figure 4.18: Doctors Gate Clough Stage (m) Duration Curve Oct 2004-Sept 2005

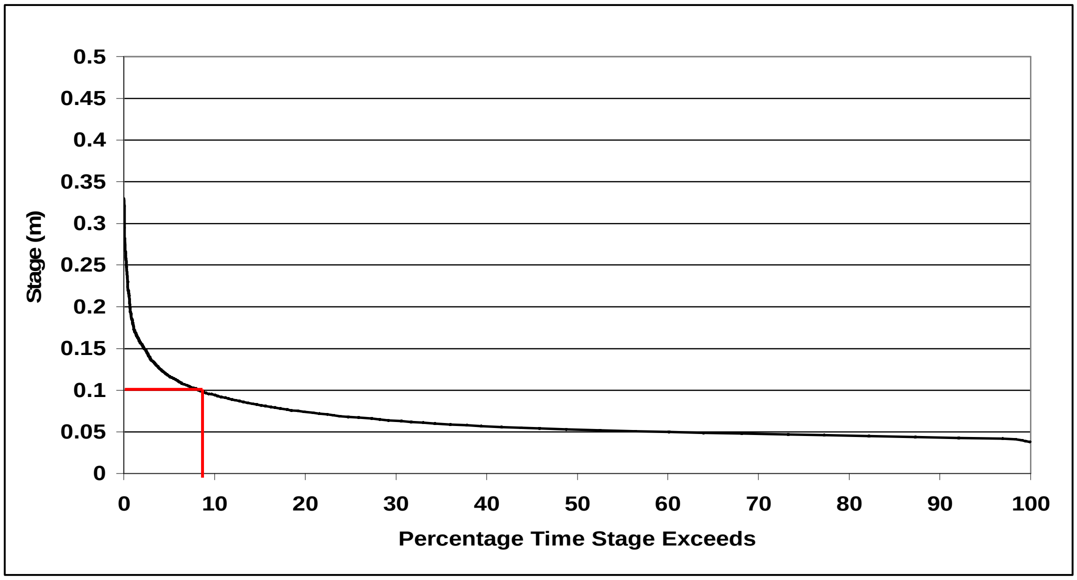


Table 4.7: Ashop Catchments Maximum Gauged Stage Levels (m) and Percentage Exceedance Time Oct 2002-Sept 2006

	DGC	UNG	NGC	UGC	RC	WC
Max Stage	0.103	0.175	0.18	0.139	0.355	0.27
2002-03 (%)	10	10.5	10	9.5	7	5
2003-04 (%)	10	21	14	10.5	8	4
2004-05 (%)	8	14	10	9.5	4	5
2005-06 (%)	9.5	11.5	13	13	5	5

4.7 Water Table

A suite of up to 15 dipwells (32 mm diameter soil tubes (drainpipes sealed at the base with numerous 5 mm holes drilled along the tube to allow water to enter) was installed on the plateau of each catchment to measure the fluctuations in water table levels which represent changes in soil water conditions (Worrall *et al* 2006). The transects were located at sites with similar topography, vegetation and management (gullies approximately 2-3 m wide and 1.5 m depth, with a peat substrate, predominantly used for grassland/grazing or dwarf shrub/grouse shooting). The dipwells were placed at set intervals from the centre of the gully along each of the transects. The intervals were 1, 3.5, 5, 8.5, 13.5, 18.5, 28.5 35.5 and up to 45.5 m from the centre of the gully transect. Table 4.8 shows the number, altitude and location of dipwells at each site and Figure 4.19 shows the dipwell number and distance between the dipwells at Within Clough. The positive distances were to the west of the gully and the negative distances to the east of the gully.

The dipwells were monitored on an approximate four-weekly interval from Apr 2003-Sept 2006 and measurements were taken on the same day over a six-hour period across the sites. The data used in the analysis ran from Jun 2003-Sept 2006 which allowed for a period of two months of stabilisation after the dipwells were installed. Water levels were measured from the top of each dipwell and the datum subtracted to provide a depth to water table from the mire surface. Weather conditions were noted on the day of measurement, particularly during periods of heavy rain. Data for January 2004 were not collected due to adverse weather conditions (deep snow cover) and individual dipwells were not measured at Within Clough after being vandalised (dipwell 5 pushed down into the ground and data not recorded from 6 Dec 2005). Such vandalism was infrequent and only occurred at Within Clough where the dipwells were within sight of the popular Pennine Way footpath. See Appendix XIII for the dipwell measurements and data lost.

Table 4.8: Ashop Catchments Dipwell Sites Locations and Land Management

Site	Location	Number of Dipwells	Altitude (m)	Land Management
Doctors Gate Clough	SK 09568 93795	12	520	No grazing after first year, no burning
Upper North Grain	SK 10840 94102	15	520	Grazing, no burning
Nether Gate Clough	SK 10021 91501	15	490	No burning after first year and grazing
Upper Gate Clough	SK 09500 91779	15	520	Grazing and burning
Red Clough	SK 08646 91791	15	520	Grazing and burning
Within Clough	SK 08419 92059	14	515	Grazing and burning, gullies blocked

Figure 4.19: Dipwell points along Transect at Within Clough

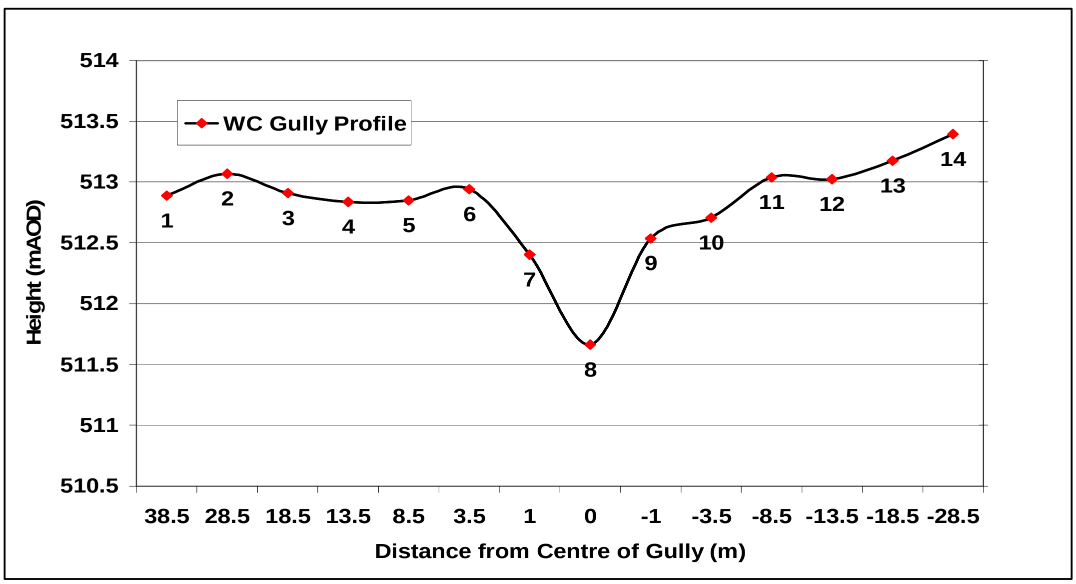
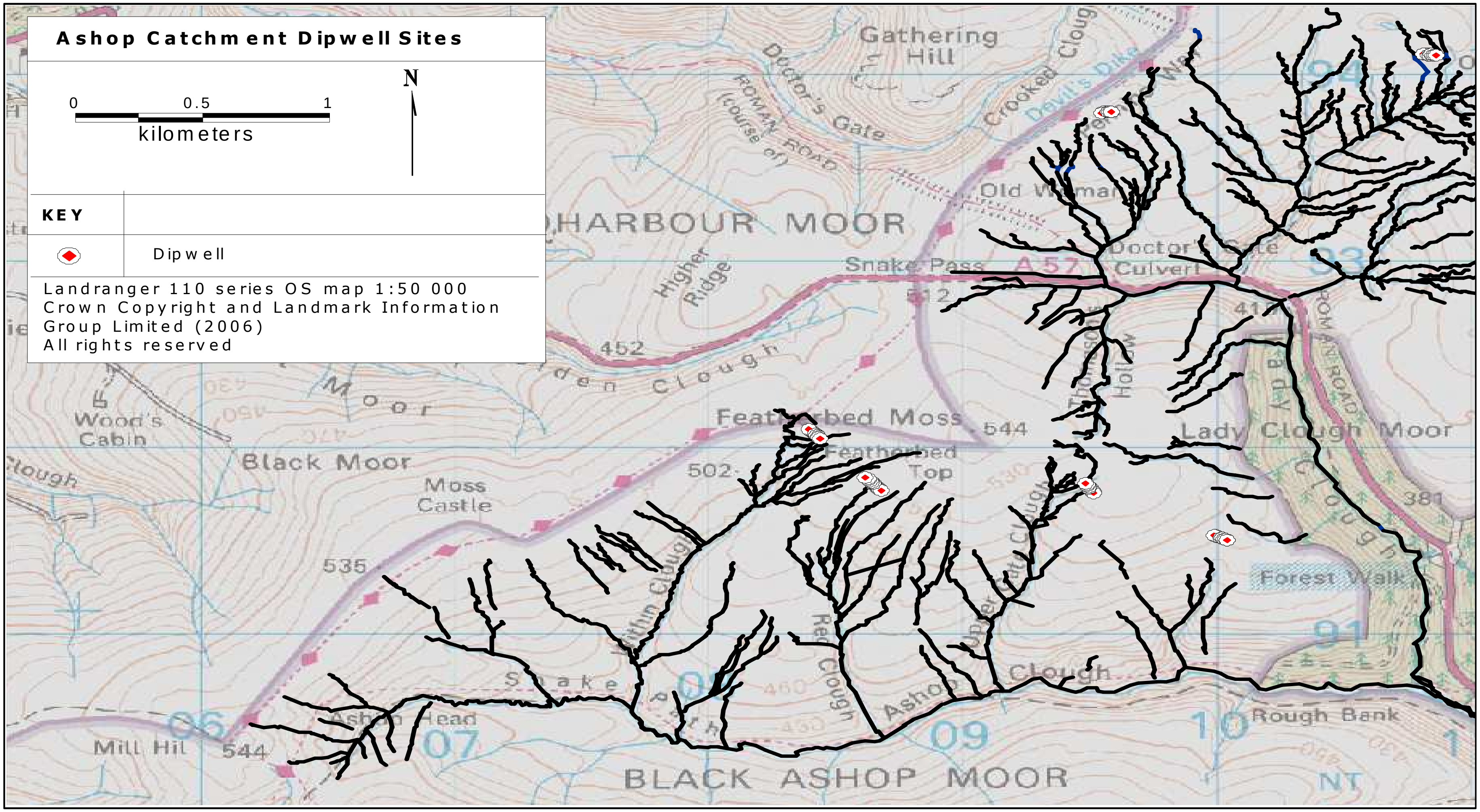


Figure 4.20 shows the location of the dipwell transects in the headwaters of the catchments. Additional topographic data were recorded in key areas such as at dipwell sites and gullies with a Leica 500 dGPS to enable an accurate position (+/- 1 cm horizontal, 2 cm vertical) to be recorded in relation to surrounding topographic conditions.

Figure 4.20: Ashop Catchment Dipwell Sites, south Pennines, Derbyshire



4.8 Geology and Pedology

A desk-top study of data already available for the study area was conducted. British Geological Survey maps 'Chapel-en-le-Frith England and Wales Sheet 99 Solid Drift Edition and Drift Edition' at 1:50 000 series provided details on the geology of the catchment. Soil Survey maps (Jarvis *et al* 1984) and digitised geology and drift maps were registered and digitised using Mapinfo v. 7.8 to estimate percentage cover of geology and soil types in the sub-catchments. The percentage cover of Winter Hill peat (1011B) was calculated as this represented the greatest volume of organic material in the sub-catchments and has been identified as being highly correlated to discolouration of surface waters (Mitchell and McDonald 1995).

4.8.1 Morphology and Topography

The following variables were estimated to assess the character of each catchment (Strahler 1964) and enable comparisons to be made for later pairing of catchments post-management intervention. A digital OS map 1:10 000 of the study site was used in conjunction with the Mapinfo v 7.8 GIS software to calculate the following variables.

Area (km^2) upstream from the gauging station;

Stream network length (km);

Drainage density (km of stream channel.km^{-2} of catchment);

Dominant Aspect (degrees deviation from north facing);

Percentage of the total stream network length in areas of the sub-catchment with slope angles less than five degrees.

General surface topography was recorded from LiDAR data (supplied by National Trust) and DEM map (supplied by Haycock Associates 2003) created using the LiDAR data. These data have been supplemented by the interpretation of aerial photographs taken by Simmons 2003 and Infoterra 2005 (supplied by the National Trust and Moors for the Future) and ground truthing during field visits.

4.9 Summary

This chapter has described the methodologies used to achieve the aim and objectives of the research set out in Section 1.5. The importance of experimental design, planning and negotiation has been highlighted in setting-up the research at the catchment-scale. A selection of methods was chosen as appropriate to site conditions and resources available. The need for extensive fieldwork was a prerequisite to obtain the necessary data over a period of time during which changes in land management were implemented. Data were collected both manually (e.g. dipwell measurements) and by automated data loggers with intensive sampling protocols, particularly during and after rainfall events when changes in terms of water colour and runoff were likely to be observed.

The use of secondary digitised data of this well-studied region provided valuable resources for assessing the catchments particularly in terms of geology, pedology, vegetation and burning regimes. These catchment characteristics were assessed to assist in selecting appropriate catchment pairings (see Table 4.2).

Standard laboratory procedures were used to analyse water quality and enable analysis and interpretation of past and future trends in water colour, water yield and DOC flux, the results of which are discussed in the subsequent chapters.

5 ANTECEDENT AND PREVAILING ENVIRONMENTAL CONDITIONS:THEIR CONTRIBUTION TO WATER QUALITY AND YIELD

5.1 Introduction

Although it is accepted that upland catchments may respond rapidly to changes in meteorological conditions (mainly rainfall and temperature), this is often complicated by the antecedent rainfall which may affect the rainfall–runoff relationship and volume of discoloured water draining from a particular catchment (Worrall *et al* 2008). In order to identify the changes resulting from management manipulation and separate them from the seasonal fluctuations, the average monthly values were analysed to determine whether changes in environmental variables were significant between pre and post management manipulation

Firstly, the annual rainfall and temperature, followed by the mean monthly rainfall, temperature and MORECS data are presented to give an overview of the climatic conditions to which all six Ashop catchments were subject during the four years of monitoring. The geographical proximity, similar altitude, vegetation and topography meant the prevailing climatic conditions across the catchments were considered similar for analytical purposes. The long-term average rainfall, temperature and MORECS data are also presented, based on rainfall records at Derwent Dam (supplied by the Environment Agency) and MORECS data (square 106) from 1961-2005 to determine whether conditions during the study period were atypical or were above or below the long-term average.

5.2 Rainfall

5.2.1 Annual Rainfall

The mean annual rainfall over the four years of the study was 1450 mm. The annual rainfall for the study area in each water year from Oct 2002-Sept 2006 is summarised in Table 5.1. The highest annual rainfall fell from Oct 2003-Sept 2004 (total 1672.2 mm) during the second year of study. The third and fourth year of study (Oct 2004-Sept 2005 and Oct 2005-Sept 2006) had comparatively low rainfall (1324 mm and 1389 mm respectively) whilst the annual rainfall during the first year of study (calibration period) was slightly higher (1412 mm). The first year of the study however, also had the highest number of days when no rain was recorded (141 days), compared to the last year of the study (124 days) and the second and third years of the study which both had 100 days when no rainfall was recorded.

Table 5.1: Ashop Catchments Daily Rainfall (mm) Oct 2002-Sept 2006

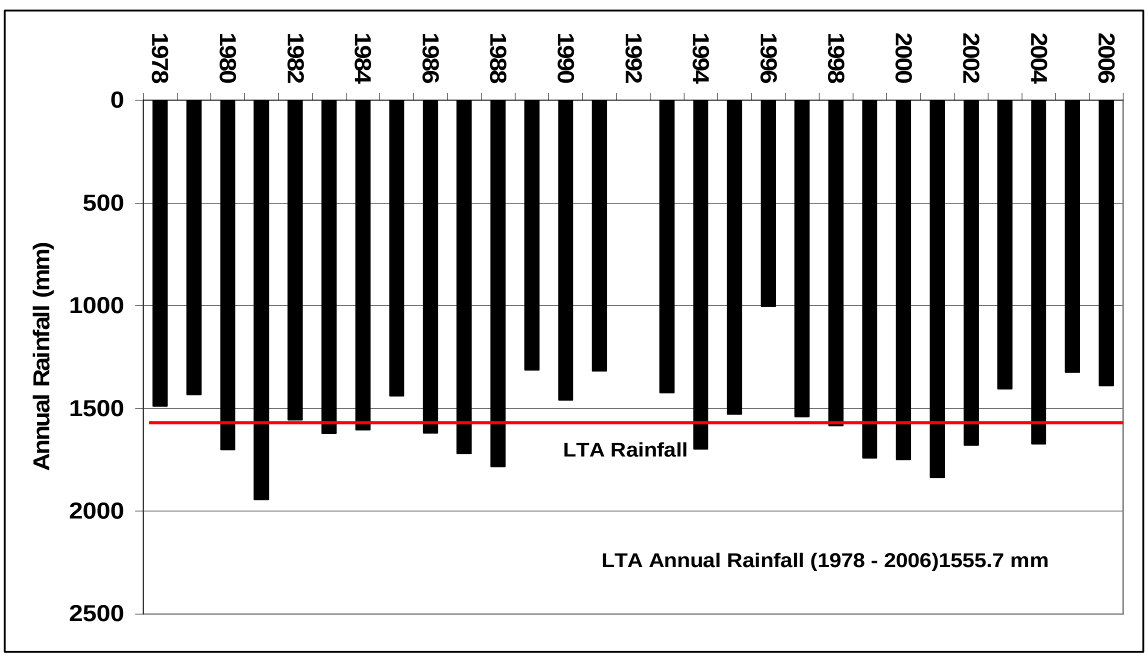
Variable	N	N* (days with no rain)	Total Annual	Daily Mean	Daily SE Mean	Daily St Dev	Daily Median	Daily Max
Oct 2002 - Sept 2003	358	141	1412.3	6.3	0.5	6.6	4	40.4
Oct 2003 - Sept 2004	366	100	1672.2	6.3	0.5	7.6	3.2	66
Oct 2004 - Sept 2005	365	100	1324.2	5.2	0.4	6.0	3	44
Oct 2005 - Sept 2006	365	124	1388.9	5.8	0.4	5.8	3.4	35.1

Figure 5.1 shows the longer-term annual rainfall (Oct-Sept) calculated for the study area from 1978-2006. The antecedent annual rainfall was retrodicted to October 1978 by correlating the monthly Ashop rainfall with the monthly rainfall recorded at Derwent Dam (supplied by the Environment Agency) for the period Oct 2002-Sept 2006. Data for several months in 1992 were missing and therefore excluded from the calculation. Equation 5.1 shows the equation used to retrodict the antecedent rainfall and the r^2 value (0.7493) which indicates a good correlation between the two data sets. The estimated long-term annual rainfall for the Ashop is thus 1555.7 mm and Figure 5.1 indicates that the rainfall years 2003, 2005 and 2006 during the study period were below average with only 2004 being above average for the area.

$$y = 0.9901x + 23.649 \qquad r^2 = 0.7493$$ **Equation 5.1**

Where y = Ashop antecedent monthly Rainfall (mm) x = Derwent Dam monthly rainfall (mm)

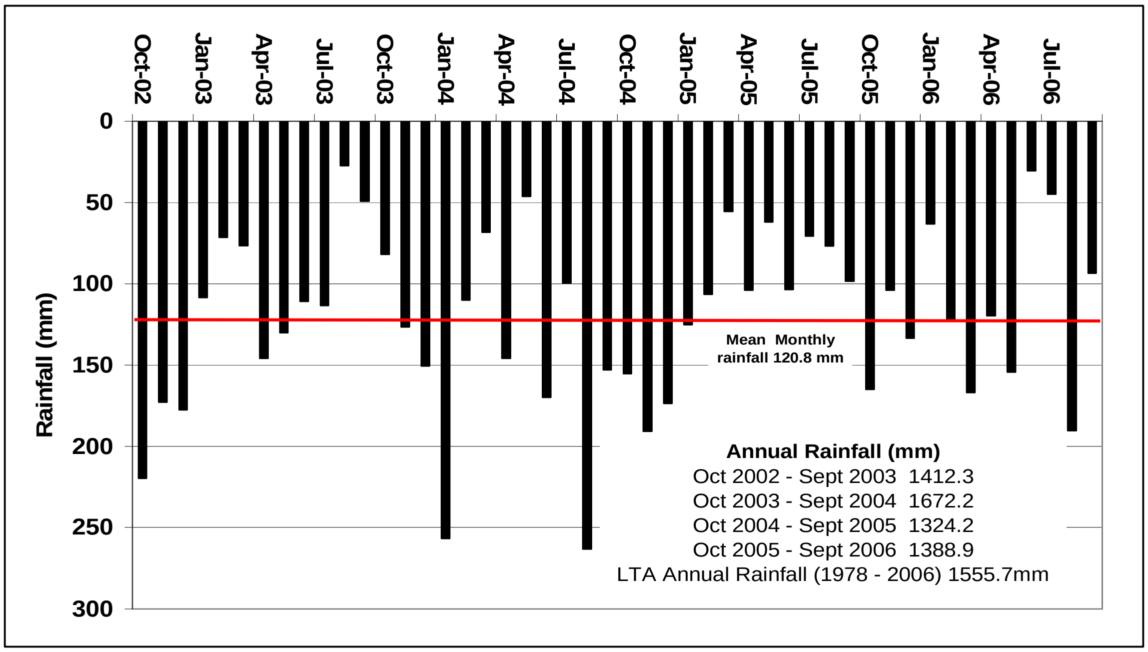
Figure 5.1: Ashop Long-Term Average Rainfall (mm) 1978 – 2006 (Data for 1978-2002 retrodicted from Derwent Dam rainfall)



5.2.2 Monthly Rainfall

Figure 5.2 shows the recorded rainfall for each month and demonstrates a seasonal pattern with more rainfall during the autumn/winter months (generally Oct–Apr) and less rainfall during the spring/summer months (May–Sept). Although the mean monthly rainfall for the study period (Oct 2002–Sept 2006) was 121 mm, there were several months when the rainfall was much higher (e.g. Oct 2002, Jan 2004, Aug 2004 and Aug 2006) or lower (e.g. Feb-Mar 2003, Aug-Sept 2003, May 2004, Mar 2005, Jan 2006, Jun 2006). The monthly descriptive statistics for each water year provide the total rainfall together with the maximum, median and mean rainfall for each month (see Appendix VI).

Figure 5.2: Ashop Catchment Monthly Rainfall (mm) Oct 2002-Sept 2006



Although the annual variability for the study period may have been low (1324–1672 mm) it emphasises the importance of the south Pennines as a relatively constant source of water supply; the individual months show large variability, but with sufficient above-average totals in any one year to provide a receipt of consistent annual rainfall. The monthly rainfall data demonstrate the high variability between individual months. For example, there are periods with a high number of days when no rainfall fell such as Jun–Oct 2003 during the first year of study, when the total monthly rainfall ranged between 27.4-113.4 $mm.mth^{-1}$.

5.2.3 Daily Rainfall

Figures 5.3a-5.3d show the daily rainfall (mm) for each of the water years commencing Oct 2002 and ending in Sept 2006. The distribution of rainfall varied between years, for example, in year two (Oct 2003-Sept 2004), only October 2003 (13 days) and May 2004 (21 days) had a high number of days when no rainfall was recorded. This can be compared to the first and third years when high numbers of days without rain were recorded between Jun–Oct 2003 and May–Oct 2005. In contrast the final year of the study (Oct 2005–Sept 2006) had a high number of days without rain in Jan–Feb 2006 (16 and 11 days respectively), when conditions are normally expected to be wet, in addition to the more typically high number of days without rain recorded during the summer in Jun–Jul 2006 (17 and 19 days respectively).

Although the numbers of days without rain were dispersed throughout the year, the mean number of days without rain for the study area over the four years was 116 days.yr^{-1}, totalling approximately one third of each year. Therefore, despite the high annual rainfall totals, there appears to still have been sufficient time for the peat soils to start to dry out and for water tables to drop and so commence the processes that may have generated the release of water colour on being recharged.

Of particular interest are those periods when “drought” conditions have prevailed. A standard “drought” period occurs when a sequence of at least 15 days without rain is recorded (Peters *et al* 2001). Figures 5.3a-5.3d show the periods without rain during the four years and despite the relatively high rainfall during the first and second year (1412 and 1672 mm), and the lower total annual rainfall (1324 and 1389 mm) in the third and fourth year, the rainfall during the latter two years was more evenly distributed throughout the year. Table 5.2 summarises the total number of days with no rainfall.

Table 5.2: Ashop Study Area – Consecutive days of no rainfall Oct 2002-Sept 2006

Number of Days	Period with no rainfall	Number of Days	Period with no rainfall
19	12/3 – 30/3/2003	6	11/5 – 15/5/2005
18	2/4 – 19/4/2003	6	25/5/ - 30/5/2005
11	23/5 – 3/6/2003	11	8/7 – 18/7/2005
9	1/8 – 9/8/2003	7	5/8 – 21/8/2005
9	11/8 – 20/8/2003	8	2/10 – 9/10/2005
7	12/9 – 18/9/2003	8	24/1 – 4/2/2006
9	10/10 – 18/10/2003	9	2/6/ - 9/6/2006
10	9/5 – 18/5/2004	6	13/7 – 18/7/2006
8	20/5 – 27/5/2004	6	23/7 - 28/7/2006

The annual and long-term average rainfall at the study sites is largely influenced by frontal weather systems. Figures 5.3a-5.3d indicate the series of rainfall events and subsequently high daily rainfall totals which occurred. The maximum daily rainfall recorded for each year is summarised in Table 5.1 and Figures 5.3a-5.3d show the dates of the maximum events (the day of rainfall being recorded over 24 hours commencing at 9.00 am GMT).

The maximum rainfall events for year two occurred during August 2004 with a maximum of 66 mm recorded on 9 August 2004 and a further 19 mm recorded on 10 August 2004 as the event continued into the following “day” (total = 85 mm).

Figures 5.3a-5.3d Ashop Catchments Daily Rainfall (mm) Oct 2002-Sept 2006

Figure 5.3a: Ashop Catchment Daily Rainfall (mm) Oct 2002 – Sept 2003

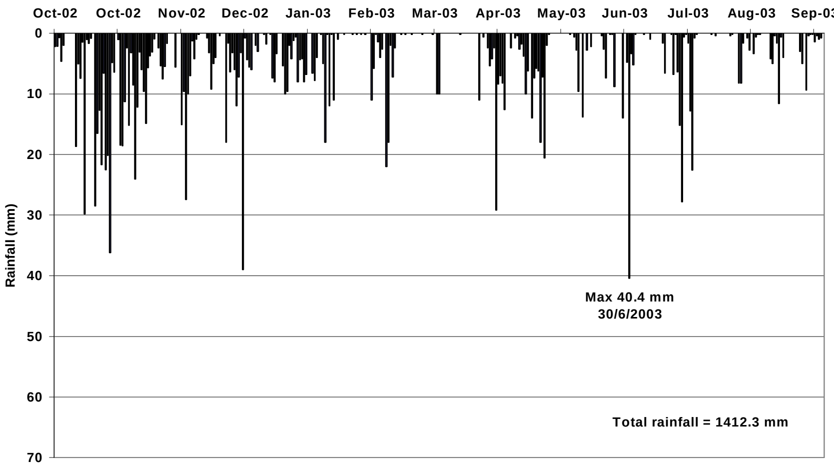


Figure 5.3b: Ashop Catchment Daily Rainfall (mm) Oct 2003 – Sept 2004

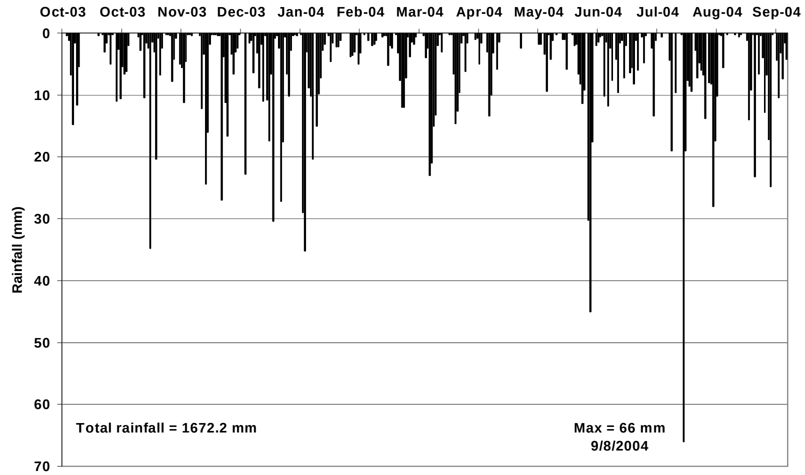


Figure 5.3c: Ashop Catchment Daily Rainfall (mm) Oct 2004 – Sept 2005

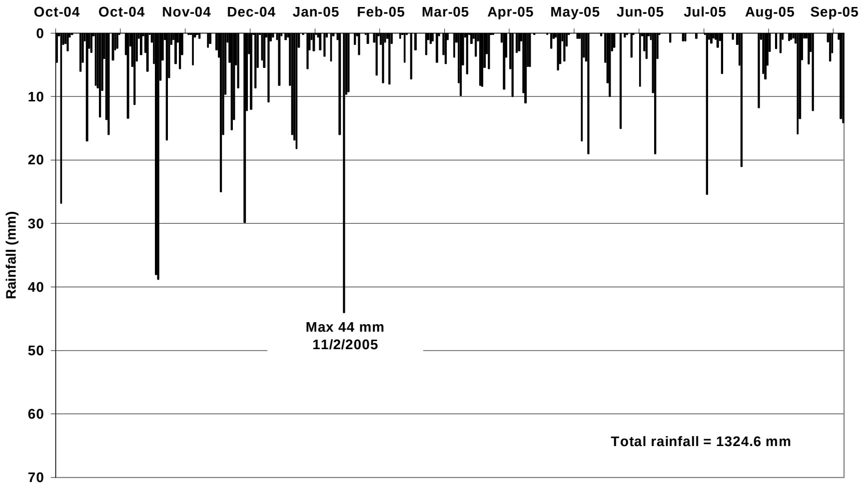
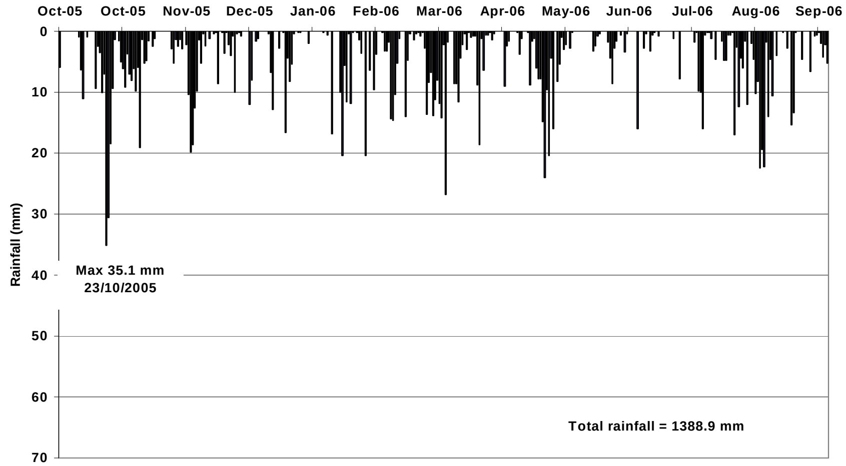


Figure 5.3d: Ashop Catchment Daily Rainfall (mm) Oct 2005 – Sept 2006



The figures also show the series of rainfall events that generally occurred during the autumn/winter. This period is associated with an episodic increase in water discolouration, triggered by the magnitude and frequency of storm precipitation, recharging of the ground water and increased runoff of water rapidly being discharged from the catchments.

5.2.4 Relationship between Water Colour and Rainfall

The temporal and spatial changes in water colour are discussed in Chapter 6, but because the relationship between water colour and meteorological factors is complex, the relationship between true colour (°H) and rainfall (mm) was examined and is discussed in the following sections. This was carried out in order to identify any potential climatic influence on water colour during the study.

5.2.4.1 Daily Water Colour and Rainfall

The work of Naden and McDonald (1989) indicated that water colour is closely associated with measures of accumulated rainfall. Figure 5.4 compares raw water response at the outlets of the Ladybower and Derwent reservoirs (the study sites drain into the Ladybower reservoir) with a measure of accumulated rainfall over a 12 month period and shows a close association between accumulated rainfall and water colour in the earlier years. The rise in water colour through the winters of 1996-1997, 1997-1998 and 1998-1999 was particularly visible as the catchment rewetted after the severe drought of 1995-1996 and the water deficit recovered. This association appeared to weaken from the winter of 1999-2000 onwards, although the drought of 2002-2003 was associated with a rise in water colour some 12-14 months later through the autumn/winter of 2004-2005, supporting Naden and McDonald's (1989) conclusion.

Figure 5.4 Monthly raw water colour (°H) and accumulated rainfall (mm) at Ladybower and Derwent Dam Jan 1993-Sept 2006

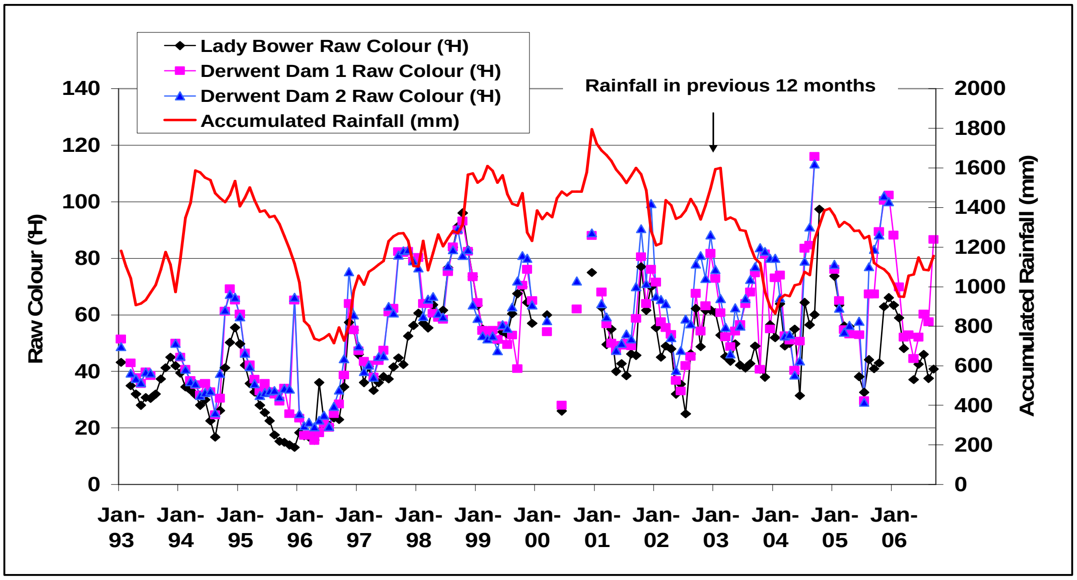


Table 5.3 presents the relationship between daily true colour (°H) and rainfall (mm) during the calibration period prior to land management changes (Oct 2002-Dec 2003).

Table 5.3: Summary of Correlations between True Colour (°H) and Rainfall (mm) Oct 2002-Dec 2003

		Dayrain	**apr30**	**apr60**	**apr120**	**apr365**	**apr420**	**apr450**
DGC TC	Pearson Correlation	0.09	-0.04	-0.27**	-0.43**	-0.18**	-0.45**	-0.55**
	Sig. (2-tailed)	0.10	0.49	0.00	0.00	0.00	0.00	0.00
	N	305	312	312	312	312	312	312
UNG TC	Pearson Correlation	0.33**	0.59**	0.39**	0.20**	0.00	0.12**	-0.02
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.99	0.03	0.77
	N	331	338	338	338	338	338	338
NGC TC	Pearson Correlation	0.39**	0.66**	0.58**	0.43**	0.15**	0.31**	0.23**
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	N	376	383	383	383	383	383	383
UGC TC	Pearson Correlation	0.43**	0.67**	0.51**	0.34**	0.14**	0.21**	0.13**
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.01	0.00	0.02
	N	361	368	368	368	368	368	368
RC TC	Pearson Correlation	0.17**	0.24**	0.03	-0.19**	-0.03	-0.30**	-0.45**
	Sig. (2-tailed)	0.00	0.00	0.62	0.00	0.64	0.00	0.00
	N	339	346	346	346	346	346	346
WC TC	Pearson Correlation	0.35**	0.66**	0.52**	0.28**	0.05	0.14**	0.04
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.33	0.00	0.43
	N	397	404	404	404	404	404	404

** indicates significance $p < 0.01$

Table 5.4 presents data for true colour (°H) and rainfall (mm) for the study period and includes data during the treatment period (Jan 2004-Sept 2006) after management was manipulated on three sites (gully-blocking at Within Clough, cessation of burning at Nether Gate Clough and removal of grazing at Doctors Gate Clough). The table shows that the relationship between the two variables generally remained the same in that the strongest correlation was between rainfall in the last month (APR 30) and daily true colour at four sites (Within Clough, Nether Gate Clough, Upper North Grain and Upper Gate Clough) suggesting the seasonal flushes of colour were closely linked to recent antecedent rainfall within the last month.

The relationship between true colour and rainfall also remained similar throughout the study at Doctors Gate Clough and Red Clough where negative correlations between the two variables continued, again suggesting that the colour was not associated with rainfall events and that other factors may have been responsible for the un-seasonal increase in colour when low rainfall conditions predominated (see Section 6.5.4). This increase in colour at the two sites was generally associated with warm weather and the oxidation of iron and was not related to discoluration by organic matter.

Table 5.4: Summary of Correlations between True Colour (°H) and Rainfall (mm) Oct 2002-Sept 2006

		Dayrain	**apr30**	**apr60**	**apr120**	**apr365**	**apr420**	**apr450**
DGC TC	Pearson Correlation	-0.003	-0.119**	-0.23**	-0.327**	-0.168**	-0.192**	-0.236**
	Sig. (2-tailed)	0.934	0.001	0.001	0.001	0.001	0.001	0.001
	N	965	965	965	965	965	965	965
UNG TC	Pearson Correlation	0.344**	0.465**	0.399**	0.213**	0.097**	0.119**	0.124**
	Sig. (2-tailed)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	N	965	997	997	997	997	997	997
NGC TC	Pearson Correlation	0.321**	0.453**	0.392**	0.252**	0.12**	0.141**	0.166**
	Sig. (2-tailed)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	N	1067	1130	1130	1130	1130	1130	1130
UGC TC	Pearson Correlation	0.339**	0.509**	0.423**	0.248**	0.154**	0.141**	0.146**
	Sig. (2-tailed)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	N	967	1020	1020	1020	1020	1020	1020
RC TC	Pearson Correlation	0.157**	0.194**	0.15**	-0.026**	0.096**	-0.033**	-0.108**
	Sig. (2-tailed)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	N	936	989	989	989	989	989	989
WC TC	Pearson Correlation	0.329**	0.463**	0.399**	0.232	0.124**	0.105	0.103**
	Sig. (2-tailed)	0.001	0.001	0.001	0.409	0.003**	0.303	0.001
	N	1033	1087	1087	1087	1087	1087	1087

** indicates significance p <0.01

5.2.4.2 Monthly Water Colour and Rainfall

The relationship between monthly mean of daily colour and monthly mean of daily rainfall was also examined to determine if the relationship between the two variables changed during the study and whether the change could potentially be associated with the manipulation of management practices during the treatment period. Table 5.5 shows the correlation (Pearson' r), r^2 and analysis of the variance of the mean. N represents the number of samples each year. The analysis found that the relationship between the two variables varied between the sites. The relationship was statistically significant during the first three years of the study at Within Clough (gullies blocked), but not in the final year (three years after the blockages were installed); statistically significant ($p < 0.01$) in the first two years and weakly significant in the last two years at Nether Gate Clough (cessation of burning), and not statistically significant during any year at Doctors Gate Clough (removal of grazing). At the control sites where no management was manipulated, the findings also differed. At Upper North Grain and Upper Gate Clough there was no significant relationship in the third and fourth year and Red Clough was only weakly significant in the second year ($p = 0.07$).

The findings suggest that in the first two years at all the sites except Doctors Gate Clough and Red Clough, there was a general pattern of low colour:low rainfall and high colour: high rainfall. This is demonstrated in Figures 5.5a-b. In the third year the rainfall was lower than in the first two years and the monthly mean of dialy colour also lower than in the other years. The relationships were found to be significant at Within Clough and Nether Gate Clough only, where management had been altered. In the fourth year, although the rainfall remained lower than in the first two years, there was an increase in the range of monthly mean daily colour, but the relationship was only weakly significant at Nether Gate and Upper Gate Clough.

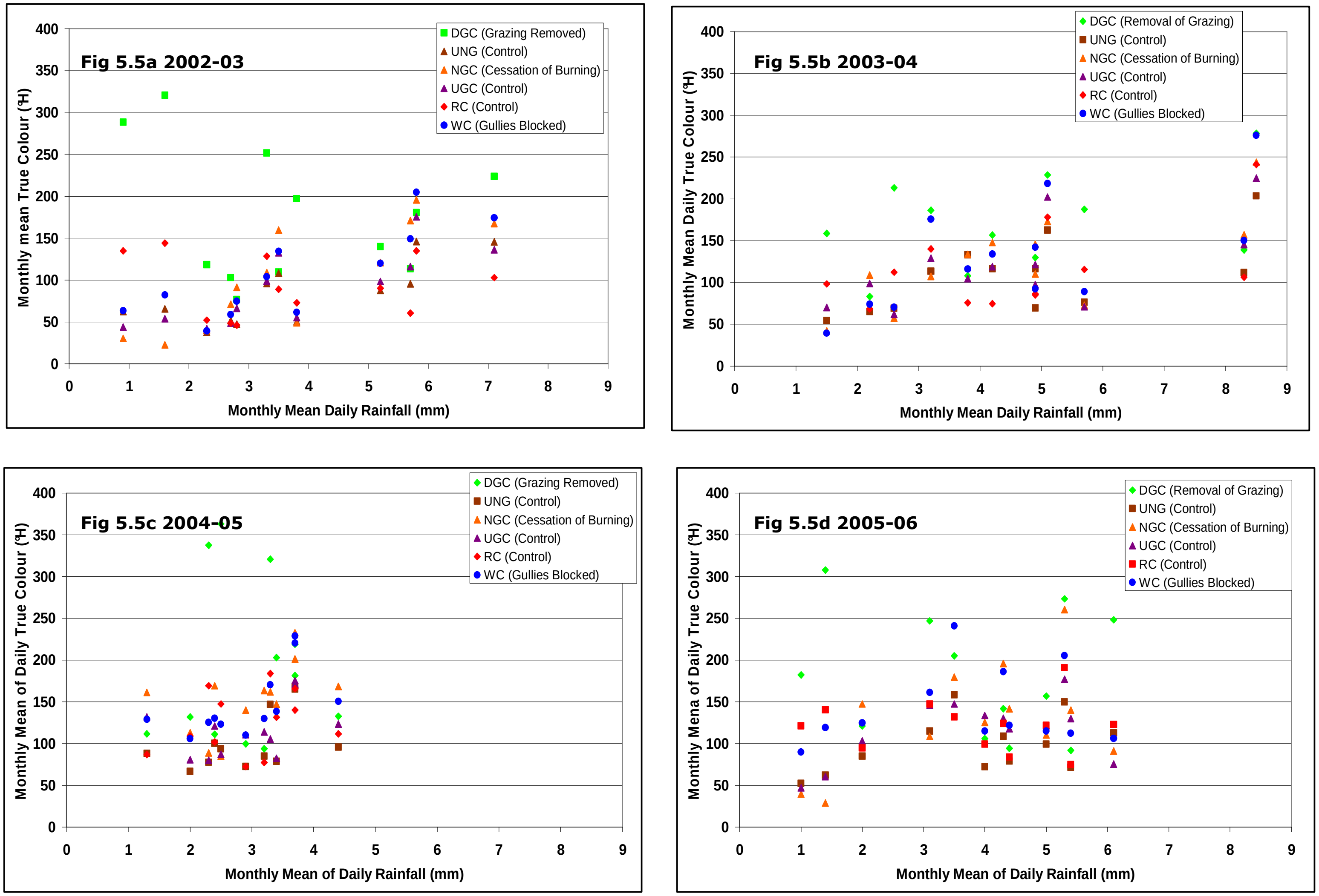
The mechanisms for the generation and discharge of water colour/DOC and their relationship with rainfall are complex with periods of low colour associated with low rainfall; high colour and low rainfall, and high colour and high rainfall. For example, in August 2006 lower monthly colour and high monthly rainfall were recorded which could suggest an exhaustion of colour following high rainfall or a failure of rainfall to rewet soils and raise water table levels (thereby flushing colour out from previously aerobic soil) and instead discharging water from the catchments largely as overland flow with little contact with peat soils and dissolution of carbon. This complex relationship is discussed further in Chapter 6 when the pattern of water discolouration and DOC is examined.

Table 5.5: Relationship between Monthly Mean of Daily True Colour (°H) and Monthly Mean of Daily Rainfall (mm) Oct 2002-Sept 2006

Variable	N	Pearsons r	ANOVA Probability	F value	r^2
DGC TC & rainfall 2002-03	12	-0.242	0.448	0.62	0.059
DGC TC & rainfall 2003-04	12	0.401	0.197	1.91	0.16
DGC TC & rainfall 2004-05	12	0.021	0.949	0	0
DGC TC & rainfall 2005-06	12	-0.163	0.614	0.27	0.026
UNG TC & rainfall 2002-03	12	0.771	0.003**	14.67	0.595
UNGTC & rainfall 2003-04	12	0.642	0.024*	7.01	0.412
UNG TC & rainfall 2004-05	12	0.492	0.104	3.19	0.242
UNG TC & rainfall 2005-06	12	0.444	0.148	2.46	0.198
NGC TC & rainfall 2002-03	12	0.847	0.001**	25.43	0.781
NGC TC & rainfall 2003-04	12	0.746	0.005**	12.57	0.557
NGC TC & rainfall 2004-05	12	0.52	0.083	3.71	0.271
NGC TC & rainfall 2005-06	12	0.521	0.082	3.73	0.272
UGC TC & rainfall 2002-03	12	0.797	0.002**	17.42	0.635
UGC TC & rainfall 2003-04	12	0.664	0.019**	7.88	0.441
UGC TC & rainfall 2004-05	12	0.387	0.215	1.76	0.149
UGC TC & rainfall 2005-06	11	0.519	0.084	3.69	0.27
RC TC & rainfall 2002-03	12	-0.058	0.858	0.03	0.003
RC TC & rainfall 2003-04	12	0.541	0.07*	4.13	0.292
RC TC & rainfall 2004-05	12	0.251	0.43	0.67	0.063
RC TC & rainfall 2005-06	11	-0.017	0.957	0	0
WCTC & rainfall 2002-03	12	0.825	0.001**	21.37	0.681
WC TC & rainfall 2003-04	12	0.688	0.013*	9	0.474
WC TC & rainfall 2004-05	12	0.595	0.041*	5.48	0.354
WC TC & rainfall 2005-06	12	0.151	0.64	0.23	0.023

** indicates significance $p < 0.01$ * indicates significance $p < 0.05$

Figure 5.5a-5.5d: Relationship of Monthly Mean of Daily True Colour (°H) and Monthly Mean of Daily Rainfall (mm) Oct 2002-Sept 2006



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

5.3 Air Temperature

5.3.1 Annual Air Temperature

The air temperature on an annual basis is summarised and presented in Table 5.6 for the period Oct 2003-Sept 2006. The temperatures recorded ranged from – 11.8 °C to 37.7 °C.

Table 5.6: Ashop Catchments Annual Mean of Air Temperatures (°C) Recorded Every 15 Minutes Oct 2003-Sept 2006

Variable	N	N*	Mean	SE Mean	St Dev	Min	Median	Max
Oct 2003 - Sept 2004	6639	2145	6.15	0.07	6.1	-10.7	5.4	32.6
Oct 2004 - Sept 2005	8559	201	8.09	0.07	6.6	-11.2	7.3	33.3
Oct 2005 - Sept 2006	7442	1318	7.58	0.09	7.8	-11.8	6.9	37.7

5.3.2 Monthly Air Temperature

Figure 5.6 shows the mean monthly temperature Oct 2002–Sept 2006. The figure illustrates the general seasonal pattern of low temperatures during the autumn/winter period commencing from November to February, followed by a steady rise in temperatures from March to a peak in August and a steady fall to October. The monthly temperatures for Oct 2002–Sept 2003 were not measured directly on site and have been calculated from the monthly temperature data for MORECS square 106 using Equation 4.14 (see Section 4.5). Descriptive statistics which include maximum, minimum and mean monthly temperatures for the study site are in Appendix VII.

Figure 5.6: Ashop Catchments Monthly Mean Temperature (°C) Oct 2002-Sept 2006 (data for Oct 2002-Sept 2003 from correlation with MORECS data)

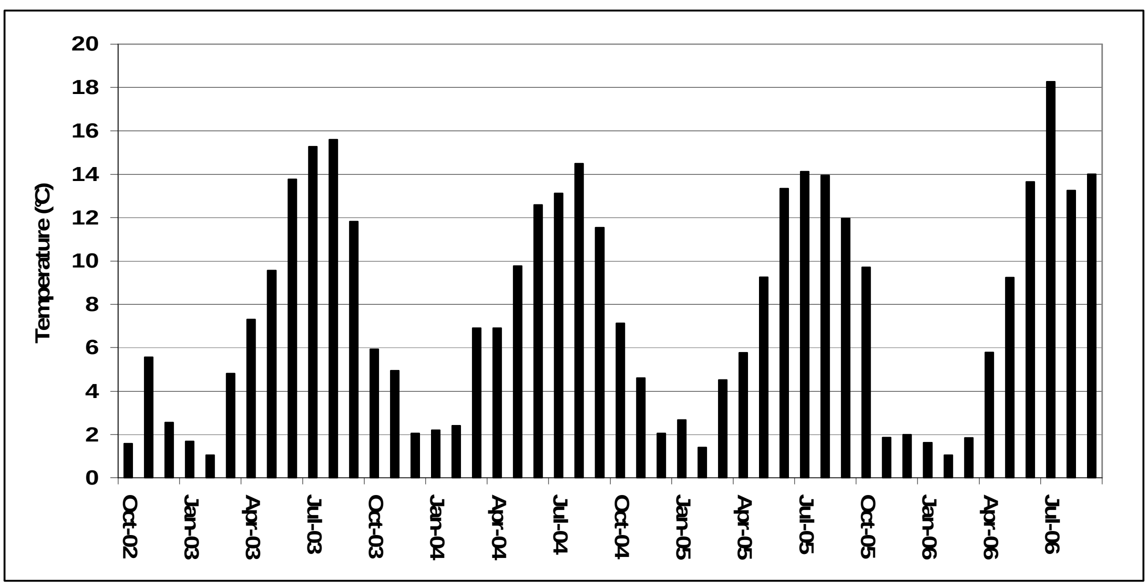
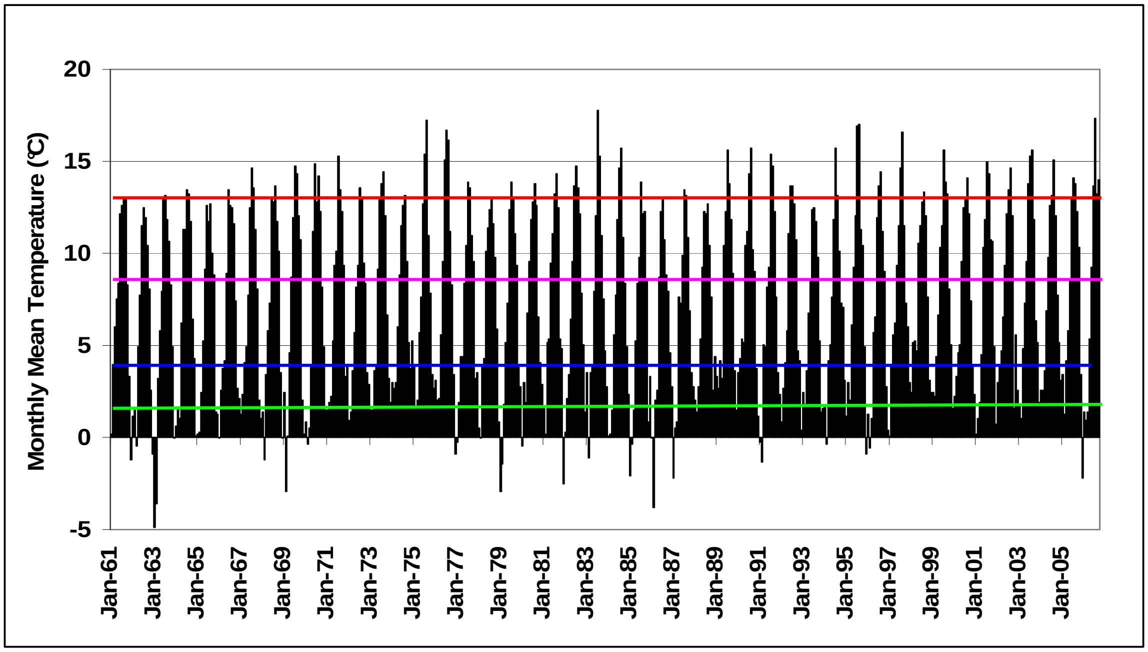


Figure 5.7 shows the longer term monthly mean temperatures for the Ashop study site calculated from the MORECS monthly temperatures for square 106 from 1961. It shows the seasonal long-term average temperatures for autumn, winter, spring and summer. Fewer periods of low temperature and more periods of high temperature

occur from 1990 onwards compared to earlier decades. The monthly mean temperatures do not, however, reflect the extreme fluctuations of air temperature that may have occurred on a temporal basis, caused particularly by diurnal changes. These extremes occur mainly during the autumn and spring when temperatures fall during the night and frosts may form. Temperatures may rise again during the day because the day length is still reasonably long and the strength of sun quite strong.

Figure 5.7: Ashop Catchment Monthly Temperature (°C) 1962-2005 Retrodicted from MORECS (Square 106) mean monthly temperature (°C) using Equation 4.14

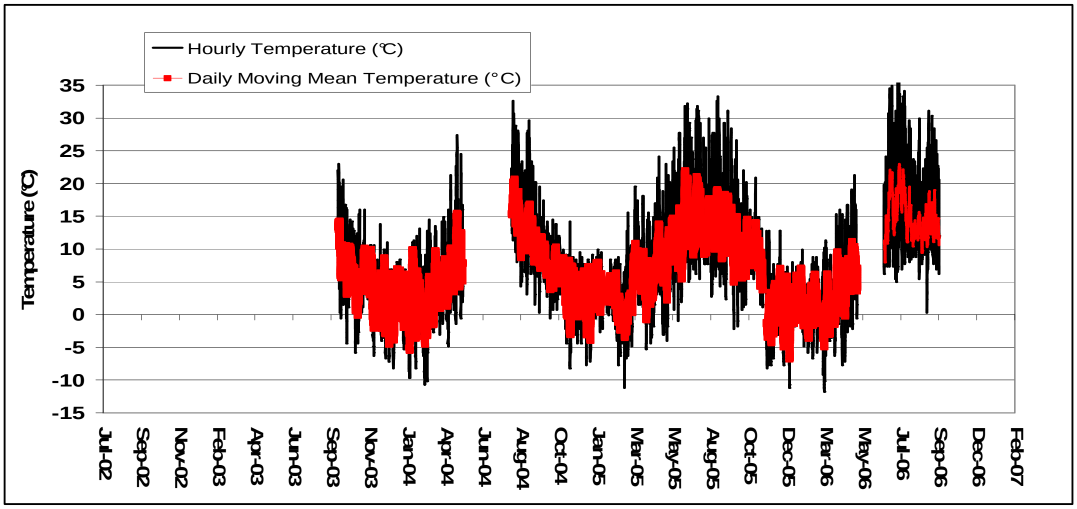


Long-Term Average Temperatures 1961 - 2006				
KEY	**Oct - Dec**	**Jan - Mar**	**Apr - Jun**	**Jul - Sep**
	(blue)	(green)	(magenta)	(red)
°C	4.4	1.8	8.9	13.8

5.3.3 Daily Air Temperature

Figure 5.8 shows the hourly temperature and the daily moving mean recorded at the study site from Sept 2003–Sept 2006. It shows the daily temperature oscillations caused by diurnal changes, with temperature differences of up to 20 °C occurring over a twenty-four hour period. Figure 5.8 also illustrates the seasonal rise in temperatures during the spring/summer and fall in temperatures during the autumn/winter. The temperatures represent the stresses imposed on the peat soils. For example, a high water table during the winter and penetration of frost down to 10 cm can allow needle ice to form readily on saturated peat surfaces during periods of low temperatures (Evans 1990, Evans and Warburton 2001). These fluctuations can create freeze-thaw action and cause "frost heave", loosen surface peat and weaken the soil structure making it more susceptible to erosion, desiccation and the generation of water colour.

Figure 5.8: Ashop Catchment Hourly Temperature (°C) Sept 2003-Sept 2006



5.3.4 Relationship between Water Colour and Temperature

5.3.4.1 Daily Water Colour and Temperature

The relationship between the daily moving mean temperature (°C) and daily true colour (°H) was examined. Table 5.7 shows the correlation between the two variables for the three complete water years in which temperature was measured (Oct 2003-Sept 2006). It should be noted that these temperature measurements were taken during the treatment period after management had been manipulated at the three sites. The relationship between the two variables was found to be significant ($p < 0.01$) at all the sites with the exception of Within Clough (gullies blocked) where the relationship was significant in the first year following gully-blocking and weakly significant in the second year only. The inverse correlation at Within Clough, Nether Gate Clough, Upper Gate Clough and Upper North Grain suggests that when temperatures were low, colour levels were generally raised. This relationship did not occur at Doctors Gate Clough and Red Clough which suggests that warmer temperatures were associated with increased colour generated from an inorganic source (see Section 6.3). However, the significance of the relationship between the two variables may simply have arisen from the large sample dataset and therefore analysis of monthly variables was also examined to determine the relationship and is discussed in Section 5.3.4.2.

Table 5.7 Relationship between Daily True Colour (°H) and Daily Moving Mean Temperature (°C) Oct 2003-Sept 2006

Variable	N	Pearsons r	ANOVA Probability	F value	r^2
DGC TC & temp 2003-04	178	0.649	<0.001**	128.41	0.422
DGC TC & temp 2004-05	233	0.734	<0.001**	269.76	0.539
DGC TC & temp 2005-06	219	0.738	<0.001**	259.15	0.544
UNGTC & temp 2003-04	179	0.422	<0.001**	38.29	0.178
UNG TC & temp 2004-05	244	-0.094	0.145	2.14	0.009
UNG TC & temp 2005-06	176	-0.444	<0.001**	0.23	0.634
NGC TC & temp 2003-04	214	0.333	<0.001**	26.41	0.111
NGC TC & temp 2004-05	266	-0.327	<0.001**	31.68	0.107
NGC TC & temp 2005-06	250	-0.263	<0.001**	60.82	0.197
UGC TC & temp 2003-04	164	0.494	<0.001**	52.4	0.244
UGC TC & temp 2004-05	236	-0.351	<0.001**	32.87	0.123
UGC TC & temp 2005-06	192	-0.263	<0.001**	14.14	0.069
RC TC & temp 2003-04	186	0.709	<0.001**	185.68	0.502
RC TC & temp 2004-05	248	0.582	<0.001**	126.22	0.339
RC TC & temp 2005-06	151	0.629	<0.001**	97.77	0.396
WC TC & temp 2003-04	176	0.452	<0.001**	44.68	0.204
WC TC & temp 2004-05	258	-0.114	0.068	3.35	0.013
WC TC & temp 2005-06	221	0.003	0.961	0	0.961

** indicates significance p <0.01   * indicates significance p <0.05

5.3.4.2 Monthly Water Colour and Temperature

The relationship between the monthly mean of daily temperature (°C) and monthly mean of daily true colour (°H) was examined. Table 5.8 shows the correlation between the two variables for the three complete water years in which temperature was measured during the treatment period (Oct 2003-Sept 2006). The findings indicate that there was a temporal and spatial difference in the relationship between temperature and water colour across the sites. Doctors Gate Clough (removal of grazing) and Red Clough (control) acted quite similarly in that the relationship between the two variables was strongly linear at Doctors Gate Clough for all three years post-management manipulation and at Red Clough in the first year only, although the relationship was statistically significant for each year at both sites. The high positive correlation again suggested that high colour was associated with high temperatures, most likely to occur during the summer and not to be associated with an organic source (see Section 6.3).

The remaining sites all had a negative correlation between water colour and temperature but only in the third and fourth year of the study (2004-05 and 2005-06) suggesting that higher water colour was associated with lower temperatures, supporting the flush of organic colour being discharged largely during the autumn/winter (see Figures 5.9a-c). This supports previous research which found that temperature was not highly correlated with DOC release (see Section 2.3.3 e.g.

Christ and David 1996, Yeakley *et al* 1998, Tipping *et al* 1999). The data does suggest that there is a stronger correlation between water colour and temperature than between water colour and rainfall. Studies by, for example Evans (1990) suggest that the low temperatures and subsequent erosion through frost action may also contribute to upland erosion. This could subsequently generate humic substances in the peat which are readily flushed from the soil during the winter.

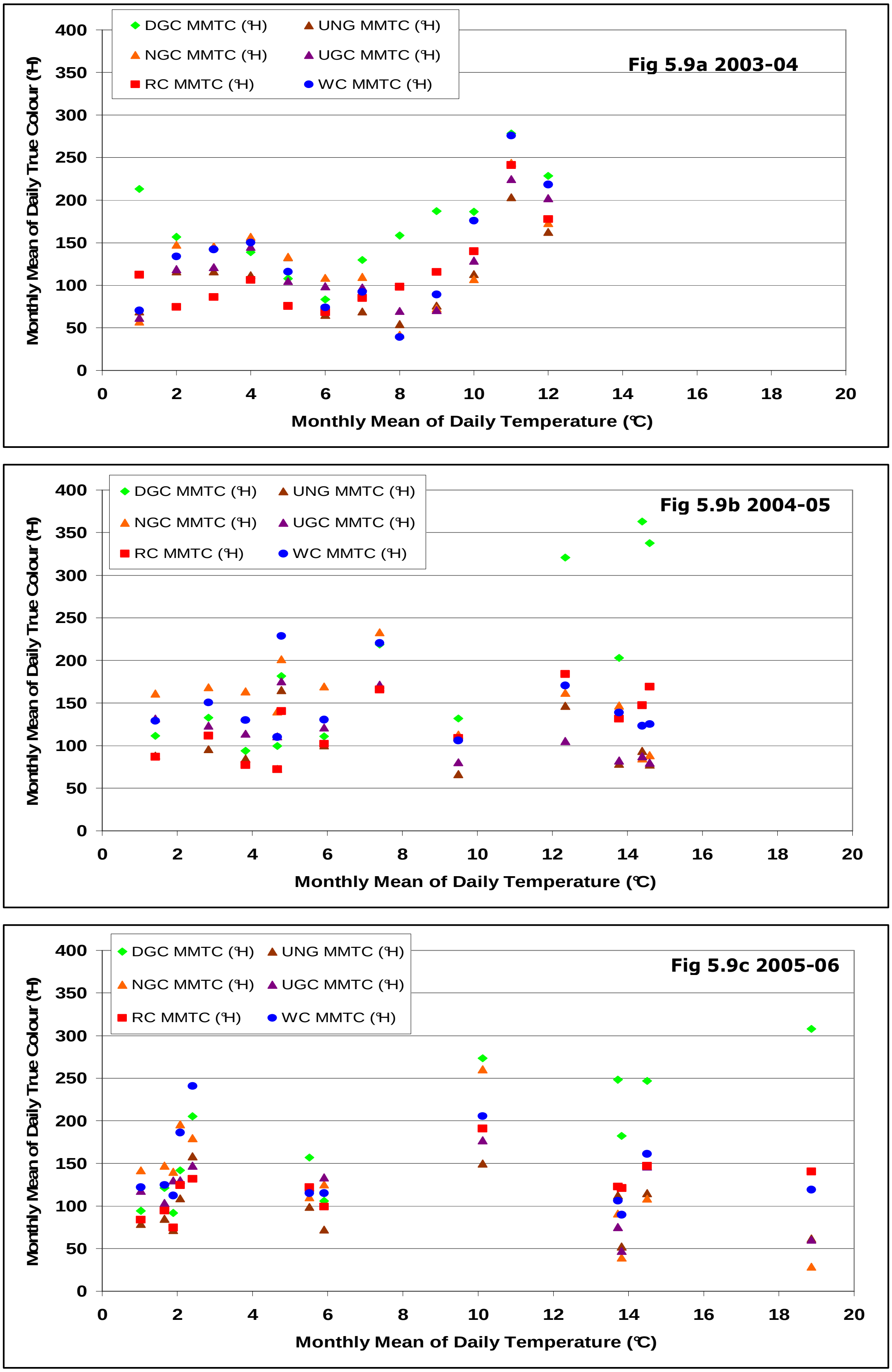
Table 5.8 Relationship between Monthly Mean of Daily True Colour (°H) and Monthly Mean of Daily Temperature (°C) Oct 2003-Sept 2006

Variable	N	Pearsons r	ANOVA Probability	F value	r^2
DGC TC & temp 2003-04	12	0.845	<0.001**	19.91	0.713
DGC TC & temp 2004-05	12	0.835	<0.001**	23.11	0.698
DGC TC & temp 2005-06	12	0.826	<0.001*	21.4	0.682
UNGTC & r temp 2003-04	12	0.526	0.118	3.07	0.277
UNG TC & temp 2004-05	12	-0.08	0.806	0.06	0.006
UNG TC & temp 2005-06	12	-0.145	0.654	0.21	0.021
NGC TC & temp 2003-04	12	0.399	0.253	1.52	0.159
NGC TC & temp 2004-05	12	-0.572	0.052	4.85	0.327
NGC TC & temp 2005-06	12	-0.582	0.047*	5.13	0.339
UGC TC & temp 2003-04	12	0.617	0.057	4.92	0.381
UGC TC & temp 2004-05	12	-0.623	0.031*	6.33	0.388
UGC TC & temp 2005-06	12	-0.472	0.122	2.86	0.223
RC TC & temp 2003-04	12	0.878	<0.001**	26.93	0.771
RC TC & temp 2004-05	12	0.698	0.012*	9.48	0.487
RC TC & temp 2005-06	12	0.562	0.057	4.62	0.316
WC TC & temp 2003-04	12	0.587	0.074	4.21	0.345
WC TC & temp 2004-05	12	-0.134	0.678	0.18	0.081
WC TC & temp 2005-06	12	-0.238	0.456	0.6	0.057

** indicates significance p <0.01 *indicates significance p <0.05

Figures 5.9a-b show that all catchments discharged high water colour that was associated with high temperatures and this occurred during a series of later summer storms (August 2004 and September 2005) when temperatures were still relatively high prior to their decrease in late autumn/winter. This suggests that the rewetting of soils, rise in water table and increased runoff may have had a greater influence on the increase in colour during these periods than solely the effects of temperature.

Figure 5.9a-5.9c: Relationship of Monthly Mean of Daily True Colour (°H) and Monthly Mean of Daily Temperature (°C) Oct 2003-Sept 2006



5.4 MORECS Data

The monthly MORECS data (square 106) covering a 40 km^2 area which includes the study site acted as an indicator of the prevailing climatic conditions affecting the hydrological and pedological processes in the area. The variables of interest were rainfall, actual and potential evaporation (AE and PE), soil moisture deficit (SMD), temperature, total sunshine hours and wind speed. The annual descriptive statistics which include the maximum, minimum and mean for each variable are presented in Tables 5.9 – 5.12 and the monthly statistics are in Appendix VIII.

Figure 5.10 illustrates the monthly rainfall, AE and SMD from Oct 2002–Sept 2006 and shows a seasonal pattern of high AE during the spring/summer and low evaporation during the autumn/winter. This pattern is related to the comparatively low rainfall during the spring/summer and higher rainfall during the autumn/winter. The SMD follows a similar pattern to the actual evaporation and the level of moisture within the soil is clearly related to the other two variables.

Figure 5.11 shows the monthly hours of sunshine, temperature and soil moisture deficit for the period Oct 2002–Sept 2006 and indicates, not surprisingly, that the hours of sun are related to a rise in temperature. The rise in temperature is also correlated with soil moisture deficit; increased deficits occur during the spring/summer as temperatures rise.

Figure 5.12 represents the wind speed, actual evaporation and soil moisture deficit and interestingly suggests that whilst actual evaporation and soil moisture deficit show a similar pattern, an increase in wind speed generally occurred during the autumn/winter and was not associated with an increase in evaporation or soil moisture deficit which have a much more marked seasonal pattern. This is probably because of the prevailing conditions in the uplands which generally have a predominantly cool, moist climate and near-saturated air during the autumn-spring which can cause low evaporation rates despite the increase in wind speed. These factors and their relationship with water discolouration are discussed in Section 5.4.1.

Table 5.9 MORECS 106 Climatic Data Oct 2002-Sept 2003

Variable	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Rain (mm)	12	0	85	12	41.5	17.2	82.6	158.5
PE (mm)	12	0	51.6	10.2	35.2	12.5	49.2	99.9
AE (mm)	12	0	50.47	9.94	34.43	12.5	46.5	98.7
SMD (mm)	12	0	26.08	9.79	33.91	0	21.7	94.6
EP (mm)	12	0	41.9	15	51.8	0	26.4	146
Sun (hrs)	12	0	119.6	18	62.5	35.7	144.8	194.5
Temp (°C)	12	0	9.03	1.48	5.11	3	8	16.5
Wind (mph)	12	0	192.2	11.1	38.3	109	199.5	237

Table 5.10: MORECS 106 Climatic Data Oct 2003-Sept 2004

Variable	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Rain (mm)	12	0	97.4	14.5	50.3	48.7	82.8	233
PE (mm)	12	0	50.41	8.49	29.41	11	47.3	87.8
AE (mm)	12	0	49.96	8.44	29.23	11	47.3	86.7
SMD (mm)	12	0	20.49	7.11	24.62	0	7.05	72.3
EP (mm)	12	0	39.7	12.7	44.1	0	26.6	119
Sun (hrs)	12	0	109.9	14.2	49.3	26.6	110.4	183.9
Temp (°C)	12	0	9.11	1.26	4.36	3.8	8.15	16
Wind (mph)	12	0	206.08	8.04	27.84	157	206.5	245

Table 5.11: MORECS 106 Climatic Data Oct 2004-Sept 2005

Variable	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Rain (mm)	12	0	74.83	8.74	30.29	41.8	66	138.9
PE (mm)	12	0	50.7	8.56	29.65	15	46.3	91.2
AE (mm)	12	0	49.9	8.3	28.76	15	46.3	90.6
SMD (mm)	12	0	19.6	7.72	26.73	0	0.85	62
EP (mm)	12	0	25.72	8.88	30.75	0	22.5	102
Sun (hrs)	12	0	106.6	16.6	57.6	41.8	101.1	198.3
Temp (°C)	12	0	9.17	1.23	4.25	3.2	8.3	15.1
Wind (mph)	12	0	250	13.3	46	206	249	379

Table 5.12: MORECS 106 Climatic Data Oct 2005-Sept 2006

Variable	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Rain (mm)	11	1	86.6	12.7	42.2	33.9	89.7	155.5
PE (mm)	11	1	55.3	11	36.5	10.7	53.6	124.8
AE (mm)	11	1	51	9.14	30.32	10.7	53.6	93.7
SMD (mm)	11	1	25.1	11.5	38.2	0	7.6	119.3
EP (mm)	11	1	36.8	10.9	36.2	0	24.5	89.8
Sun (hrs)	11	1	120.4	20.7	68.7	28.8	121.3	280.7
Temp (°C)	11	1	9.64	1.66	5.52	2.9	10.6	18.1
Wind (mph)	11	1	231.45	7.77	25.77	188	235	273

Figure 5.10: Monthly Rainfall (mm), AE (mm) and SMD (mm) (provided by MORECS for Square 106) Oct 2002-Sept 2006

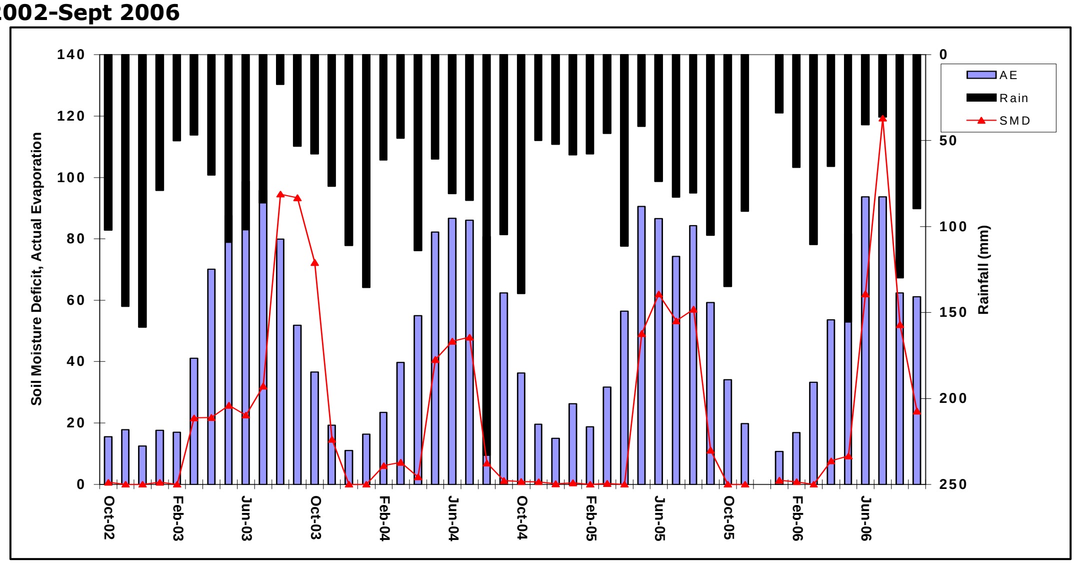


Figure 5.11: Monthly Sun (hrs), Temperature (°C) and SMD (mm) (provided by MORECS for Square 106) Oct 2002-Sept 2006

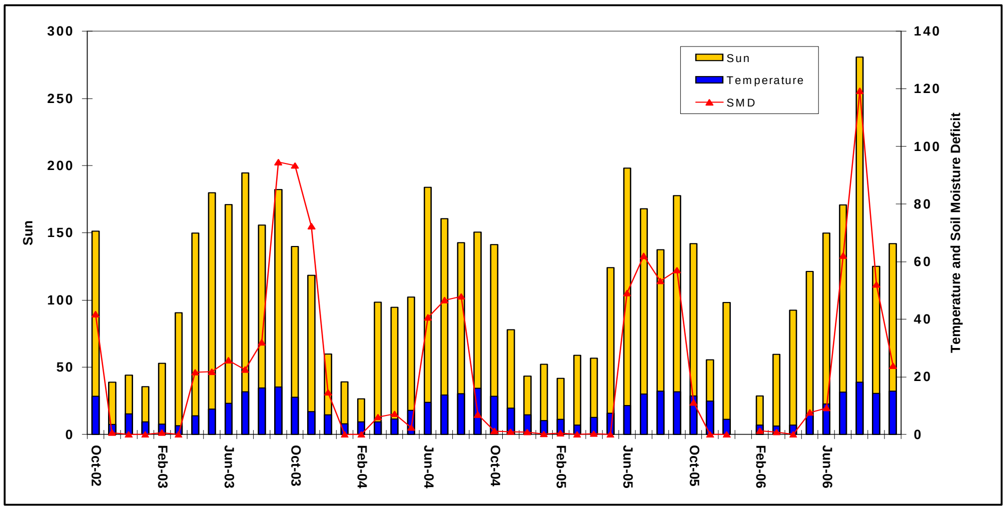
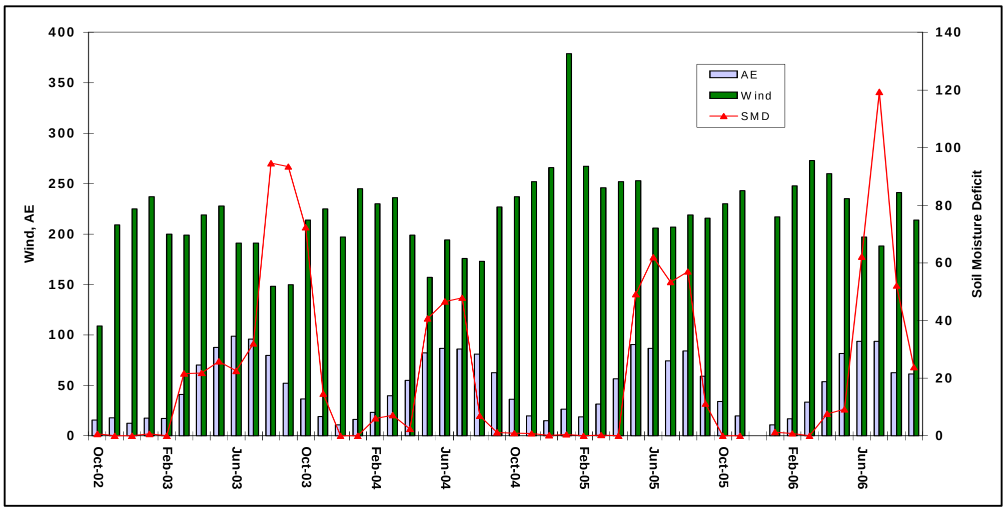


Figure 5.12: Monthly AE (mm), SMD (mm) and Wind Speed (mph) (provided by MORECS for Square 106) Oct 2002-Sept 2006

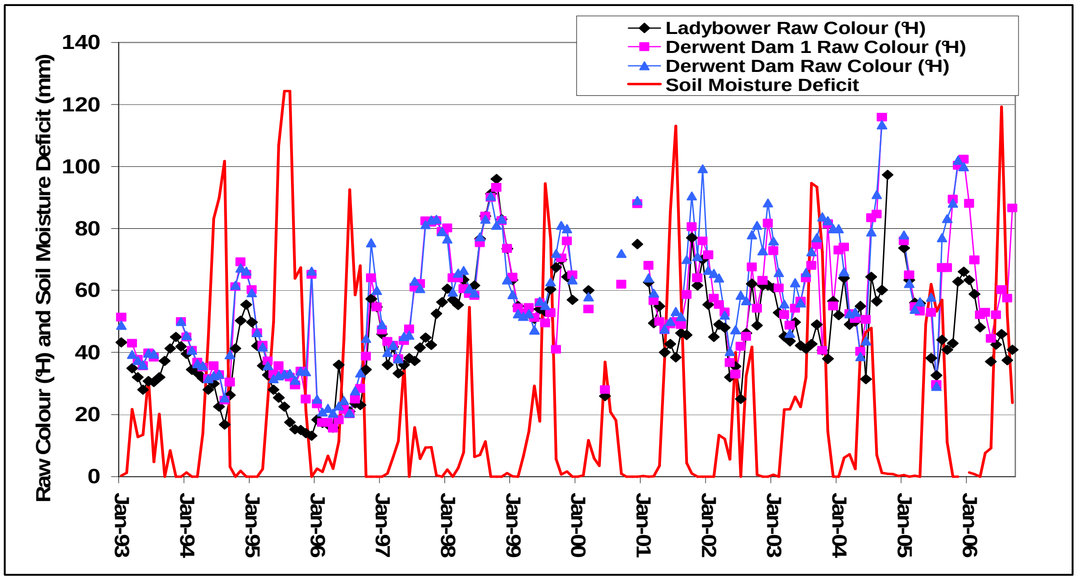


5.4.1 Relationship between Monthly Water Colour and MORECS Data

5.4.1.1 Water Colour and Soil Moisture Deficit

The widely accepted close association between water colour and drought is a product both of rainfall and evapotranspiration, since soil water levels are determined by both of these factors. Measurement of evapotranspiration can be difficult but the most commonly used estimate is calculated using the UK Meteorological Office Rainfall and Evaporation Calculation System (MORECS). This programme allows the calculation of Potential Evapotranspiration (PE), Actual Evapotranspiration (AE) and Soil Moisture Deficit (SMD). Although the calculations are areal values for 40x40 km grid squares covering Great Britain and are supplied on a monthly basis, they are generally accepted as being representative. Figure 5.13 shows the pattern of SMD and water colour at the abstraction points to Bamford WTW from the Ladybower and Derwent reservoirs (the study site catchments drain into Ladybower reservoir). It shows that SMD was high in the summer and low in the winter months with a regular pattern of increase of water colour in the autumn/winter following a decrease in SMD as the catchment rewet and colour was subsequently flushed out.

Figure 5.13: Bamford WTW Raw Water Colour and MORECS Soil Moisture Deficit Jan 1993-Sept 2006



Figures 5.14 a-d show the relationship between SMD and water colour for each of the water years and demonstrates a general pattern of low water colour at Within Clough (gullies blocked), Nether Gate Clough (cessation of burning), Upper North Grain (control) and Upper Gate Clough (control) when SMD was high. That is, when soil conditions were predominantly dry, water draining from the catchments was low in colour and was likely to comprise mainly of groundwater when baseflow conditions prevailed. When SMD was recorded as 0, that is, as the soil began to recharge to saturation capacity, there was a wide range of colour at the sites which could indicate the flush of colour as the sites rewet, followed by the exhaustion of colour when relatively low colour was recorded. High colour was associated with high SMD at Doctors Gate Clough (removal of grazing) and Red Clough (control), that is, during the summer episodes of high colour were discharged from the sites, particularly during baseflow conditions. The increase in colour at these sites during the summer was caused by the oxidation of iron and was generally not organic in origin (see Section 6.3).

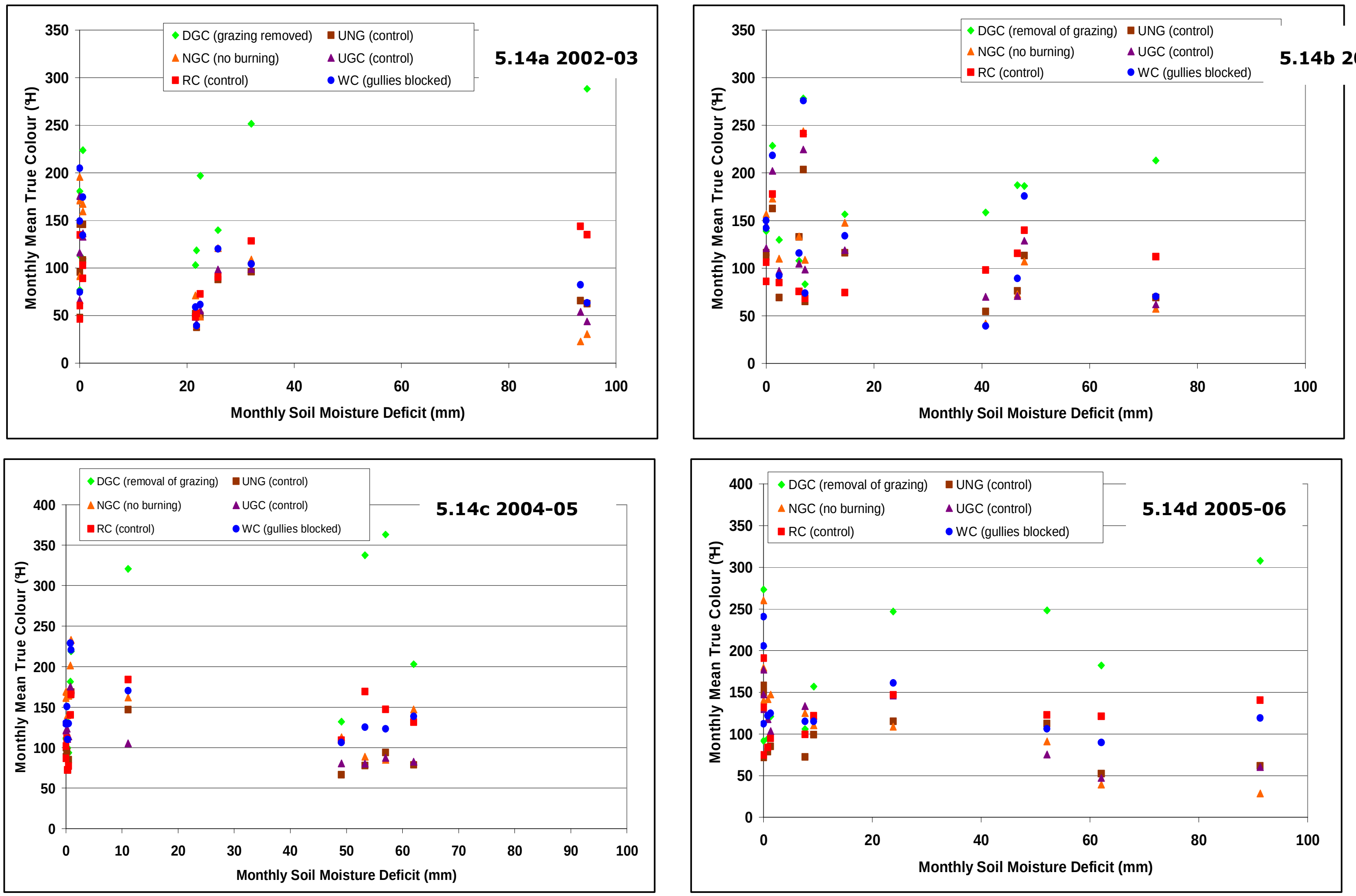
Table 5.13 shows the analysis of monthly mean of daily true colour and monthly SMD and indicates an inverse relationship at four of the sites (Within Clough, Nether Gate Clough, Upper North Grain and Upper Gate Clough) which suggests that when water colour was high, SMD was generally low. This relationship was only significant at Nether Gate Clough (cessation of burning) and Upper Gate Clough (control) where there was a noticeable seasonal pattern of colour production with high colour discharged during the autumn/winter and low colour in the spring/summer. However, the data are not specific to each catchment and are only accurate to the nearest MORECS 40x40 km square making it difficult to draw conclusions from the data.

Table 5.13 Relationship between Monthly Mean of Daily True Colour (°H) and Monthly Soil Moisture Deficit Oct 2003-Sept 2006

Variable	N	Pearsons r	ANOVA Probability	F value	r^2
DGC TC & SMD 2002-03	12	0.771	0.003**	14.63	0.594
DGC TC & SMD 2003-04	12	0.295	0.351	0.96	0.087
DGC TC &SMD 2004-05	12	0.573	0.051	4.9	0.329
DGC TC & SMD 2005-06	11	0.622	0.041*	5.67	0.387
UNGTC & SMD 2002-03	12	-0.389	0.212	1.78	0.154
UNGTC & SMD 2003-04	12	-0.459	0.133	2.67	0.211
UNG TC & SMD 2004-05	12	-0.439	0.154	2.38	0.192
UNG TC & SMD 2005-06	11	-0.427	0.19	2.01	0.183
NGC TC & SMD 2002-03	12	-0.737	0.006**	11.86	0.543
NGC TC & SMD 2003-04	12	-0.698	0.012**	9.5	0.487
NGC TC & SMD 2004-05	12	-0.745	0.005**	12.47	0.555
NGC TC & SMD 2005-06	11	-0.781	0.005**	14.1	0.61
UGC TC & SMD 2002-03	12	-0.584	0.046*	5.16	0.341
UGC TC & SMD 2003-04	12	-0.564	0.056	4.66	0.318
UGC TC & SMD 2004-05	12	-0.757	0.004**	13.42	0.573
UGC TC & SMD 2005-06	11	-0.774	0.005**	13.43	0.599
RC TC & SMD 2002-03	12	0.57	0.053	4.82	0.325
RC TC & SMD 2003-04	12	0.02	0.994	0	0
RC TC & SMD 2004-05	12	0.361	0.249	1.5	0.13
RC TC & SMD 2005-06	11	0.231	0.494	0.51	0.054
WC TC & SMD 2002-03	12	-0.479	0.115	2.97	0.229
WC TC & SMD 2003-04	12	-0.41	0.186	2.02	0.168
WC TC & SMD 2004-05	12	-0.394	0.205	1.84	0.155
WC TC & SMD 2005-06	11	-0.373	0.259	1.45	0.139

** indicates significance p <0.01 *   indicates significance p <0.05

Figure 5.14a-5.14d: Relationship of Monthly Mean of Daily True Colour (°H) and Monthly Soil Moisture Deficit (mm) Oct 2002-Sept 2006



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

5.4.1.2 Water Colour and Actual Evaporation

Figure 5.15 shows the pattern of Actual Evaporation (AE) and water colour at the inlets to Bamford WTW from the Ladybower and Derwent reservoirs (the study site catchments drain into Ladybower reservoir). It demonstrates how AE oscillated between high evaporation during the summer months and low evaporation during the winter months the atmosphere was more saturated, and less able to absorb moisture. The peaks in water colour generally occurred when the evaporation rates were low, that is, during the winter months, following a period of high evaporation when the vegetation and peat soils were prone to desiccation as the water table lowered, soils became aerobic and microbial activity and subsequent humification rates were raised (Christ and David 1996, Scott *et al* 1998, 2001, Worrall and Burt 2004).

Figure 5.15 Bamford WTW Raw Water Colour and MORECS Actual Evapotranspiration Jan 1993-Sept 2006

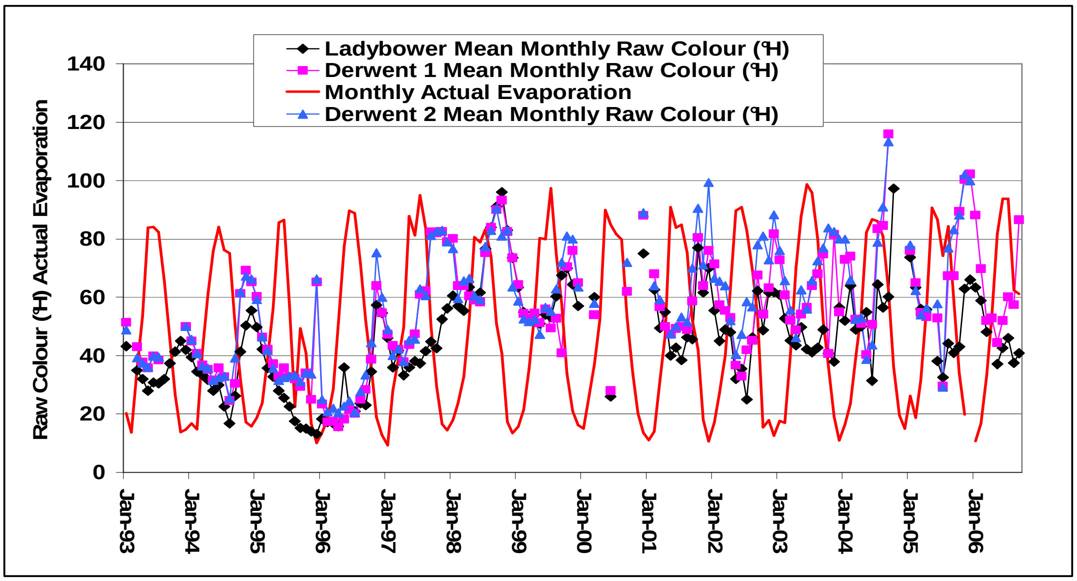
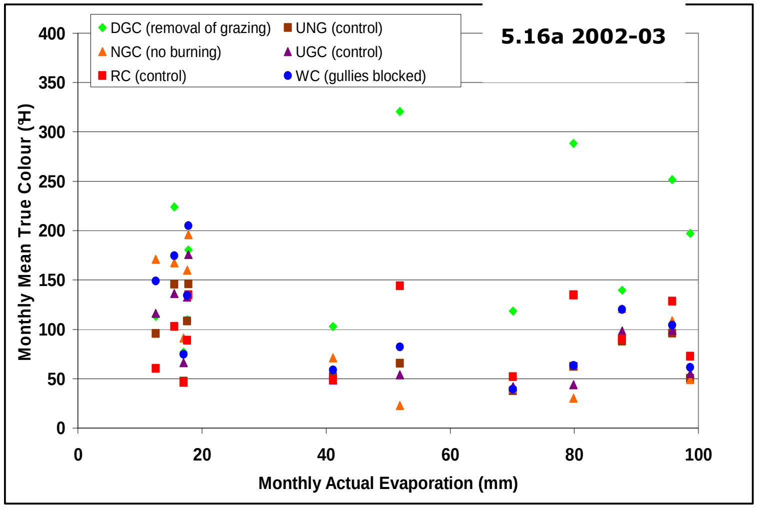
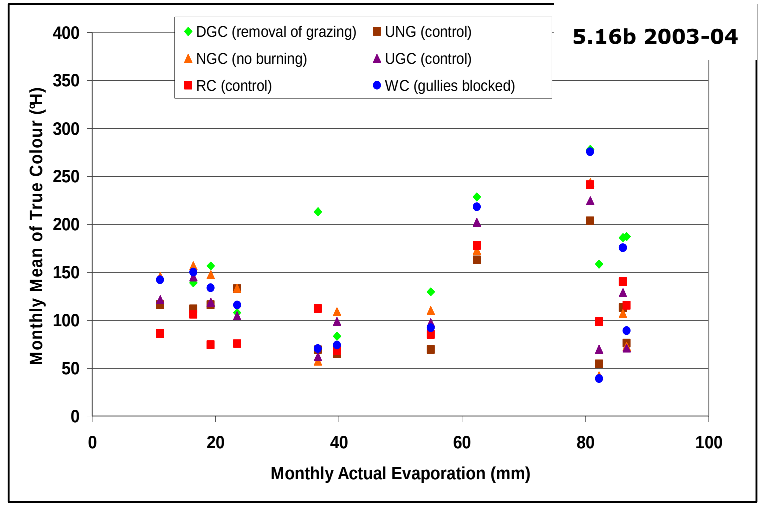


Figure 5.16 a-d shows the relationship between AE and true colour for each of the water years from Oct 2002-Sept 2006. It demonstrates a similar pattern to that associated with SMD, that is, an inverse relationship with low water colour at Within Clough (gullies blocked), Nether Gate Clough (cessation of burning), Upper North Grain (control) and Upper Gate Clough (control) when AE was high which generally occurred during the summer months. Figures 5.16a, c-d demonstrate this pattern in the first, third and fourth year. In the second year (Figure 5.16b) water colour was highest when AE was high and this was likely to have been caused by an early flush of colour being discharged in August-September 2004 during a series of summer storms when monthly mean

Figure 5.16a-5.16d: Relationship of Monthly Mean of Daily True Colour (°H) and Monthly Actual Evaporation (mm) Oct 2002-Sept 2006





KEY

DGC = Doctors Gate Clough

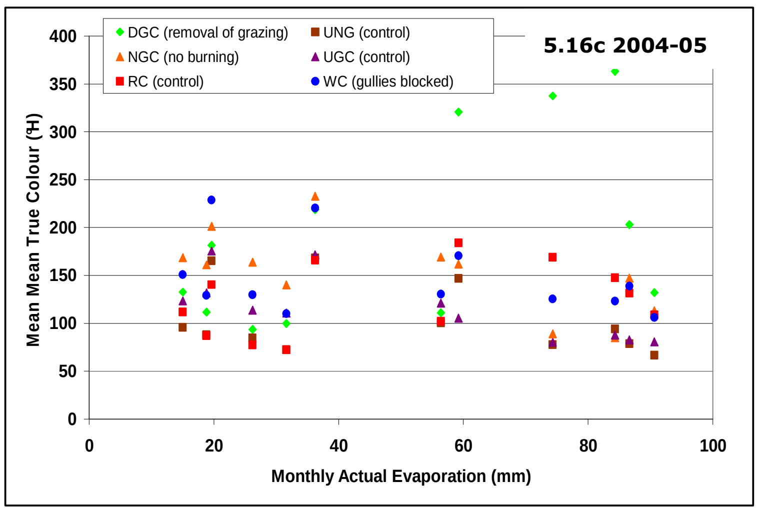
UNG = Upper North Grain

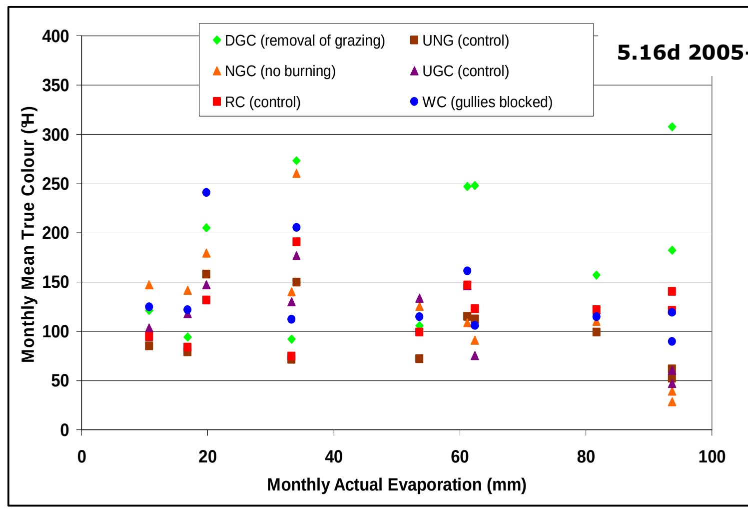
NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough





evaporation rates were still high, but catchments rewet and discharged high colour. Doctors Gate Clough (removal of grazing) and to a lesser extent, Red Clough (control) both produced high colour during periods when AE was high (when colour was associated with the oxidation of iron and not organic matter – see Section 6.3).

Table 5.14 shows the relationship between the monthly mean of daily true colour and monthly AE for each water year for each site. The statistical analysis confirms the inverse relationship between true colour and AE at four sites (treated sites - Within Clough, Nether Gate Clough, and control sites - Upper North Grain, Upper Gate Clough) when the correlation between the two variables (Pearson's r) was negative in the first, third and fourth year. The relationship between the two variables was weakly linear (poor r^2) at all sites and was statistically significant or weakly significant at Nether Gate Clough (cessation of burning) and Upper Gate Clough (control) in the first, third and fourth year. At Within Clough, the relationship was weakly significant in the first year, prior to gully-blocking. At Upper North Grain (control) there was no significant relationship in any of the years. These findings suggest that the relationship between AE and colour was not strongly linear and that other factors such as soil moisture deficit and rainfall, antecedent climatic conditions, and potentially, anthropogenic factors such as land management could influence the generation of water colour.

Table 5.14: Relationship between Monthly Mean of Daily True Colour (°H) and Monthly Actual Evaporation (mm) Oct 2003-Sept 2006

Variable	N	Pearsons r	ANOVA Probability	F value	r^2
DGC TC & AE 2002-03	12	0.404	0.193	1.95	0.163
DGC TC & AE 2003-04	12	0.525	0.079	3.81	0.276
DGC TC &AE 2004-05	12	0.534	0.074	3.99	0.285
DGC TC & AE 2005-06	11	0.455	0.159	2.35	0.207
UNGTC & AE 2002-03	12	-0.46	0.132	2.68	0.212
UNGTC & AE 2003-04	12	0.023	0.943	0.01	0.001
UNG TC & AE 2004-05	12	-0.351	0.263	1.4	0.123
UNG TC & AE 2005-06	11	-0.408	0.213	1.8	0.167
NGC TC & AE 2002-03	12	-0.617	0.033*	6.15	0.381
NGC TC & AE 2003-04	12	-0.157	0.626	0.25	0.025
NGC TC & AE 2004-05	12	-0.662	0.019*	7.79	0.438
NGC TC & AE 2005-06	11	-0.751	0.008**	11.65	0.564
UGC TC & AE 2002-03	12	-0.536	0.072	4.03	0.287
UGC TC & AE 2003-04	12	0.098	0.763	0.1	0.01
UGC TC & AE 2004-05	12	-0.756	0.004**	13.38	0.572
UGC TC & AE 2005-06	11	-0.586	0.058	4.72	0.344
RC TC & AE 2002-03	12	0.193	0.547	0.39	0.037
RC TC & AE 2003-04	12	0.563	0.056	4.65	0.317
RC TC & AE 2004-05	12	0.386	0.216	1.75	0.149
RC TC & AE 2005-06	11	0.276	0.412	0.74	0.076
WC TC & AE 2002-03	12	-0.562	0.057	4.62	0.316
WC TC & AE 2003-04	12	0.144	0.655	0.21	0.021
WC TC & AE 2004-05	12	-0.409	0.187	2.01	0.167
WC TC & AE 2005-06	11	-0.467	0.148	2.51	0.218

** indicates significance $p < 0.01$ * indicates significance $p < 0.05$

5.5 Water Colour Prediction by Regression Modelling

The association between water colour and a number of measures of rainfall and drought was examined statistically using a stepwise regression approach to determine water colour at the Derwent Dam inlet (Raw 2) using the Minitab v.14 software programme. The data for the equation were taken from MORECS data for the period Oct 1993-Dec 1994. This 14-month period was selected to maximise the available data and so improve the predictive ability of the equation. The length of time period also corresponds with the calibration period at the study sites (i.e. 14 months Oct 2002-Dec 2003) from which data were used to predict changes in water colour for the remainder of the study. The Annual Precipitation Rate (APR) rainfall was calculated from the Derwent Dam Meteorological Office Station from 1992 data supplied by the Environment Agency. The regression equation allowed a prediction of water colour to be made based on the current variables, that is, actual evapotranspiration (AE), soil moisture deficit (SMD) and precipitation (Rf), and act as a warning of high colour levels. In addition, it is possible to compare the predicted water colour with observed water colour at monitored catchments and so determine differences which may result from other factors such as changes in land management.

The results shown in Table 5.15 illustrate that when the variables Actual Evapotranspiration (AE), Soil Moisture Deficit (SMD) and rainfall in the previous 12 months (rf) were entered into the equation, the r^2 was 0.6424. When SMD was removed this lowered the r^2 value to 0.6009 and finally when rainfall in the previous 12 months was also removed this lowers the r^2 value again to 0.5492. The final equation takes the form:

Derwent Dam 2 inlet = -37.921-0.69AE+0.16SMD-0.88rf **Equation 5.1**

Where AE = Actual Evaporation, SMD = Soil Moisture Deficit, Rf = 12 month rainfall average.

Table 5.15: Minitab stepwise regression results

Backward elimination. F-to-Remove: 4

Response is Avr Raw 2 (Hazen units) on 3 predictors, with N = 13

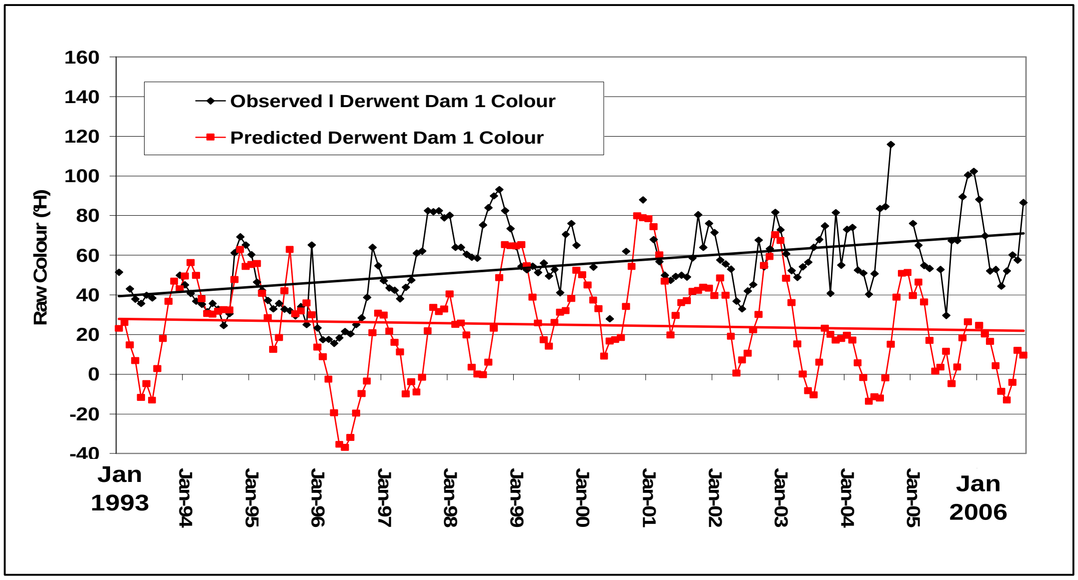
N (cases with missing observations) = 2 N (all cases) = 15

Step	1	2	3
Constant -	- 37.921	6.462	60.075
Monthly Actual Evaporation (AE)	-- 0.69	0.46	0.39
T-Value	-2.70	3.74	3.66
P-Value	0.025	0.004	0.004
Monthly Soil Moisture Deficit	0.16		
T-Value	1.02		
P-Value	0.334		
Rainfall 12 month moving mean	0.88	0.57	
T-Value	1.50	1.14	
P-Value	0.167	0.281	
S	9.88	9.90	10.0
R-Sq	64.24	60.09	54.92
R-Sq(adj)	52.32	52.11	50.82
Mallows C-p	4.0	3.0	2.3

Figure 5.17 shows the observed and predicted raw colour at Derwent Dam inlet 2 based on Equation 5.1. It indicates that if AE, SMD and antecedent rainfall are used to predict the raw colour at Derwent Dam inlet 2, then the raw colour levels should respond to such climatic variables with an anticipated rise in colour being flushed out in the autumn/winter and a reduction in colour during the spring/summer. The predicted raw colour does show such peaks in water colour throughout the period Jan 1993-Sept 2006, but from Jun 1996 the predictive ability of the equation weakens and the predicted colour is lower than the observed colour recorded at Bamford WTW (ANOVA $p < 0.01$).

The data suggest that the drought indices alone cannot account for the escalation in water colour since 1996 and that other factors such as landuse may contribute to the rise in colour. However, it could also be that the 1995-96 drought in itself may have induced a threshold change in colour response. Many researchers (for example, Hibbert 1969, Gustard and Wesselink 1993, Evans and Warburton, 2001, Monaghan *et al* 2007), have used a paired catchment study to overcome the non-stationarity of water quality from changes in climate and examine changes in hydrology and water quality associated with changes in landuse. The intention of this study was therefore to monitor selected catchments and compare observed with predicted levels of water colour to determine if changes in land management had a significant effect on water quality.

Figure 5.17: Observed and Predicted Raw Colour Derwent Dam 2 Inlet Jan 1993-Sept 2006



5.6 Summary

This chapter has presented the annual, monthly and daily meteorological data for rainfall and temperature measured at the study site. Whilst it is acknowledged that there may have been some spatial variation in these variables, the proximity of the catchments to each other and similarity in rainfall and temperature patterns to weather stations located within a 10-mile radius suggest that the level of accuracy and prevailing conditions across the catchments is acceptable. MORECS data for the 40 x 40 km square covering the study area also demonstrated the prevailing conditions in the area which may have influenced the generation and discharge of water colour and DOC. The potential influence of climate on these processes has been briefly discussed within the chapter. Examples include the general pattern of days without rainfall, particularly when combined with periods of high temperatures which could exacerbate the desiccation and humification of peat soils to generate a store of humic substances to be released on the catchments rewetting following the on-set of storm events or more frequent rainfall.

The chapter also discussed antecedent rainfall and temperature records. Rainfall data (1978-2006) indicate that the long-term average annual rainfall in a water year (Oct-Sep) was 1557 mm, but during this study only 2003-04 was above average (1672 mm) whilst the remainder of the years were below average (1324-1412 mm). The intensity and frequency of rainfall events was greatest in the second and third years of study and comparatively low both in frequency and intensity in the final year (2005-06).

Temperature data also indicated some variation between the study years. The extremes of temperature suggest the potential in summer for surface desiccation of bare soils which could reduce the infiltration capacity during rainfall events and so lower the ability for soils to rewet and water tables to recharge by creating a layer of baked, tarry peat on the the soil surface (Evans *et al* 1999, Lenton and Huntingford 2003, Worrall *et al* 2004). During the winter the extreme temperatures could freeze surface layers and also prevent infiltration during rainfall events whilst needle-ice could increase erosion and so expose deeper layers of previously unexposed peat soils with larger carbon storage and potentially leach greater levels of water colour and DOC as they desiccate.

The relationship between the meteorological variables and water colour/DOC is complex and was discussed in Section 2.3.1. The monthly data show a variation in meteorological conditions during the four years with a general pattern of warm, dry conditions during the spring/summer in the first and last year of monitoring and cooler, wetter conditions prevailing in the second and third year. Their influence on the generation and discharge of DOC and water colour was not consistent and a number of varied responses occurred on the catchments, particularly at Doctors Gate Clough and Red Clough where warm, dry conditions were associated with elevated colour, although not necessarily organic in origin. However, the remaining catchments also had a varied response of water colour to rainfall, temperature, SMD and AE.

Analysis for 1993-94 data indicated a relationship between water colour and climatic variables: rainfall in the previous 12 months, actual evaporation and soil moisture deficit. However, regression modelling failed to account for the escalation in colour since 1995 and reiterates the main aim of the study which was to determine if land management could have a significant effect on water quality in addition to the influence of climate. Such variability emphasises the importance of using a paired catchment approach to overcome the variability and non-stationarity of colour/DOC and so determine if changes on the catchments have resulted from manipulation of landuse. This approach is discussed in Chapter 8 using a paired catchment approach to determine changes caused by land management manipulation.

6 WATER QUALITY AT A CATCHMENT SCALE

6.1 Introduction

This chapter describes the results and analysis of water quality changes that occurred on the six Ashop catchments over the four year study period from Oct 2002 – Sept 2006. A time series of data for this period is given for the annual, daily and monthly variables to demonstrate the magnitude and range of temporal and spatial change during the study. A number of rainfall ("storm") events are also presented which show the change in water quality during and after storm events. The water years (1st Oct-30th Sept) referred to in the study have been used in preference to the Julian calendar year to define annual changes as the 1st October is considered the end of the evaporation season, when the groundwater storages are generally at a similar level each year (Shaw 1994).

6.2 Water Colour

6.2.1 Annual Water Colour

A summary of the annual true (filtered) water colour (°H) for each water year (Oct-Sept) is presented in Tables 6.1-6.4, which provide statistics for the mean, standard error mean, standard deviation, median, maximum and minimum true colour (°H) on each of the six catchments in the study. The data presented in Table 6.1 show the statistics for daily water colour during the calibration period (Oct 2002-Sept 2003) prior to changes in land management, whilst Tables 6.2-6.4 present data post-management intervention. N* represents the number of missing samples in a water year which usually occurred in blocks of three to five days at the end of a sample run when the sampler had failed due to battery exhaustion, sampler malfunction or extreme weather conditions. Although every effort was made to maximise the sample data, the environmental factors largely dictated the number of samples collected and varied between each catchment.

Table 6.1 Ashop Catchments Annual Statistics of Daily True Colour (°H) Oct 2002 -Sept 2003

Variable	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
DGC	239	126	162	5.49	84.88	40.34	145.64	460.01
UNG	273	92	79.53	3.15	51.99	19.5	59.26	254.68
NGC	308	57	108.5	4.6	80.73	15.93	91.83	338.42
UGC	307	58	87.77	3.56	62.31	17.85	64.47	279.46
RC	282	83	93.76	2.76	46.43	20.05	90.94	218.31
WC	322	43	100.19	3.61	64.7	14.56	77.73	354.33

Table 6.2 Ashop Catchments Annual Statistics of Daily True Colour (°H) Oct 2003-Sept 2004

Variable	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
DGC	239	127	163.87	3.98	61.6	64.9	152.9	343.5
UNG	253	113	101.74	3.76	59.77	37	83.1	346.9
NGC	266	100	129.32	5.2	84.8	11	116.05	471
UGC	237	129	117.4	5.23	80.56	27	91.3	436.3
RC	256	110	117.94	3.94	63.08	24.7	109.35	412.3
WC	242	124	120.45	4.93	76.73	22.3	102.3	391.5

Table 6.3 Ashop Catchments Annual Statistics of Daily True Colour (°H) Oct 2004-Sept 2005

Variable	N	N*	Mean	SE	St Dev	Minimum	Median	Maximum
DGC	233	132	195.15	6.78	103.57	60.9	170.2	488.1
UNG	244	121	102.07	3.07	47.94	36.5	88.8	272
NGC	273	92	153.65	4.56	75.4	24.2	150.9	365.5
UGC	236	129	110.66	3.61	55.53	37.7	98.15	289.3
RC	255	110	125.51	2.57	41.11	55	126.8	253.1
WC	260	105	145.78	3.49	56.33	69.62	129.49	318.26

Table 6.4 Ashop Catchments Annual Statistics of Daily True Colour (°H) Oct 2005-Sept 2006

Variable	N	N*	Mean	SE	St Dev	Minimum	Median	Maximum
DGC	252	113	187.46	5.47	86.91	58.96	166.06	507.79
UNG	225	140	98.7	3.83	57.46	24.59	77.68	264.56
NGC	287	78	121.28	4.75	80.42	9.17	115.27	422.46
UGC	240	125	105.1	4.3	66.56	4.96	87.58	331.12
RC	201	164	120.67	2.57	36.49	39.87	121.95	236.8
WC	263	102	132.59	3.71	60.13	26.74	119.56	311.98

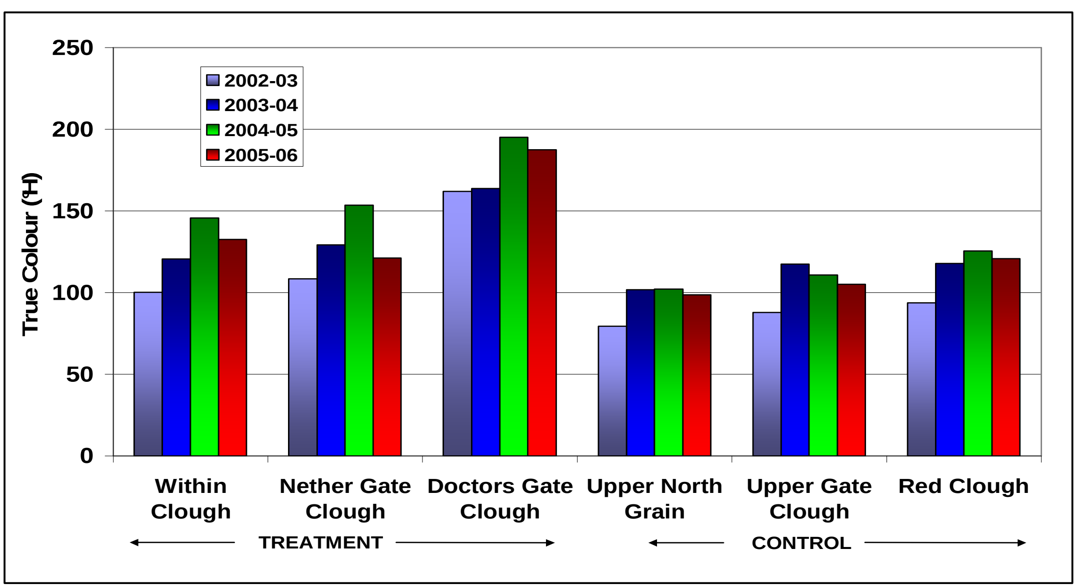
KEY

DGC – Doctors Gate Clough   UNG – Upper North Grain   NGC – Nether Gate Clough

UGC – Upper Gate Clough   RC - Red Clough   WC - Within Clough

Figure 6.1 presents the annual mean true colour (°H) for the six catchments. Within Clough, Nether Gate Clough and Doctors Gate Clough were all selected for treatment (see Section 4.2) and the remainder of the sites acted as controls where no land management was manipulated. The figure clearly shows that the annual true colour was consistently higher on the treatment sites compared to the control sites throughout the study (i.e. both during the calibration and post management manipulation). There was a noticeable rise in annual mean colour between the second and third year on the treatment sites, but this did not occur on the control sites and in the final year there was a larger decrease in annual mean colour on the treatment sites compared to the control sites. Detailed statistical analysis follows in the rest of the section.

Figure 6.1: Ashop Catchments Annual Mean True Colour (°H) Oct 2002-Sept 2006

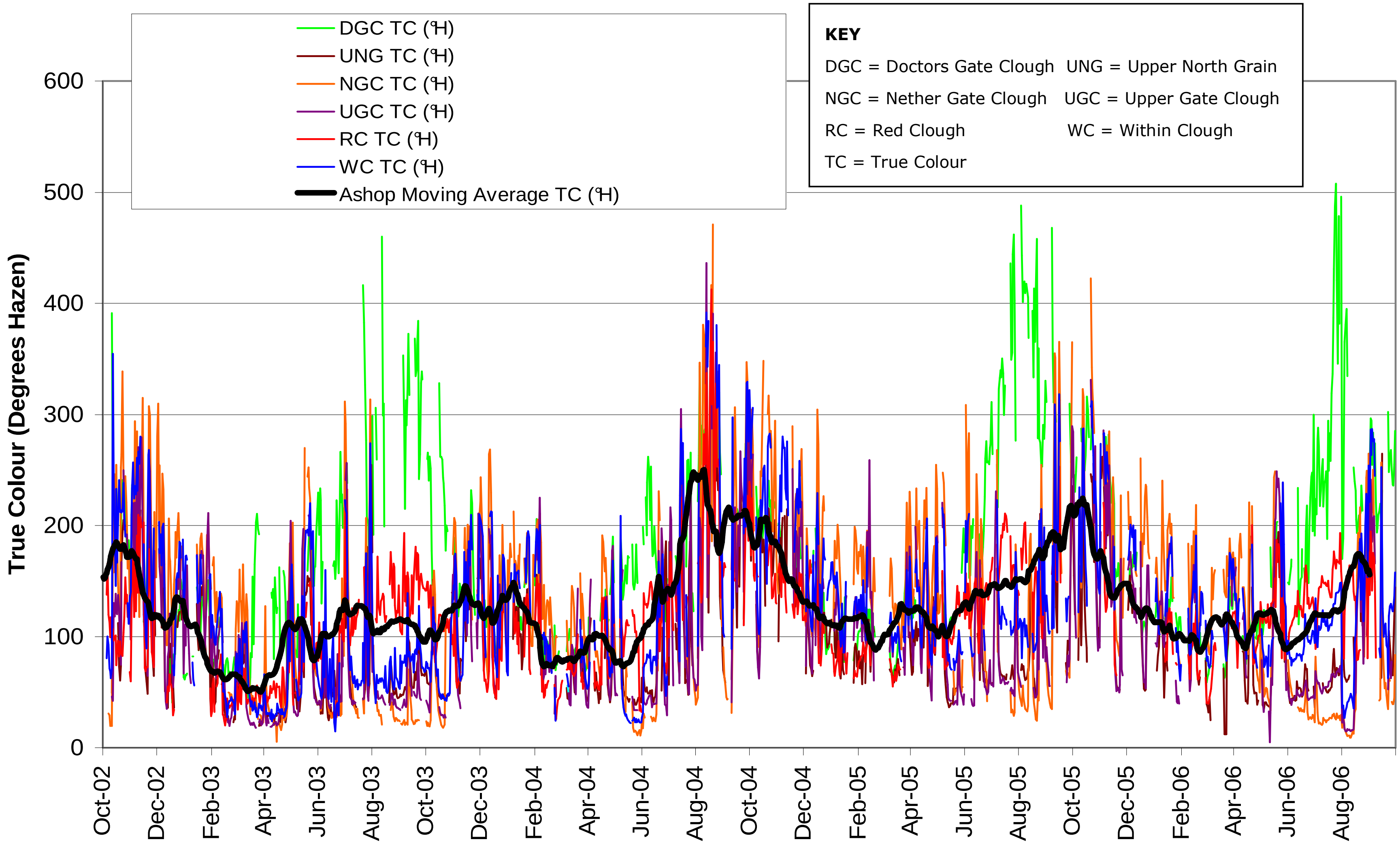


6.2.2 Daily Water Colour

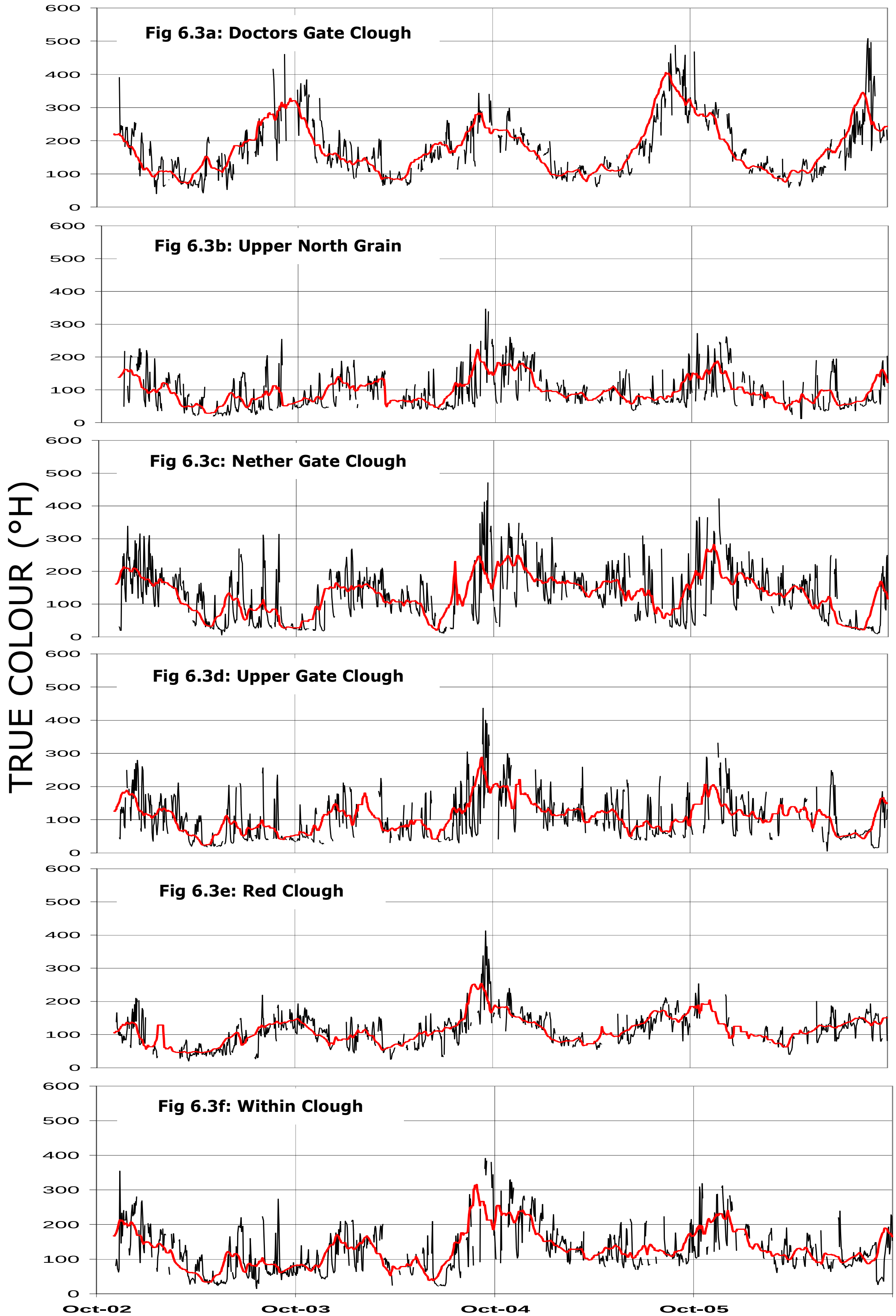
Figure 6.2 and Tables 6.1-6.4 shows the temporal and spatial variation in true colour between the catchments. Figure 6.2 shows the daily true colour for each of the six catchments from Oct 2002-Sept 2006 and the solid black line depicts the trend using the monthly moving mean of daily true colour (°H) for the sites. Figures 6.3a-6.3f show a time series of daily true colour (°H) from Oct 2002-Sept 2006 for each individual catchment with the monthly moving mean over a 30-day period. The figures show a clear seasonal pattern of colour that generally increased during the autumn/winter when the humic and fulvic acids were flushed out of the soils, decreasing again following the exhaustion of colour when saturation of soils is likely to have dominated during the mid-late winter. The maximum true colour for four of the catchments (Upper North Grain, Nether Gate Clough, Upper Gate Clough and Within Clough) was recorded between August and November and this exemplified the "autumn" flush of colour discharged from the catchments (see Tables 6.1-6.4 and monthly descriptive statistics in Appendix IX).

There are, however, some other notable observations regarding the pattern of colour discharged from the sites. Figure 6.2 shows that the "autumn flush" in the winter of Oct 2003-04 was lower than the preceding winter (2002-03) and succeeding winters (2004-05, 2005-06). This was largely due to the prevailing meteorological conditions, that is, drought conditions caused by long periods of no rainfall, high temperatures and a "dry" winter with low rainfall (see Sections 5.2.2 and 5.3) which failed to recharge the groundwater and raise water table levels during the winter of 2003-04.

Figure 6.2: Ashop Catchments Daily True Colour (°H) Oct 2002-Sept 2006



Figures 6.3a-f: Ashop Catchments Daily True Colour (°H) Oct 2002 -Sept 2006



KEY Daily True Colour Moving Mean of Daily True Colour

The continued aerobic conditions in the top layers of the soil (acrotelm) and lack of rainfall (which under normal winter rainfall levels would result in a rise in water colour levels with the reinstatement of saturated, aerobic conditions and a flushing out of the acids) resulted in the autumn of 2003-04 not generating the higher colour levels normally associated with the seasonal flush. As the drought then continued through the winter/spring of 2003-04, the colour response was delayed until late summer (August 2004) when a series of thunderstorms began to recharge the groundwater and the colour was then flushed out during the late summer/autumn 2004. Table 6.2 shows the maximum true colour for water year 2003-04 which was discharged during August 2004 for all the catchments e.g. 471 °H at Nether Gate Clough.

This drought period appears to have triggered a longer-term response as the colour flush seen in the subsequent winters of 2004-05 and 2005-06 was also relatively high and indicated an increase in water colour levels, which, although showing some signs of recovery in 2005-06, did not appear to return to the levels pertaining during winter 2002-03 (pre-management manipulation). The data therefore show that true water colour increased on all of the catchments during the monitoring period irrespective of any changes in land management during the period of study. However, it should be emphasised that this is perhaps a too simplistic view and the benefit of a paired catchment study has enabled comparisons to be made with true colour levels on both the "control" catchments where no management was altered, against the "treated" catchments and so determine if changes occurring on the manipulated catchments were significant and were greater or less than predicted. These relationships are discussed in Chapter 8.

6.2.2.1 Seasonal Variation in Water Colour at Doctors Gate Clough and Red Clough

In contrast to the low colour levels generally observed on other catchments during the spring/summer, Figure 6.2 and 6.3a show true colour at Doctors Gate Clough peaked during the summer of each water year with colour higher during these periods than the typical "autumn flush" associated with the release of humic acids and carbon export from these upland catchments. A pattern of elevated colour in summer, although not as extreme, was also observed at Red Clough (see Figure 6.3e). The minimum true colour for Oct 2004 – Sept 2005 only reached 61 °H (Mar 2005) at Doctors Gate Clough and 55 °H (Mar 2005) at Red Clough whilst maximum colour at these sites reached 508 °H (Jul 2006) and 193 °H (Jul 2006) at Red Clough.

It appears that water colour on these two catchments was not solely a result of DOC. Water colour at Doctors Gate Clough may have been derived predominantly from organic matter during the autumn/winter months, but also from iron (Fe) at other periods of warm, stable weather. Water quality is discussed in more details in

Sections 6.3-6.6. There may have been a combination of leaching of iron from the substrate; high turbidity caused by suspended sediment and increased activity of biological organisms prevailing during periods of warm, stable weather when baseflow conditions predominated. Water was generally approaching neutral during these conditions with pH recorded at 6.0–7.5. This combination of factors can encourage the release of phosphates from the substrate and so promote algal growth (Klug 2005). Large, gelatinous mats of algae were observed at Doctors Gate Clough during these conditions, both floating on the surface and within the water column. The composition of iron and the algal growth is discussed in Section 6.3.

6.2.3 Daily True Colour Distribution

In addition to the typical seasonal pattern of true colour, there were spatial and temporal differences in the distribution of colour levels both between water years and between the catchments in the study. Figures 6.4a-d show the daily colour distribution for each catchment between the water years Oct 2002 – Sept 2006 and indicate they were generally not normally distributed. Statistical analysis of daily true colour (°H) data was completed by comparing pre-management colour distribution (2002-2003) with colour distribution in the post-management period (2003-04, 2004-05 and 2005-06) to determine if the character or distribution of the water colour had changed as a result of the management changes. Statistical tests (Mann Whitney U and Kolmogorov Smirnov) were chosen to compare the medians and annual datasets of years 2, 3 and 4 with year 1 for each catchment, that is, the pre-management calibration period (year 1) against each post-management year. The results are presented in Table 6.5.

Figures 6.4a-d show that the distribution of water colour changed between the water years, for example, the distribution curve was much flatter at Nether Gate Clough in 2003-04 compared to 2002-03, indicating the range of water colour discharged from the catchment was much larger than the calibration year with a greater frequency of highly discoloured water immediately after treatment by the cessation of burning. Statistical analysis of the daily true colour data found that the differences in the colour distribution were all highly significant between year 1 and each subsequent year following management manipulation on all of the catchments (Kolmogorov Smirnov $p < 0.001$). Therefore, irrespective of management changes, the distribution of daily colour was significant between year 1 and the subsequent years. However, these differences may have been caused by a number of events. The changing climatic conditions between each year, further complicated by the hysteresis effect on soil properties in generating water colour may have caused differences in distribution between one year and the next. In addition, the number of samples in the analysis differed each year because of equipment failure or extreme weather conditions (see Tables 6.1-6.4) and may account for some change in distribution.

Figures 6.5a-d show boxplots of the mean and range of daily true colour (°H) for each water year from Oct 2002–Sept 2006 and show the spatial differences in colour between the catchments. The figures demonstrate the level of consistency between the sites in the order of those catchments discharging the highest water colour. Doctors Gate Clough consistently had the highest mean water colour followed by Nether Gate Clough and Within Clough (the three treated catchments), then Red Clough, Upper Gate Clough and Upper North Grain (the three control catchments). The hierarchy was maintained throughout the study period. Table 6.5 shows statistical analysis of the median and variance differences between year 1 and the subsequent years which were highly significant on all catchments (Mann Whitney $p < 0.01$, ANOVA $p < 0.05$) with the exception of Doctors Gate Clough when the median and mean difference between year 1 and year 2 was not significant (Mann Whitney $p = 0.185$, ANOVA $p = 0.914$). The data and statistical analysis suggest that the processes and catchment response in generating colour is indeed complex when considering daily data and these issues are discussed in Section 8.2.

Figure 6.4a-d: Ashop Catchments Daily True Colour Distribution Oct 2002-Sept 2006

Fig 6.4a: Distribution 2002-03

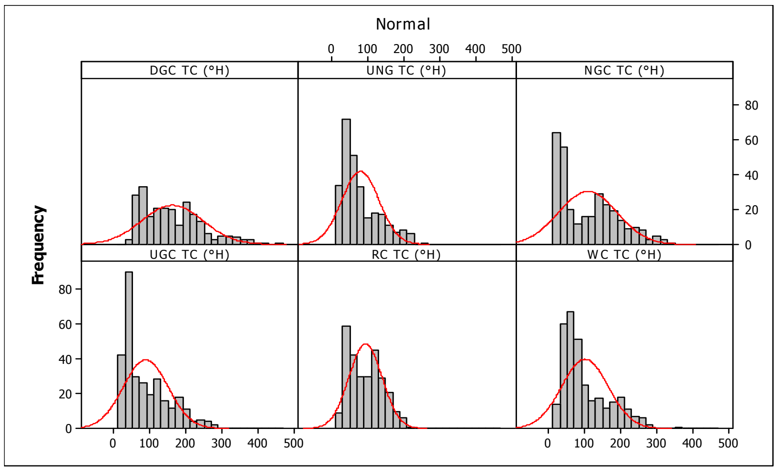


Fig 6.4b: Distribution 2003-04

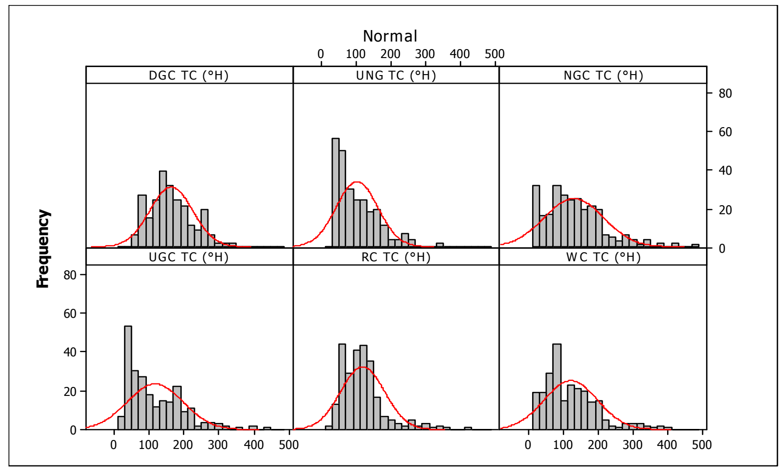


Fig 6.4c: Distribution 2004-05

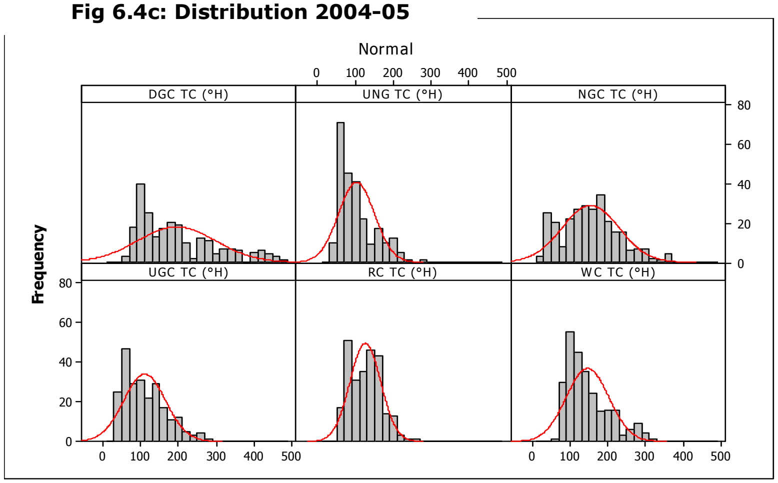
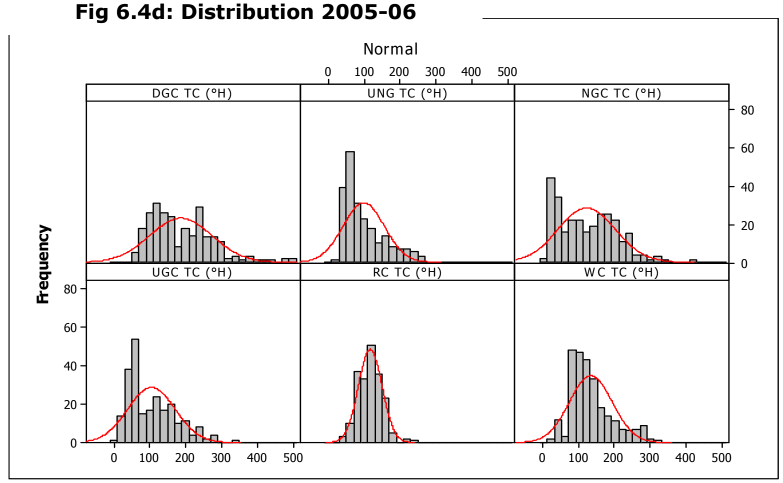


Fig 6.4d: Distribution 2005-06



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

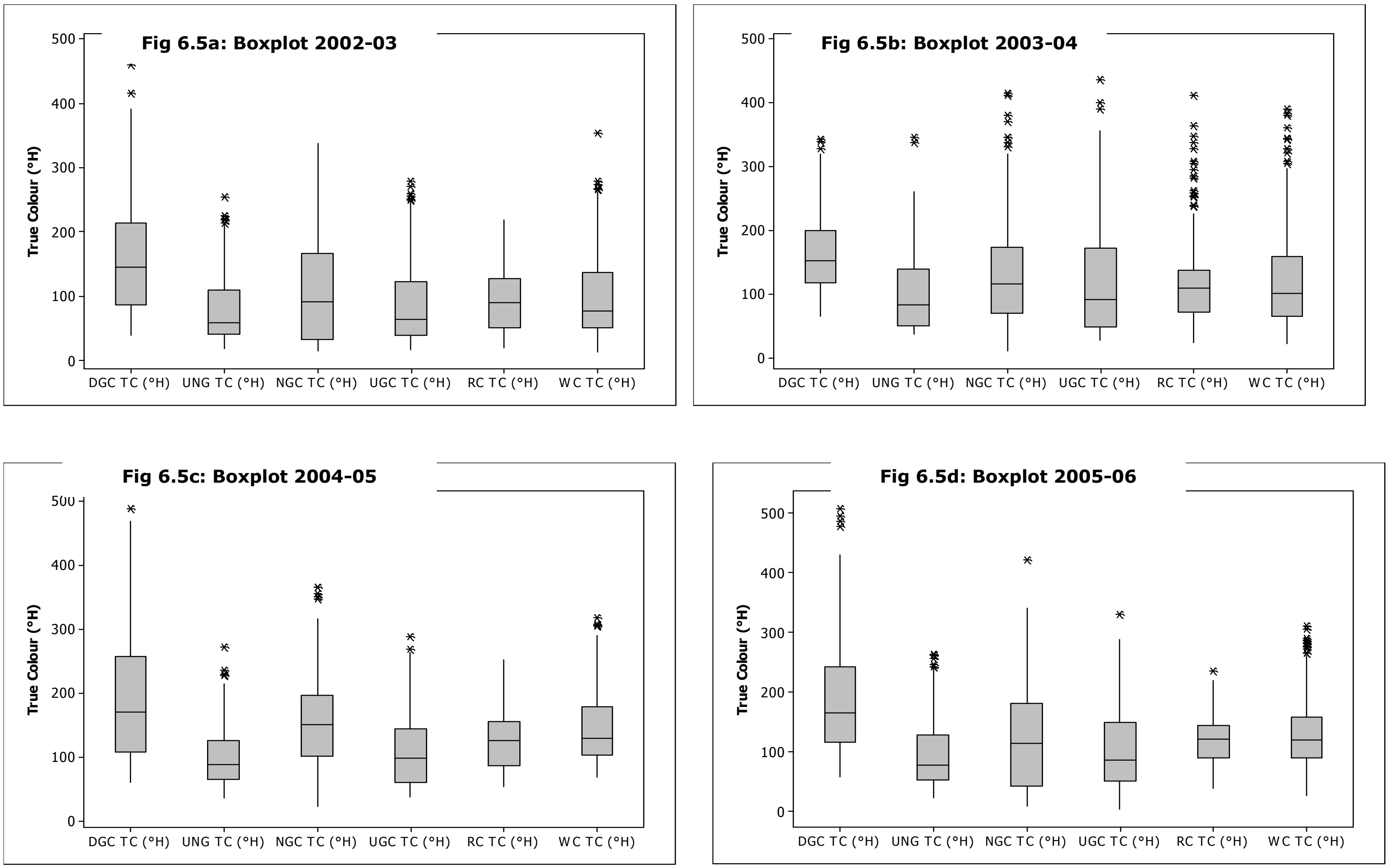
UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

TC = True Colour

Figure 6.5a-d: Ashop Catchments Boxplot of Daily True Colour (°H) Oct 2002 – Sept 2006



KEY

DGC = Doctors Gate Clough

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RC = Red Clough

WC = Within Clough

TC = True Colour

Table 6.5: Statistical Analysis Daily True Water Colour (°H) Comparing Each Treatment Year with the Calibration Year (2002-03) at the Same Catchment

Variable	N	Median	Mean	Std Dev	Mann Whitney U Probability p-value	Kolmogorov Smirnov Probability p-value	ANOVA p-value	F Value
DGC TC (°H) 2002 -03	241	145.64	162	84.8				
DGC TC (°H) 2003-04	239	152.9	163.87	61.6	0.185	<0.001**	0.914	0.01
DGC TC (°H) 2004-05	233	170.2	195.15	103.6	<0.001**	<0.001**	<0.001**	13.52
DGC TC (°H) 2005-06	252	166.04	187.46	86.9	<0.001**	<0.001**	0.002**	9.81
UNG TC (°H) 2002-03	273	59.26	79.53	52				
UNG TC (°H) 2003-04	253	83.1	101.74	59.8	<0.001**	<0.001**	<0.001**	20.76
UNG TC (°H) 2004-05	244	88.8	102.07	47.9	<0.001**	<0.001**	<0.001**	26.04
UNG TC (°H) 2005-06	227	77.68	98.7	57.5	<0.001**	<0.001**	<0.001**	13.18
NGC TC (°H) 2002-03	309	91.83	108.5	80.7				
NGC TC (°H) 2003-04	266	116.05	129.32	84.6	<0.001**	<0.001**	<0.001**	9.36
NGC TC (°H) 2004-05	268	150.9	153.65	75.4	<0.001**	<0.001**	<0.001**	46.65
NGC TC (°H) 2005-06	287	115.27	121.28	80.4	0.003**	0.019*	0.048*	3.94
UGC TC (°H) 2002-03	307	64.47	87.77	62.3				
UGC TC (°H) 2003-04	237	91.3	117.4	80.6	<0.001**	<0.001**	<0.001**	23.39
UGC TC (°H) 2004-05	236	98.15	110.66	55.5	<0.001**	<0.001**	<0.001**	19.76
UGC TC (°H) 2005-06	240	87.58	105.1	66.6	<0.001**	<0.001**	0.002**	9.81
RC TC (°H) 2002-03	282	90.94	93.76	46.4				
RC TC (°H) 2003-04	256	109.35	117.94	63.1	<0.001**	<0.001**	<0.001**	25.97
RC TC (°H) 2004-05	250	126.8	152.51	41.1	<0.001**	<0.001**	<0.001**	73.75
RC TC (°H) 2005-06	201	121.95	120.67	36.5	<0.001**	<0.001**	<0.001**	46.87
WC TC (°H) 2002-03	327	77.73	100.19	64.7				
WC TC (°H) 2003-04	242	102.3	120.45	76.7	0.0007**	0.001**	0.001**	11.53
WC TC (°H) 2004-05	260	129.49	145.78	56.3	<0.001**	<0.001**	<0.001**	80.08
WC TC (°H) 2005-06	263	119.56	132.59	60.1	<0.001**	<0.001**	<0.001**	38.65

** indicates significance p <0.01   * indicates significance p <0.05

KEY

DGC = Doctors Gate Clough   UNG = Upper North Grain   NGC = Nether Gate Clough

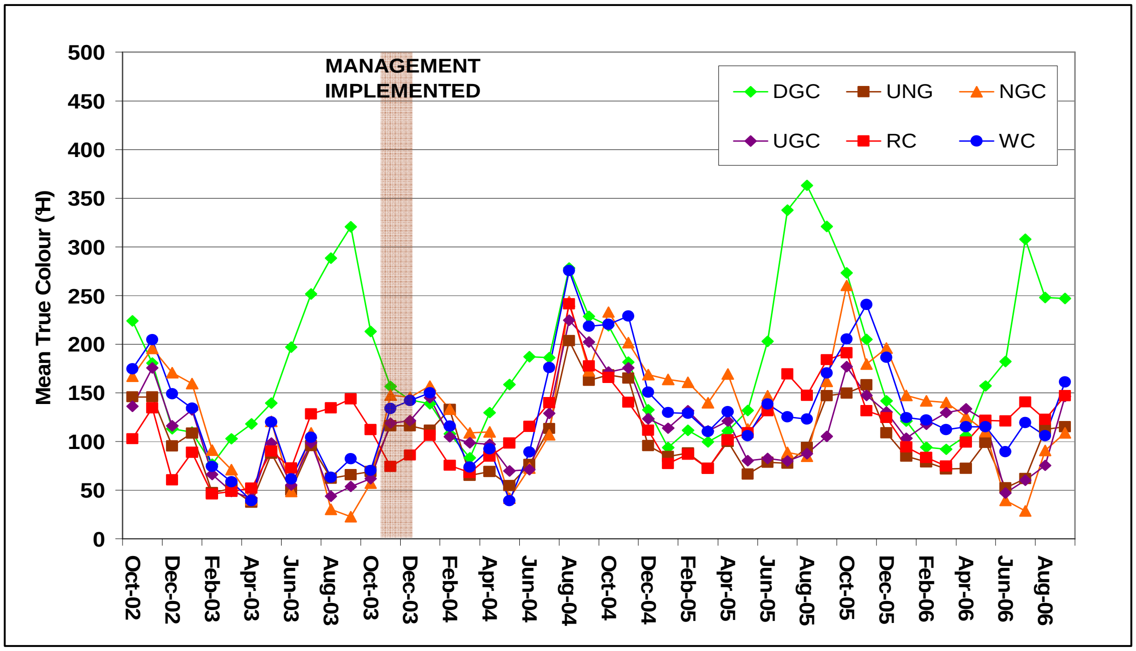
UGC = Upper Gate Clough   RC = Red Clough   WC = Within Clough

TC = True Colour

6.2.4 Monthly Water Colour

The monthly mean true colour for each catchment was also examined to determine any long-term pattern, changes that might have arisen pre- and post-management intervention or spatial changes in colour between catchments. Figure 6.6 shows the monthly mean true colour (°H) and illustrates the temporal and spatial differences in colour from Oct 2002-Sept 2006. The figure shows the typical seasonal variation with highest colour found in the autumn 'flush', but also the anomalously high colour being discharged in summer at Doctors Gate Clough and to a lesser extent at Red Clough during the summer months each year. (See Appendix IX for monthly descriptive statistics of true water colour for each catchment).

Figure 6.6: Ashop Catchments Monthly True Colour (°H) Oct 2002-Sept 2006



KEY

DGC = Doctors Gate Clough
UNG = Upper North Grain
NGC = Nether Gate Clough
UGC = Upper Gate Clough
RC = Red Clough
WC = Within Clough
TC = True Colour

Figures 6.7a-6.7f show the monthly mean true colour (°H) for each individual catchment. The extremes of high colour discharged at Doctors Gate Clough during the spring/summer and to a lesser extent at Red Clough are clearly illustrated. The remainder of the catchments produced the more typical seasonal 'flush' of colour during the autumn/winter throughout the study. Figures 6.8a-6.8d show that throughout the four years Doctors Gate Clough consistently had a higher mean water colour than the remaining catchments, followed in order by Nether Gate Clough, Within Clough, Red Clough, Upper Gate Clough and Upper North Grain. This order continued in the second year, but altered in the third year when the colour levels were elevated at each site. In this year, although Doctors Gate Clough, Nether Gate Clough and Within Clough (the treated catchments where management was manipulated) remained highest in water colour, Red Clough produced a higher colour and displaced Upper Gate Clough, whilst Upper North Grain continued to have the lowest mean colour. In the final year Doctors Gate Clough produced the highest mean colour, but this was followed by Within Clough (gullies blocked) with the second highest mean colour, despite there being a decrease in the mean colour at the site from 2004-05 to 2005-06. Red Clough had the same mean water colour as Within Clough for the final year, although the standard deviation was lower (27.11) compared to Within Clough (32.92). Nether Gate Clough mean water colour was also lower in the final year although the site was less coloured than both Within Clough and Red Clough after the change in management with only Upper Gate Clough and Upper North Grain being consistently less coloured than Nether Gate Clough. These findings are summarised in Table 6.6.

Table 6.6: Summary of Change in Ranks of Ashop Catchments Monthly Mean True Colour (°H) Oct 2002-Sept 2006

Year	Site	Rank	Year	Site	Rank
2002-03	Within Clough	3	2002-03	Upper North Grain	6
2003-04		3	2003-04		6
2004-05		3	2004-05		6
2005-06		2.5	2005-06		6
2002-03	Nether Gate Clough	2	2002-03	Upper Gate Clough	5
2003-04		2	2003-04		4
2004-05		2	2004-05		4
2005-06		4	2005-06		5
2002-03	Doctors Gate Clough	1	2002-03	Red Clough	4
2003-04		1	2003-04		5
2004-05		1	2004-05		5
2005-06		1	2005-06		2.5

KEY

1 = Most highly coloured 6 = Least highly coloured

This change in order of mean water colour, suggests that Doctors Gate Clough (removal of grazing) was consistently more discoloured than the remainder of the sites throughout the study; Red Clough (control) also increased in colour year on year. The remaining treated sites – Within Clough (gullies blocked) and Nether Gate Clough (cessation of burning) both recovered in the final year with a mean decrease in colour of 21 °H and 9 °H respectively. Upper Gate Clough and Upper North Grain (control sites) also had an escalation and recovery in colour between the second and third and also the third and fourth year, but to a lesser degree than at both Within Clough and Nether Gate Clough. Upper Gate Clough and Upper North Grain true colour decreased by ~2 °H between the second and third year (2003-04 and 2004-05), and 9 °H and < 2 °H respectively in the final year. These findings are summarised in Table 6.7 and Table 6.8 for full statistical results.

Figure 6.7a-f: Ashop Catchments Monthly Mean True Colour (°H) 2002-2006

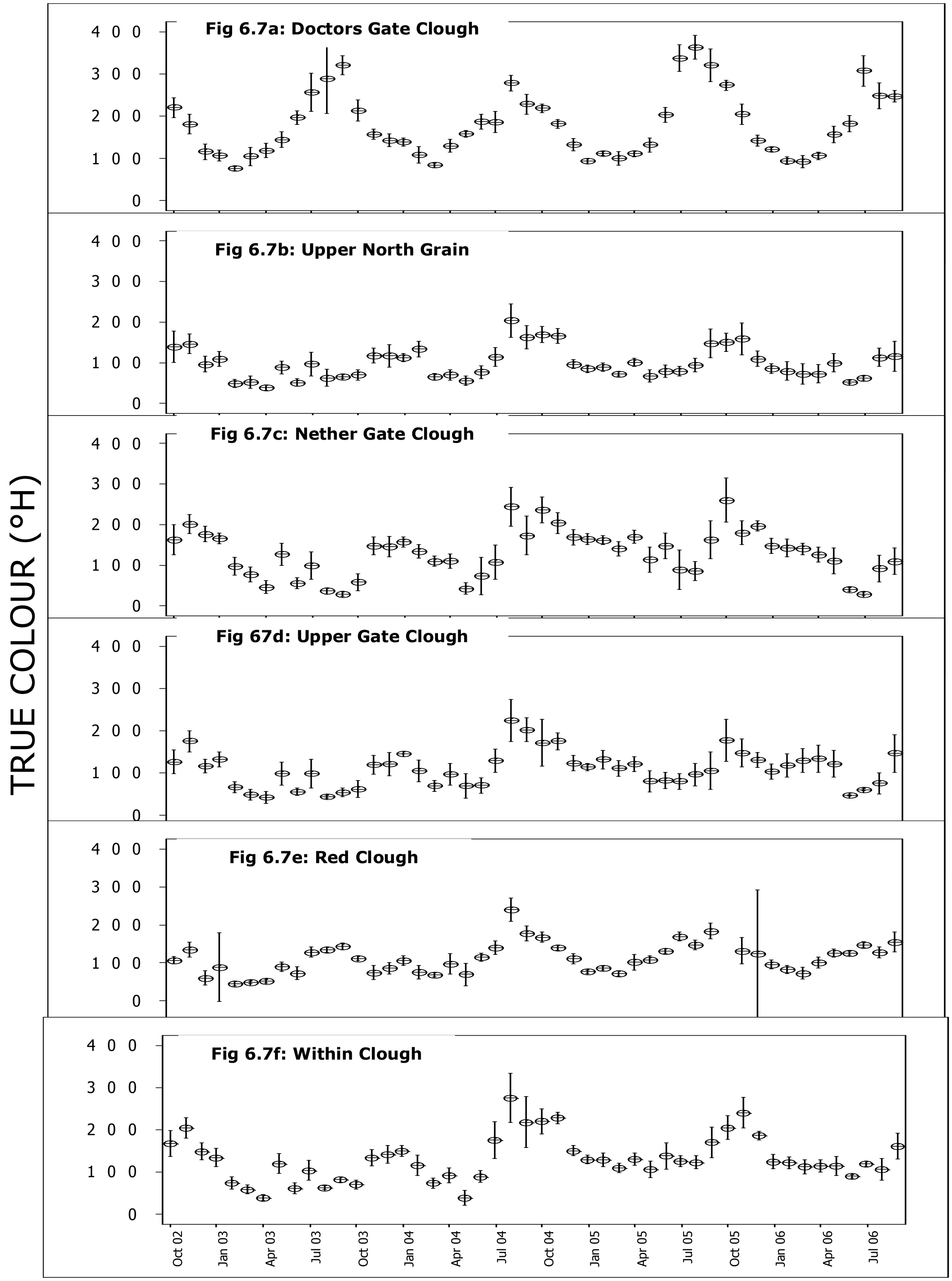
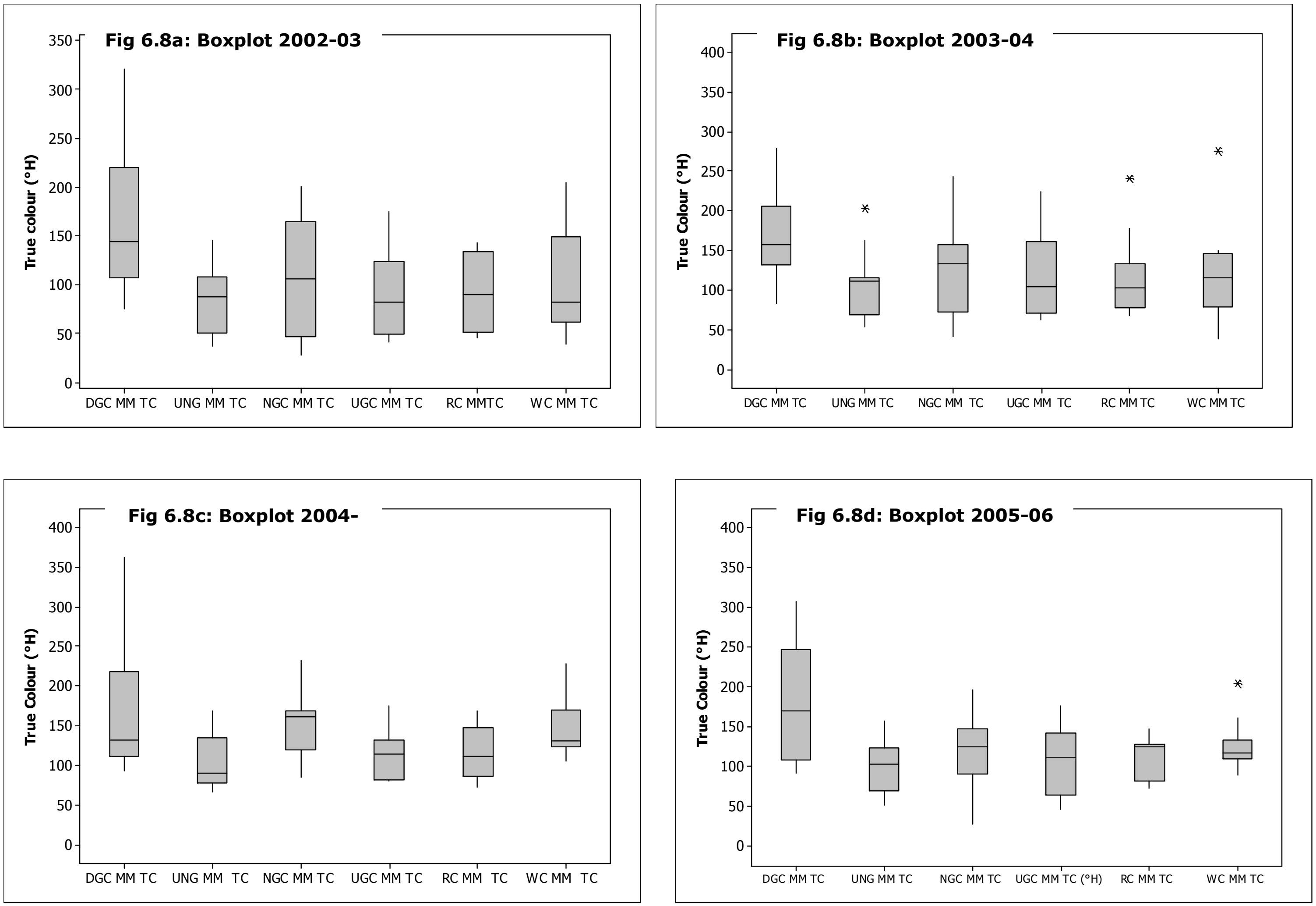


Figure 6.8a-6.8d: Boxplots of Monthly True Colour (°H) Oct 2002 – Sept 2006



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

MMTC = Monthly Mean of Daily True Colour

Table 6.7: Summary of Ashop Catchments Change in Monthly Mean True Colour (°H) Oct 2002-Sept 2006

Site	Treatment/Control	Year	True Colour (°H)
Within Clough	Gullies Blocked	2002-03 and 2003-04	Increase
		2003-4 and 2004-05	Increase
		2004-05 and 2005-06	Decrease
Nether Gate Clough	Cessation of Burning	2002-03 and 2003-04	Increase
		2003-4 and 2004-05	Increase
		2004-05 and 2005-06	Decrease
Doctors Gate	Removal of Grazing	2002-03 and 2003-04	Increase
		2003-4 and 2004-05	Increase
		2004-05 and 2005-06	Increase
Upper North Grain	CONTROL	2002-03 and 2003-04	Increase
		2003-4 and 2004-05	Decrease
		2004-05 and 2005-06	Decrease
Upper Gate Clough	CONTROL	2002-03 and 2003-04	Increase
		2003-4 and 2004-05	Decrease
		2004-05 and 2005-06	Decrease
Red Clough	CONTROL	2002-03 and 2003-04	Increase
		2003-4 and 2004-05	Increase
		2004-05 and 2005-06	Increase

Appendix IX and Tables 6.7 and 6.8 show that the true colour levels for each catchment in the final year were generally lower than years two and three, but still did not recover or improve on the mean colour discharged in the first water year prior to any land management manipulation. However, the overall rise in water colour between the first and last year of monitoring on all the catchments irrespective of land management manipulation may mask more complex patterns and therefore the differences between mean water colour for each year were examined to determine if the changes that occurred were statistically significant, particularly on the treated catchments where the changes in water colour may have resulted from management manipulation.

Table 6.8 presents the results of the statistical analysis using the non-parametric test Mann Whitney U to test differences in the median, Kolmogorov Smirnov to test differences in the distribution of data sets and the ANOVA to test differences in the variance. The ANOVA test was used because it is generally robust even when non-normal data are analysed where Type 1 error rate is close to the nominal value (alpha) and is robust to moderate violations of homogeneity of variance when large samples sizes are used (McCuen 2002).

Table 6.8: Statistical Analysis Monthly True Water Colour (°H): Comparison of Calibration Year (2002-03) with Subsequent Years on each Catchment

Variable	N	Median	Mean	Std Dev	Mann Whitney U Probability p-value	Kolmogorov Smirnov Probability p-value	ANOVA P value	F value
DGC TC (°H) 2002 -03	11	144.1	167.38	75.42				
DGC TC (°H) 2003-04	12	157.6	167.63	54.37	0.735	0.728	0.993	0
DGC TC (°H) 2004-05	11	132.6	180.22	93.98	0.896	0.993	0.723	0.13
DGC TC (°H) 2005-06	12	169.6	181.29	74.38	0.689	0.97	0.601	0.2
UNG TC (°H) 2002-03	11	87.68	84.04	36.99				
UNG TC (°H) 2003-04	11	111.67	105.27	45.7	0.189	0.461	0.245	1.44
UNG TC (°H) 2004-05	12	91.04	103.22	36	0.255	0.187	0.222	1.59
UNG TC (°H) 2005-06	10	104.01	101.52	35.01	0.169	0.493	0.281	1.23
NGC TC (°H) 2002-03	12	105.22	107.52	58.95				
NGC TC (°H) 2003-04	11	137.46	126.51	57.53	0.601	0.889	0.444	0.61
NGC TC (°H) 2004-05	12	161.51	152.9	42.9	0.089	0.249	0.049*	4.47
NGC TC (°H) 2005-06	11	125.25	121.28	51.79	0.735	0.91	0.628	0.24
UGC TC (°H) 2002-03	12	82.26	88.12	43.16				
UGC TC (°H) 2003-04	9	104.8	119.1	57.84	0.189	0.334	0.175	1.99
UGC TC (°H) 2004-05	10	113.9	117.05	33.18	0.148	0.131	0.088	3.2
UGC TC (°H) 2005-06	8	112.47	107.81	44.8	0.263	0.809	0.338	0.97
RC TC (°H) 2002-03	11	90.3	92.63	38.48				
RC TC (°H) 2003-04	11	102.32	115.1	50.44	0.34	0.461	0.246	1.42
RC TC (°H) 2004-05	11	111.58	119.43	33.96	0.115	0.461	0.099	3
RC TC (°H) 2005-06	7	125.98	127.07	27.11	0.415	0.34	0.258	1.38
WC TC (°H) 2002-03	11	82.1	102.28	25.46				
WC TC (°H) 2003-04	9	116	123.24	67.56	0.447	0.679	0.445	0.61
WC TC (°H) 2004-05	11	130.37	148.54	41.63	0.026**	0.023**	0.033**	5.25
WC TC (°H) 2005-06	10	117.13	127.07	32.92	0.13	0.089	0.216	1.64

** indicates significance p <0.01   * indicates significance p <0.05

KEY

DGC = Doctors Gate Clough   UNG = Upper North Grain   NGC = Nether Gate Clough

UGC = Upper Gate Clough   RC = Red Clough   WC = Within Clough

TC = True Colour

The statistics indicate that there were no significant differences in the median, distribution or variance of monthly mean true water colour (°H) on all of the control catchments (Upper North Grain, Upper Gate Clough and Red Clough) between the water years. At Within Clough (gullies blocked) there was a statistically significant rise in true colour (°H) and the difference between year 1 (Oct 2002-Sept 2003, calibration period), and year 3 (Oct 2004-Sept 2005, post-management) (ANOVA p = 0.033, Mann Whitney U p = 0.026, Kolmogorov Smirnov p = 0.023). This change could be attributed to the increased disturbance in the top layers of the peat during gully blocking and a rise in the water table following the installation of gully blocks and subsequent flush of colour discharged from the catchment when rewet following the autumn/winter storms. There were also significant changes in the variance of mean monthly water colour at Nether Gate Clough (cessation of burning) (ANOVA p = 0.049) between year one and year three. However, there was no significant statistical change at Doctors Gate Clough where sheep grazing had been removed.

6.3 Water Quality and Heavy Metals

The methodologies used to analyse water samples for heavy metals can be referred to in Section 4.4.4. Appendix X shows results of the laboratory analysis.

6.3.1 Water Colour and Iron

Figure 6.9a shows the content of iron (Fe) in samples analysed from the sites from Mar-Sep 2006 and shows that Doctors Gate Clough (removal of grazing), Within Clough (gullies blocked) and Red Clough (control) samples consistently had a higher iron content compared to the three remaining sites. Table 6.9 and Figure 6.10a show that when the relationship between iron and true colour was tested, only Doctors Gate Clough had a reasonable r^2 (0.7138) compared with Red Clough and Within Clough where the relationship between iron and true colour was much weaker (r^2 0.0878 and 0.0141 respectively). This suggests that whilst the high iron content was associated with high colour at Doctors Gate Clough there was a range of lower iron levels at Within Clough and Red Clough resulting in the poor relationship. Despite the iron levels remaining low at Nether Gate Clough (cessation of burning), there was also a reasonable relationship between iron and true colour (r^2 0.7204) suggesting a similar distribution to that at Doctors Gate Clough, that is, a range of iron levels associated with a range of colour values, albeit at lower values compared to Doctors Gate Clough.

Table 6.9: Ashop Catchments relationship between Iron (mgl^{-1}) and True Colour (°H) Mar-Sept 2006

Site	Mgt	Mean Fe (mgl^{-1})	Independent Variable	Dependent Variable	Slope	Constant	N	r^2
Within Clough	Gullies blocked	1.31	Fe	True Colour	9.396	129.33	15	0.0141
Nether Gate Clough	Cessation of burning	0.22	Fe	True Colour	309.18	30.02	12	0.7204
Doctors Gate Clough	Removal of grazing	4.71	Fe	True Colour	21.798	107.94	12	0.7138
Upper North Grain	CONTROL	0.69	Fe	True Colour	94.418	40.126	9	0.2533
Upper Gate Clough	CONTROL	0.41	Fe	True Colour	119.02	72.631	15	0.387
Red Clough	CONTROL	2.06	Fe	True Colour	4.932	117.3	15	0.0878

The analysis suggest there may have been spatial differences in total iron concentrations in the soils, although the regression analysis indicates the importance of the interactions that occurred between humic substances and metal ions which take place through ion-exchange, surface adsorption, chelation and coagulation (Rydin and Jeglum 2006). The total iron concentration is important because of its impact on other ions with which it may readily bind and/or the sorption rate of trace elements, the decomposition of organic matter and nutrient cycling.

Iron at the study sites is likely to occur in two redox states: the soluble reduced Fe^{2+} and oxidised Fe^{3+} which is insoluble at pH >4. The Fe^{3+} oxidised from a lowering of groundwater levels and/or weathering processes will also precipitate in surface waters because of its insoluble nature. The ability of Fe^{3+} to oxidise is therefore broadly correlated with water table depth and provided oxygen is present (with lowering of water table levels or exposure of eroded peat soils for example), chemical reactions will move towards an oxidised state. However, once water tables rise again, the reactions are driven towards a reduced state (Tipping *et al* 2006). These reactions are largely mediated by microbial activity which increases once peat soils are rewet, but still oxygenated, particularly within the upper layers of the peat (acrotelm). When the wetland soils are depleted of oxygen the reduced forms of compounds become more mobile, for example ferrous iron (Fe^{2+}).

The increase in acidity from carbon humification and the production of humic and fulvic acids, together with the legacy of sulphur deposition from atmospheric pollution (the area is located between the two large conurbations of Manchester and Sheffield) may form weak acids in water which then allows the Fe^{2+} to oxidise when conditions are reduced and discolour surface waters as it is discharged from the iron-rich ground waters. The high cation binding capacity of dissolved organic matter particularly facilitates metal mobility where pH is < 5 and metal solubility is high (Shaw 1994).

These processes are likely to have occurred at varying degrees on the catchments and therefore the chemical reactions from the formation of iron oxides during oxidation and iron hydroxides during reduction and rewetting may account for the spatial and temporal differences in iron concentration at the sites. The iron concentration at Doctors Gate Clough, Red Clough and Within Clough is likely to be associated particularly with Fe^{3+} oxidation when water table levels decreased during warm, dry conditions and pH levels increased. These findings are supported by the natural geology of the three catchments that have a higher percentage of sandstone underlain than the remaining three catchments (Doctors Gate Clough and Red Clough having the highest percentage) – see Figure 3.7.

6.3.2 Water Colour and Aluminium

Figure 6.9b shows the content of aluminium (Al) in samples analysed from the study site from Mar-Sept 2006 and illustrates the temporal and spatial variation across the sites. Aluminium occurs naturally in the geology of the area and is associated particularly with the Kinder shale (Wolverson-Cope 1998). The differences in aluminium at each site may indicate the differences in geology and area of shale contributing to the water quality (see Figure 3.7). However, similarly to iron concentration, when Al^{3+} is present in humic waters with a low pH, it will precipitate out due to its insoluble nature, causing a rise in aluminium (Worrall *et al* 2006).

Such precipitation may be exacerbated by the seasonal drying/rewetting of the sites as aerobic/anaerobic conditions fluctuate, combined with the flushes of aluminium during runoff events. These changing physical and chemical processes may therefore account for differences in the observed aluminium content of samples. Table 6.10 and Figure 6.10b show the relationship between aluminium and true colour at the sites.

Table 6.10: Ashop Catchments relationship between Aluminium (mgl^{-1}) and True Colour (°H) Mar-Sept 2006

Site	Management	Mean Al (mgl^{-1})	Indep Variable	Dependent Variable	Slope	Constant	N	r^2
Within Clough	Gullies blocked	0.17	Al	True Colour	568.23	47.578	11	0.9399
Nether Gate Clough	Cessation of burning	0.12	Al	True Colour	568.84	23.672	11	0.9356
Doctors Gate Clough	Removal of grazing	0.17	Al	True Colour	614.95	129.74	11	0.495
Upper North Grain	CONTROL	0.12	Al	True Colour	596.95	28.427	8	0.9498
Upper Gate Clough	CONTROL	0.15	Al	True Colour	718.64	8.003	11	0.9727
Red Clough	CONTROL	0.12	Al	True Colour	168.05	112.71	11	0.1487

The analysis indicates the relationship between aluminium and true colour differed greatly between sites. Doctors Gate Clough and Red Clough shared a similar relationship between the two variables where there was a poor regression between aluminium and true colour (r^2 0.4947 and 0.1487 respectively). Aluminium and colour were however, strongly related at Within Clough (r^2 0.9399) (gullies blocked), Nether Gate Clough (r^2 0.9356), (cessation of burning), Upper North Grain (r^2 0.9498) (control) and Upper Gate Clough (r^2 0.9727) (control). The good linear relationship shown by the high r^2 values is likely to have been caused by a correlation of high colour:high aluminium (see Figures 6.9b and 6.9d). Literature suggests that the spatial and temporal difference in aluminium may be associated with changes in pH (McMahon and Neal 1990) and acidic conditions have been found to prevail where Al was found in high concentrations. This supports similar results found at the study sites. For example, on 4 Sep 2006 analysis of the daily sample at Within Clough found the pH to be 3.93, whilst aluminium was 0.416 mgl^{-1} and true colour was 287 °H, compared to 5 May 2006 when pH measured 6.46, aluminium 0.081 mgl^{-1} and true colour 73 °H. Figure 6.9b shows similar changes in levels of aluminium at Doctors Gate Clough and Red Clough which were noticeably lower during May 2006 compared to Sept 2006.

6.3.3 Water Colour and Manganese

Figure 6.9c shows the content of manganese (Mn) in samples analysed from the sites from Mar-Sept 2006 and illustrates the temporal and spatial variation between the sites during the monitoring period. Although manganese is a transition metal that is again found naturally within the geology and soils of the study site, it is most abundant in its soluble form Mn^{2+} and insoluble Mn^{4+}. The concentrations of manganese can have great seasonal variation, for example, the levels of manganese were much higher in Jul 2006 compared to May and Sept 2006 at all sites.

The mobility of manganese is particularly associated with the depletion of oxygen and the manganese compound Mn^{2+}. Transfer to its insoluble Mn^{4+} state is largely governed by oxidation and reduction actions during the redox process controlled by microbial and chemical actions (Nealson 1983). Similar in reaction to Fe^{2+}, the reduction of Mn^{4+} to Mn^{2+} will allow oxidation of Mn^{2+} when conditions are reduced and so discolour surface water supplies. Manganese is found in particularly high concentrations when these anaerobic ground water conditions prevail due to the greater residence times and oxygen-free conditions (Jaudon *et al* 1989) and this is likely to be the cause of high manganese observed during the summer at the sites when these conditions existed in summer 2006.

In addition, manganese is released into soil during mineral weathering and will enter surface waters through runoff processes when conditions permit the formation of the mobile Mn^{2+} state. Manganese therefore originates generally from diffuse near-surface soil sources with highest concentrations observed at high flows as a result of soil flushing (Neal *et al* 1996).

Table 6.11 and Figure 6.10c show that the relationship between manganese and true colour also varied between the sites. Doctors Gate Clough and Red Clough differed in response with a reasonable regression at Doctors Gate Clough (r^2 0.6425) and a poor regression at Red Clough (r^2 0.1235). However, at the remaining sites the relationship between manganese and true colour was inverse with poor negative regressions at Upper North Grain (r^2 0.2616), Upper Gate Clough (r^2 0.3713) and Within Clough (r^2 0.2748) and a reasonable inverse regression at Nether Gate Clough (r^2 0.6482).

Table 6.11: Ashop Catchments relationship between Manganese (mgl^{-1}) and True Colour (°H) Mar-Sept 2006

Site	Management	Mean Mn (mgl^{-1})	Indep Variable	Dependent Variable	Slope	Constant	N	r^2
Within Clough	Gullies blocked	3.3	Mn	True Colour	-38.1	268.08	11	0.2748
Nether Gate Clough	Cessation of burning	4.34	Mn	True Colour	-69.12	394.44	11	0.6482
Doctors Gate Clough	Removal of grazing	1.95	Mn	True Colour	81.83	72.86	11	0.6425
Upper North Grain	CONTROL	3.85	Mn	True Colour	-22.74	188.82	8	0.2616
Upper Gate Clough	CONTROL	2.94	Mn	True Colour	-64.21	307.4	11	0.3713
Red Clough	CONTROL	3.14	Mn	True Colour	8.82	105.8	11	0.1235

Previous researchers have found a relationship between runoff and Mn through the mixing of soil water and deep groundwater components associated with storm runoff particularly during the autumn (Reid *et al* 1981). However, Heal *et al* (2003) have also found high levels of Mn released during low baseflow conditions. In the current study Mn levels were particularly high during periods of low discharge on all sites, for example, at Upper North Grain the daily discharge on 23 Jul 2006 and 1 Sept 2006 was 26 ls^{-1} and 91 ls^{-1} whilst Mn levels were recorded as 6.2 mgl^{-1} and 1.9 mgl^{-1}. Similarly at Nether Gate Clough the mean daily discharge on the same dates was 9 ls^{-1} and 20 ls^{-1} whilst Mn levels were recorded at 5.7 mgl^{-1} and 3.0 mgl^{-1}, suggesting similar responses to that found by Heal *et al* (2003).

Figures 6.9a-d: Ashop Catchments Iron, Aluminium, Manganese (mgl^{-1}) and True Colour (°H) Mar-Sept 2006

Fig 6.9a: Iron (mgl^{-1}) Mar-Sept 2006

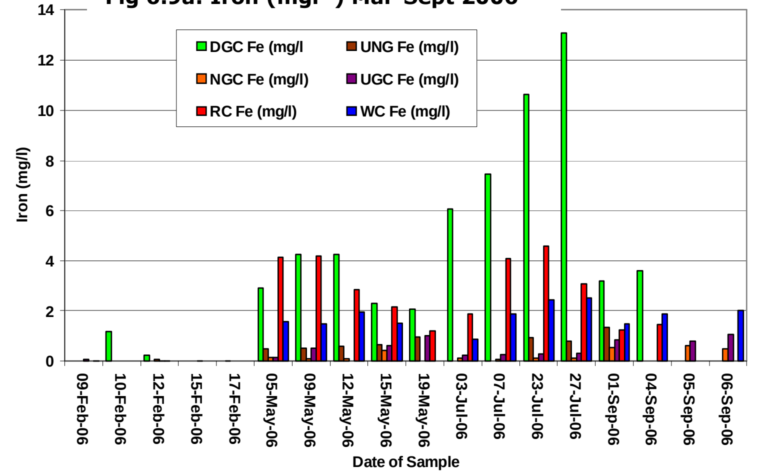


Fig 6.9b: Aluminium (mgl^{-1}) Mar-Sept 2006

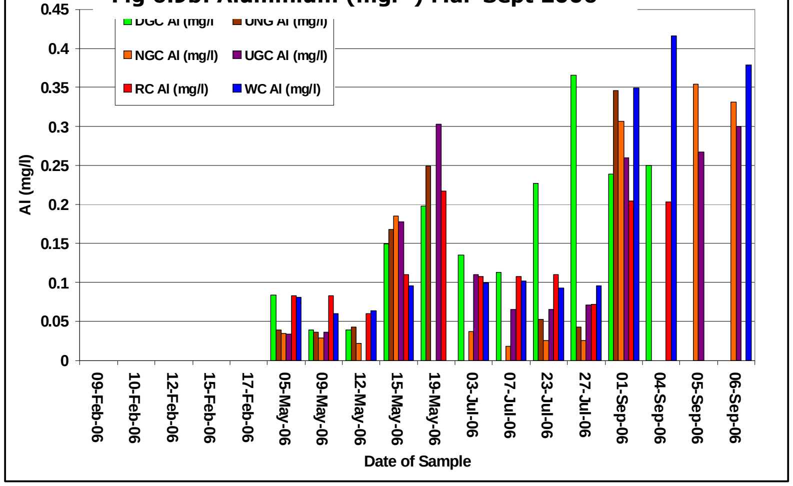


Fig 6.9c: Manganese (mgl^{-1}) Mar-Sept 2006

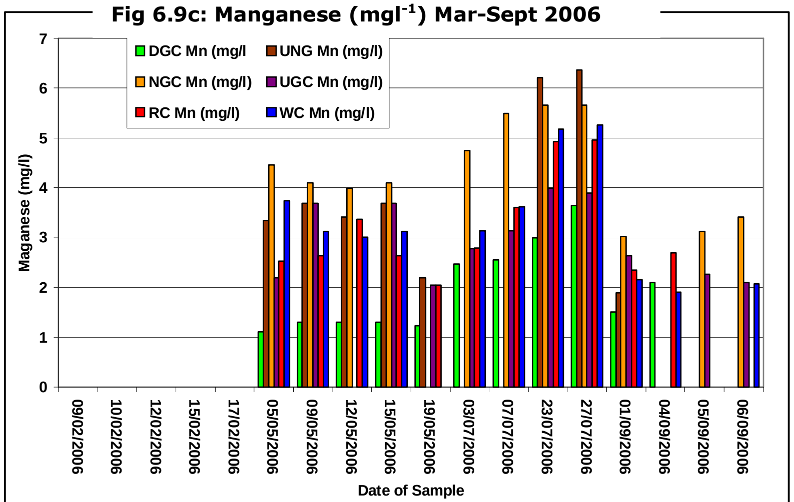
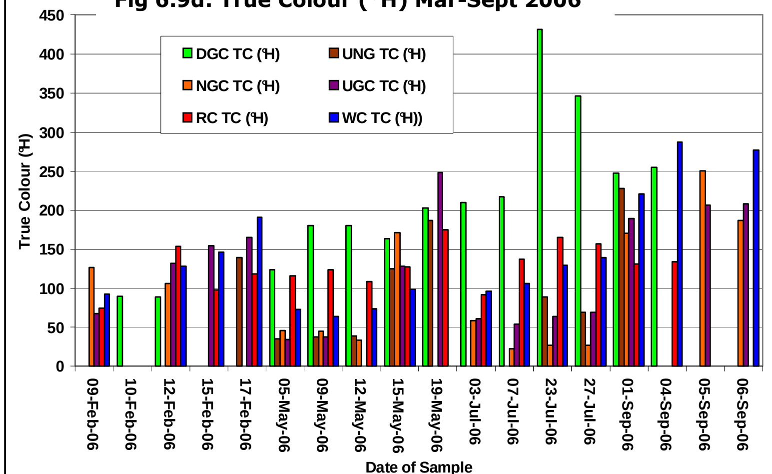


Fig 6.9d: True Colour (°H) Mar-Sept 2006



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

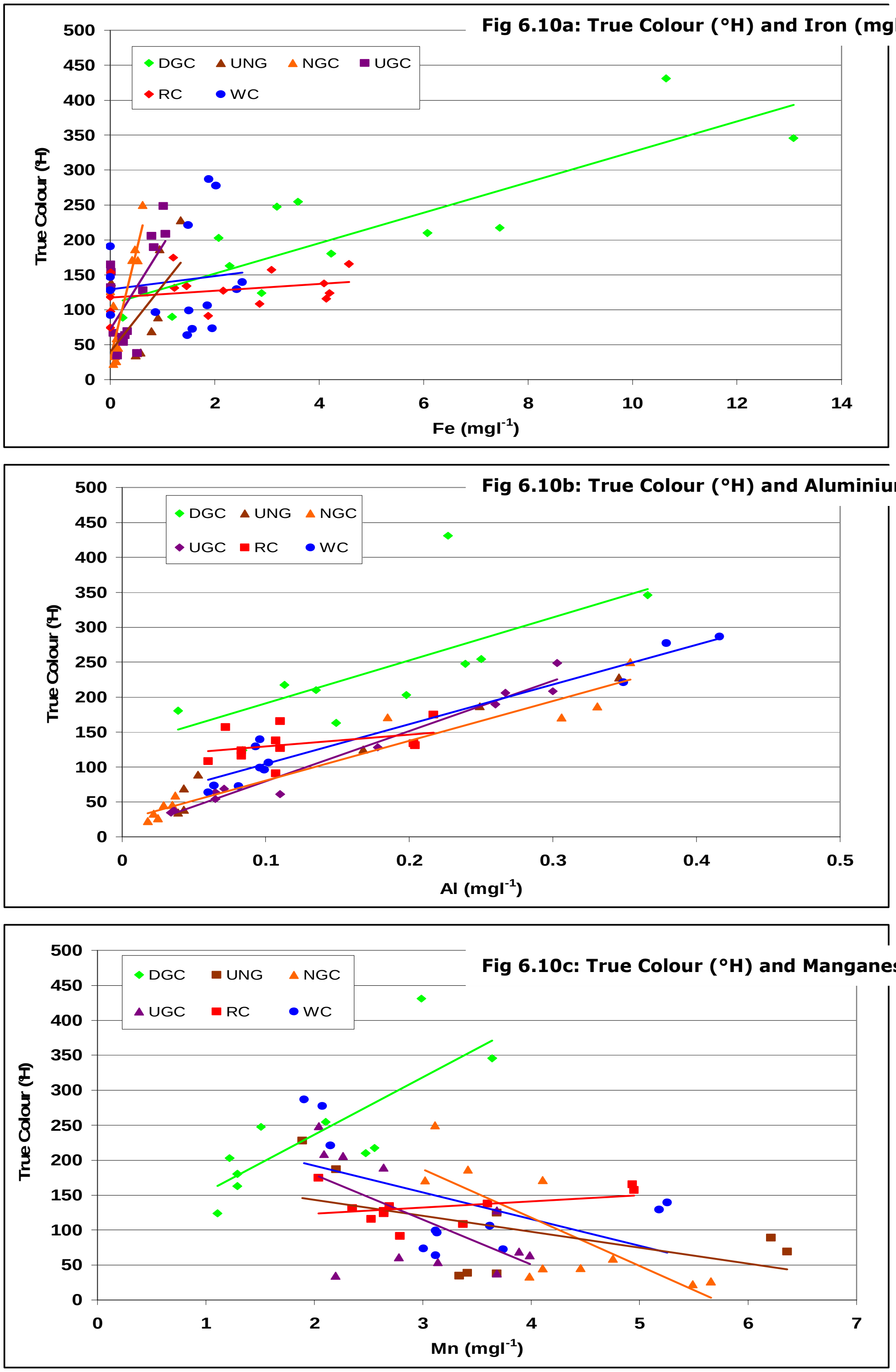
TC = True Colour

Fe = Iron

Al = Aluminium

Mn = Manganese

Figures 6.10a-c: Ashop Catchments Relationship between True Colour (°H) and Heavy Metals: Iron, Aluminium, Manganese (mgl^{-1}) a Mar-Sept 2006



6.3.4 Water Quality and Algae

The presence of floating algal mats was first observed at Doctors Gate Clough during Mar/Apr 2003 and resulted in a number of samples being analysed to determine its composition and potential to decrease water quality. Laboratory analysis by STL (Bridgend) found the following biological organisms to be present in a sample taken on 14 Oct 2003.

Diatoms:	*Bacillariophyta -Frustulia*	2785 cells.ml^{-1}
Green algae:	*Chlorphyta - Staurastrum*	81696 cells.ml^{-1}
Blue-green algae:	*Cyanobacteria - Oscillatoria*	92836 cells.ml^{-1}

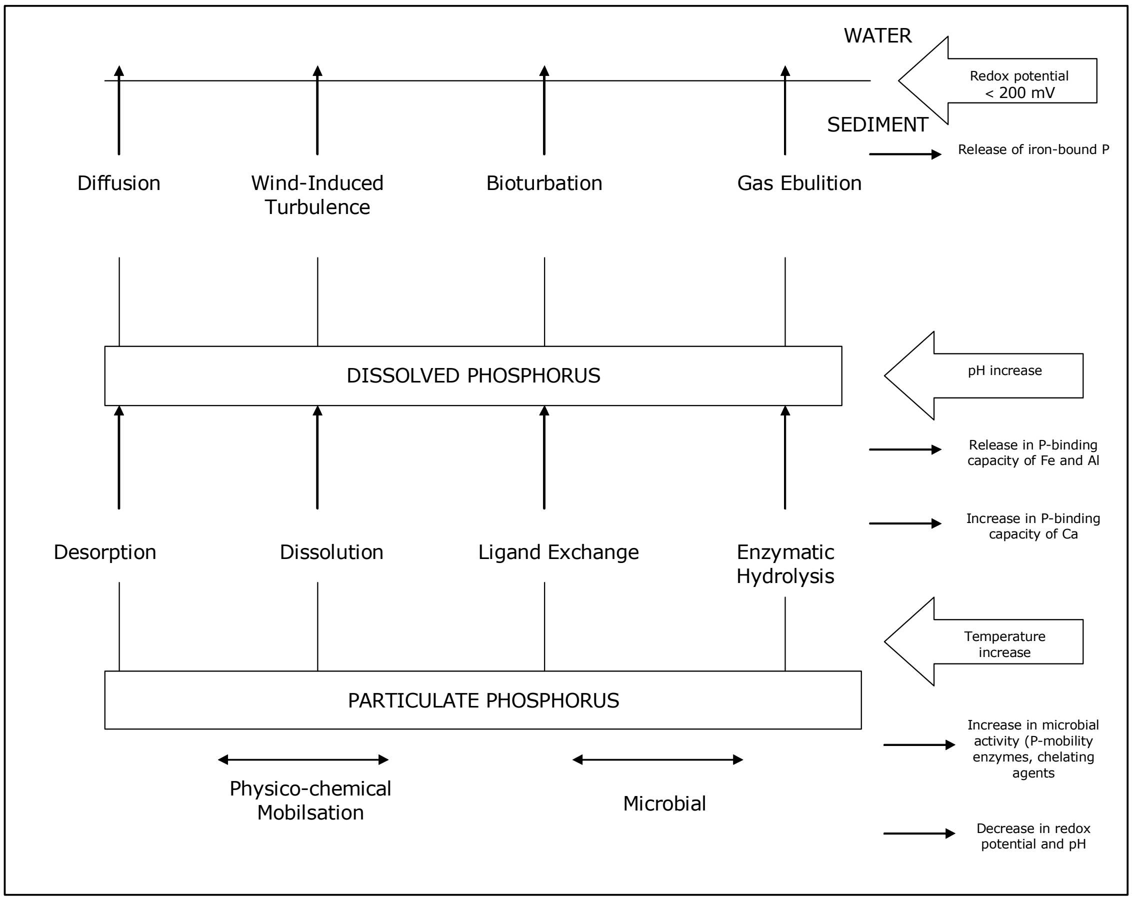
Further laboratory analysis on a sample collected in May 2004 was conducted by Helen Pickett, Principal advisor, Biology (Severn Trent Water plc). She reported the presence of free bacteria was very clear, but no evidence of the development of filamentous structures or any other biological activity. It was also noted the samples stained strongly for iron, but had no reaction for manganese, copper or lead. Figure 6.11 shows the algal mats and precipitated iron at Doctors Gate Clough during Jul 2006.

Figure 6.11: Algal mats and precipitated iron at Doctors Gate Clough, July 2006

Previous researchers, for example Meilli (1992) have also found high concentrations of phosphorous (P) in highly coloured humic waters, most of which occurs as inorganic orthophosphate (PO_3^{4-}). He found that the orthophosphate would only interact in the presence of ferrous iron (Fe^{2+}), both of which are associated with high molecular weight humic substances found in peat soils. Bostrom *et al* (1982) also found that the availability and mobilisation of total phosphorous from peat soils could be determined by the redox potential whereby Fe-bound P is released at potentials below 200 mv when Fe^{3+} is reduced to Fe^{2+}.

The acidity of soils and soil water has also been found to affect the availability of P with it readily precipitating as highly insoluble Fe or Al phosphates with optimum availability occurring between pH 5.5-6.5, decreasing at pH <4.5 or > 7 (Lucas and Davis 1961). Temperature increases associated with increased microbial activity (increasing biochemical oxygen demand (BOD) whilst decreasing redox potential and pH) have also been related to increasing P availability by producing phosphate-mobilising enzymes and chelating agents. Figure 6.12 shows these important processes and environmental factors affecting the release of phosphate.

Figure 6.12: Processes and Environmental Factors Affecting the Release of Phosphate in Water (adapted from Bostrom *et al* 1982)



The increase in P (which is normally a limiting factor in plant growth) and the cumulative effects of rises in temperature (higher pH caused by decreases in humic substances during the spring/summer) and rise in Biochemical oxygen demand (BOD - reducing microbial activity) as a result of a rise in plant growth and nutrient cycling, particularly observed at Doctors Gate Clough. The increase in nutrients created eutrophication resulting in algae and algal blooms during extreme eutrophic conditions which generally prevailed during warm climatic conditions when rainfall input and streamflow were low. The turbidity caused by a build-up of green algal matter and gelatinous mats was further exacerbated by the presence of particulated iron suspended in the water column released firstly by temperature increase and processes which reduced the P-binding capacity of Fe and Al, and secondly following an increase in pH which then released the iron-bound P and increased eutrophication (see Figure 6.11). The iron could not be removed during normal filtration water analysis, resulting in the high rates of water colour when the iron oxidised at Doctors Gate, Red Clough and Within Clough during the summer.

6.4 Short Term Variation in Water Quality

It was not possible to sample each catchment on an hourly basis over the four year study because of restrictions on resources, but for one season an effort was made to obtain hourly samples from two streams during storm events in order to obtain a detailed response. The two sites sampled were Within Clough (gullies blocked) and Upper Gate Clough (control). Two storm events have been selected from a series of twenty storms to illustrate the changes in water colour, discharge, pH and conductivity during and after a storm event. Storm 1 (from 12/11/2003 to 13/11/2003) and Storm 2 (from 8/5/2004 to 9/5/2004) illustrate the short-term response to a storm event. The characteristics of each storm are shown in Table 6.12 and the prevailing climatic conditions were considered to be similar at both sites due to their proximity. Table 6.13 shows the hydrological and hydrochemical catchment response to storms.

Table 6.12: Characteristics of Storm 1 (12/11 - 13/11/2003) and Storm 2 (8/5 – 9/5/2004)

Storm	Total rainfall (mm)	Rain duration (h)	7-day API (mm)	30-day API (mm)
1	10.4	6	3.8	58.8
2	5.6	22	33.2	98.4

Table 6.13: Hydrochemical and Hydrological Catchment Response to Storms

	WC Storm 1	WC Storm 2	UGC Storm 1	UGC Storm 2
Baseflow per km ($ls^{-1}km^{-1}$)	59	49	7	33
Peak Discharge per km ($ls^{-1}km^{-1}$)	210	82	140	46
Time to Peak (h)	1.5	3	4	4
Minimum Colour (°H)	85	176	49	148
Maximum Colour (°H)	225	262	204	248
Time to Maximum Colour (h)	3	5	4	5
Mean Colour (°H)	181	230	161	209
Minimum pH	3.78	4.52	3.63	4.29
Time to Minimum pH (h)	4	8	4	6
Maximum pH	5.62	5.33	6.13	5.89
Maximum Conductivity (μScm^{-1})	107	51	127	150
Time to Maximum Conductivity (h)	4	14	4	7
Minimum Conductivity (μScm^{-1})	63	42	58	45

The water sampler was automatically activated when the stage reached 0.1 m at Upper Gate Clough and 0.2 m at Within Clough, but the two storm events differed greatly both in their hydrological response to the rainfall event and subsequent discharge and hydrochemical composition following the on-set of the storm and the next 24 hours during which hourly water samples were automatically collected from each stream.

Table 6.13 and Figure 6.13 show that both catchments reacted in a similar way to the reasonably intense rainfall event (10.6 mm in 6 hours) during storm 1. The discharge increased rapidly, shown by the steep rising limb of the hydrograph and the water quality changed very quickly, reaching a peak in true colour, acidity and conductivity within 3 to 4 hours of the increase in discharge. These variables began to decrease as the discharge lessened, but the discharge had not returned to baseflow levels after 24 hours and the water quality parameters were also still higher on both catchments compared to those prior to the commencement of the storm. Table 6.13 and Figure 6.13 show the range of water quality, particularly water colour (e.g. 85-225 °H at Within Clough) during storm 1 and its change hour by hour.

Table 6.13 and Figure 6.14 show the different response to the small increase in rainfall intensity (5.6 mm in 22 hours) during storm 2. Table 6.12 shows the antecedent rainfall conditions prevailing at the sites during the previous 7 and 30 days before each storm. Storm 2 was clearly preceded by wet conditions so that baseflow prior to the rise in stage was already relatively high compared to conditions prior to storm 1 and only required a further small increase in stage to trigger the sampling mechanism. Nevertheless, despite the small and steady rise in discharge illustrated by the hydrographs in Figure 6.14, there was still an increase in true colour and acidity within 5 to 6 hours of the increase in discharge which returned to levels similar to those prior to the storm within 24 hours at Upper Gate Clough, but remained higher at Within Clough. Figure 6.14 again shows the range of water colour (e.g. 176-262 °H at Within Clough) during storm 2 and the hourly change as the colour, acidity and conductivity increased and then declined as the discharge subsided.

Figure 6.13: Hydrological and Hydrochemical Response to Storm 1 (11/11 - 12/11/2003) at Within Clough and Upper Gate Clough

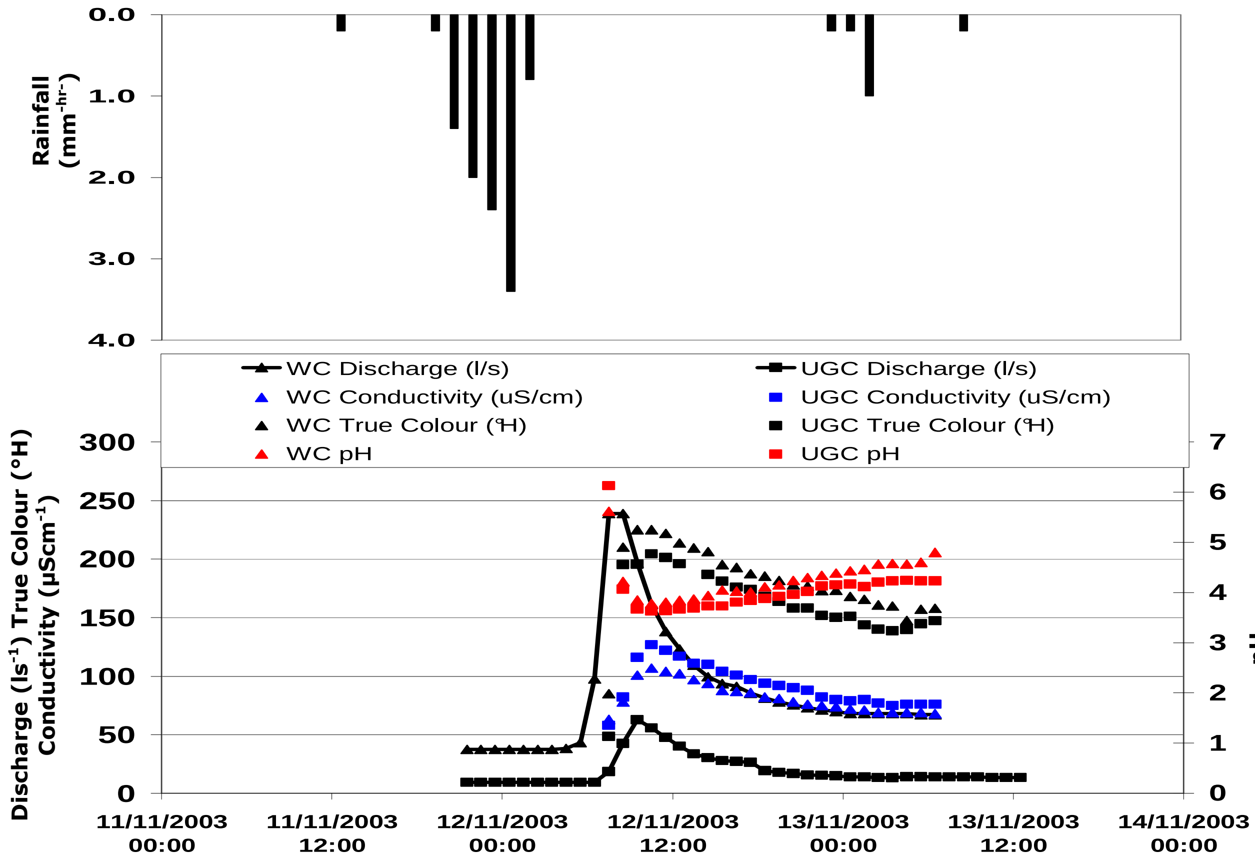
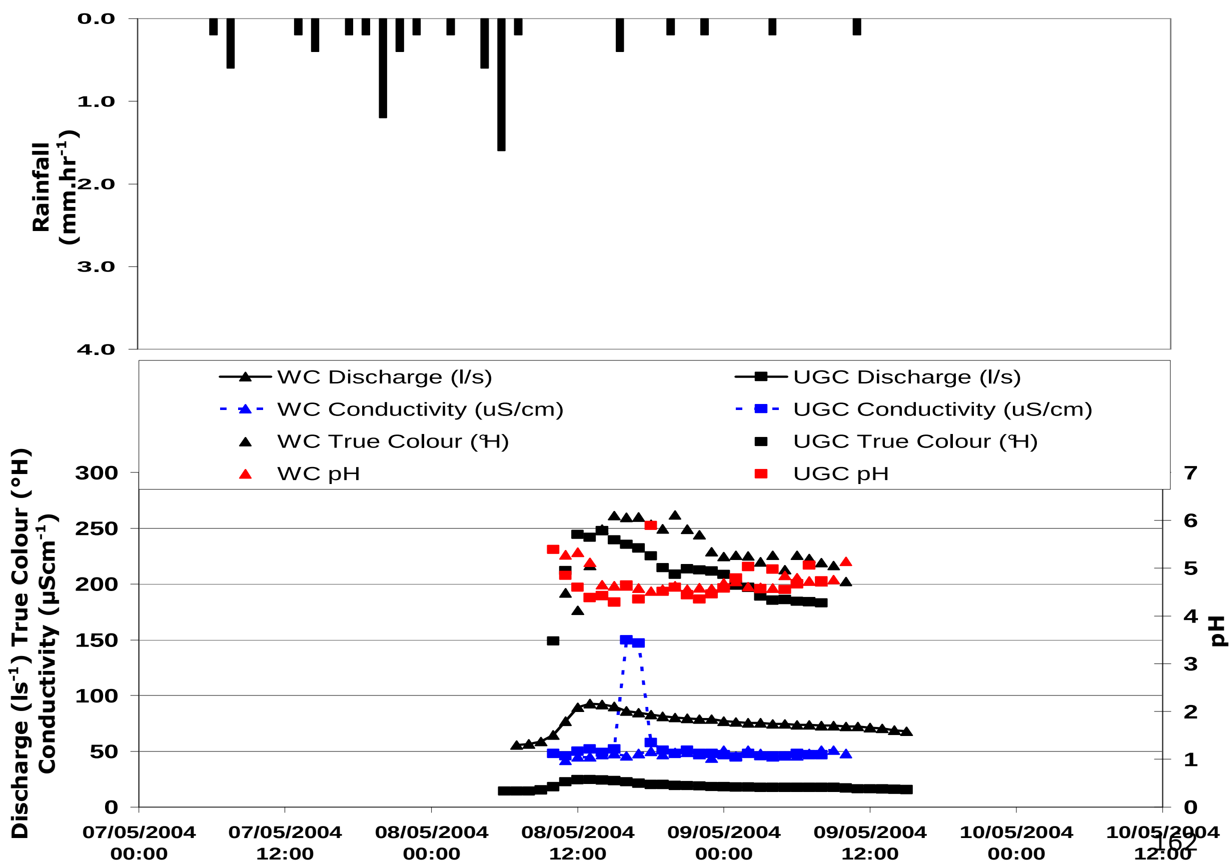


Figure 6.14: Hydrological and Hydrochemical Response to Storm 2 (8/5 - 9/5/2004) at Within Clough and Upper Gate Clough



Although these short-term changes are key to understanding the processes that occur, the demands on resources did not practically allow such intense sampling to be maintained for long periods and these limitations are discussed further in Section 10.3. The selected alternative hourly intake producing a single composite daily sample representative of water quality over 24 hours was chosen as a more viable option. A quality control check suggests that such a sampling strategy produced samples representative of change over 24 hours. For example, the mean true colour at Within Clough for storm 1 was 181 °H whilst the daily composite sample for the two days over which the storm and sampling occurred (12/11-13/11/2003) had true colour of 108 and 173 °H, and the mean true colour at Upper Gate Clough for storm 2 was 209 °H when the daily composite sample for 8/5-9/5/2004 was 187 and 150 °H. Although the daily composite sample values were both lower than the mean true colour during the storm event, the normal daily composite sample would also have included samples during baseflow and low flow when colour would typically be lower. The daily sample therefore appears representative of short-term changes occurring at the sites. The hourly changes seen during the storm events seem to be related to runoff and therefore there is a need to consider the hydrology of a catchment and its influence on water quality. These aspects are discussed in Chapter 7

6.5 Summary

The following points summarise the results and main observations in water colour and water quality made at the study sites during the four year monitoring period:

- All catchments showed a clear seasonal pattern of true colour which generally increased during the autumn/winter period when the humic and fulvic acids are flushed from the soils and decreasing again following the exhaustion of colour when saturation of soils is likely to dominate during the mid-late winter.

- Climatic influences on the generation of colour were noticeable: the "autumn flush" in the winter of Oct 2003-04 was lower than the preceding winter (2002-03) and succeeding winters (2004-05, 2005-06). This level of discolouration was largely controlled by prevailing climatic conditions which "stored" the water colour during the drier winter of 2003-04 and released it during late summer/autumn 2004. This elevated release of colour was caused by a prolonged period of drought, low rainfall and low water table levels creating aerobic conditions which promoted peat humification and subsequently high water colour on soils being rewet.

- The drought-period appeared to have triggered a longer-term response as colour levels in the winter of 2004-05 remained high. They showed some signs of recovery in 2005-06, although the concentrations of colour did not fall to the levels in winter 2002-03 prior to management manipulation. The data therefore show that true water colour increased on all of the catchments irrespective of any changes in land management during the period of study.

- There was no statistically significant difference in the mean, median and variance of monthly true colour between the calibration period (year 1 2002-03) and post management manipulation in year 2 (2003-04), year 3 (2004-05) and year 4 (2005-06) on all control catchments.
- There was a statistically significant rise in the mean, median and variance of monthly true colour between the calibration period (year 1 2002-03) and post management manipulation in year 3 (2004-05) at Within Clough (gullies blocked) and Nether Gate Clough (cessation of burning)

6.5.1 Gully Blocking and Water Colour

The significant rise in water colour at Within Clough (gullies blocked) in the third year may have been caused by the increased disturbance in the top aerobic layers of peat during the blocking and by the subsequent rise in the water table and flushing out of colour upon the catchment rewetting following completion of the blocking.

6.5.2 Cessation of Burning and Water Colour

The significant rise in water colour at Nether Gate Clough (cessation of burning) in the third year may also have resulted from the observed rise in water table levels, rewetting of soils and subsequent flushing of colour from previously aerobic peat layers. However, it is unclear if this significant rise was a short or long-term trend (the difference between year 1 and year 4 was not statistically significant).

6.5.3 Removal of Grazing and Water Colour

A significant rise in water colour at Doctors Gate Clough (removal of grazing) occurred during the summer of each year and chemical analysis showed samples contained large quantities of iron. During the winter months the catchment also discharged high colour associated with organic matter. The rise in iron may have been associated with the wetting/drying effects as depth to water table levels rose and fell, but it is unclear if this significant rise was a short or long-term trend (the difference between daily colour between year 1 and 2 was not significant, but was significant between year 1 and year 3 and year 4). However, difference in monthly mean colour (reducing effect of outliers of colour) was not statistically significant between any year at Doctors Gate Clough.

6.5.4 Heavy Metals and Water Colour

Analysis of Fe, Al, Mn showed that water quality varied temporally and spatially. Water colour at Doctors Gate Clough (removal of grazing) and Red Clough (control) were particularly discoloured during each summer when warm, dry conditions prevailed. The discolouration is likely to have been caused by iron oxidation ($Fe3+$), further exacerbated by the reducing effects of phosphates associated with iron and subsequent eutrophication resulting in abundant algal blooms and increased turbidity. Within Clough (gullies blocked) also had increased iron concentrations during the final year. Nether Gate Clough (cessation of burning) had low iron concentrations, but higher manganese associated with the geology of the catchment.

6.5.5 Short-term Variation in Water Quality

Hourly sampling during storm events showed the range of true colour, pH and conductivity on two catchment streams and demonstrated the rapid response to changes in discharge and resultant flushing of colour and variation in hydrochemical qualities. The increase in colour during these events was clearly related to runoff and this relationship and changes in response to land management manipulation is discussed in Chapter 7.

7 VARIABILITY IN CATCHMENT-SCALE RUNOFF AND DOC FLUX

7.1 Introduction

Previous researchers (e.g. Webster *et al* 1992, Elliott *et al* 1999, Burt 2001, Holden and Burt 2003) have acknowledged that land management manipulation may alter hydrological processes, water retention and the pathways of runoff from a catchment. Other workers have shown (e.g Mitchell and McDonald 1995) that one can manipulate water quality by catchment management. This is important in terms of changing not only water yield but also the flux of water colour, DOC and compounds from the uplands and the subsequent impact of these changes at the water treatment works in terms of additional treatment costs and potential health risks. The temporal and spatial changes during the study are discussed, particularly with regard to those changes associated with gully blocking, cessation of burning and removal of grazing as means of sustainable land management.

7.2 Area Specific Discharge

7.2.1 Measurement of Area Specific Discharge

Table 7.1 shows the change in discharge (ls^{-1}) resulting for each cm change of stage and the change in discharge per unit area ($ls^{-1}.km^{-2}$) for each catchment. The relatively large change in discharge per unit area for each cm stage at Doctors Gate Clough (catchment area 0.185 km^2) compared to Upper North Grain where the change in discharge per unit area was relatively small (catchment area 1.26 km^2) means that a 1 cm change in stage requires a relatively greater change in flow from each unit area at Doctors Gate Clough. The methodologies and determination of discharge rating equations are discussed in Section 4.6.2.1 and Figure 4.16 shows the differences between the catchments. The effect of the accepted level of error on observed changes in area specific discharge (ASQ) at each site is discussed in Section 7.2.3.

Table 7.1: Ashop Catchments Change in Discharge (ls^{-1}) for each Change in cm of Stage (m)

Catchment	Discharge Rating equation y = ls^{-1} X = stage in cm	N	r^2	Change in Q for each change in cm of stage (ls^{-1})	Change in Q per unit area ($ls^{-1}.km^{-2}$)
Doctors Gate Clough	y = 299.49x - 12.246	13	0.8974	2.99	16.46
Upper North Grain	y = 381.84x - 8.7081	17	0.7254	3.82	3.03
Nether Gate Clough	y = 199.47x - 19.102	15	0.6579	1.99	6.60
Upper Gate Clough	MISSING OR PROBLEM DATA				
Red Clough	y = 244.34x - 48.562	14	0.8252	2.44	4.40
Within Clough 1	y = 824.45x - 87.741	8	0.9914	8.24	7.24
Within Clough 2	y = 610.29x - 75.999	7	0.9577	6.10	5.36

7.2.2 Annual Area Specific Discharge

The area specific discharge (ASQ) is a measurement of the discharge per unit area of an upstream catchment and is of importance in terms of water supply and flood prediction in determining the volume of water that might be discharged from a particular catchment. Although discharge is a useful variable to compare changes in stream flow over time, it is difficult to make a spatial comparison and compare catchments of different sizes directly. This can be overcome by comparing the ASQ ($ls^{-1}.km^{-2}$) of each catchment.

A summary of the annual ASQ ($ls^{-1}.km^{-2}$) for each water year (Oct-Sept) is presented in Tables 7.2-7.5. These provide statistics for the mean, standard error mean, standard deviation, median, maximum and minimum ASQ for the six catchments in the study. The tables show that the ASQ is related to the size of the catchment and the data show that the larger catchments generally have a lower ASQ, whilst the smaller catchment (Doctors Gate Clough and Nether Gate Clough) have the largest ASQ.

Table 7.2 shows ASQ during the calibration period (Oct 2002-Sept 2003) prior to changes in land management, whilst Tables 7.3-7.5 present data post management intervention. The descriptive statistics for monthly data are in Appendix XI. Data for Upper Gate Clough post management are not presented because of the high number of days when data were not recorded or equipment malfunctioned when inaccurate data were recorded. Similarly data for Doctors Gate Clough are not presented for water year Oct 2005-Sept 2006.

The result of most interest was that all the catchments with the exception of Within Clough and Doctors Gate Clough showed a statistically significant rise in the median and mean ASQ levels between calibration year 1 (2002-03) and treatment year 2 (2003-04) ($p < 0.01$). This is perhaps not surprising at Upper North Grain, Red Clough, and Nether Gate Clough as the ASQ levels caused by the prevailing drought conditions in the first water year (2002-03) and numbers of days when no rain was recorded discussed in Section 5.2.3, differed from the subsequent years when rainfall was higher resulting in increased discharge rates.

Table 7.2: Ashop Catchments Annual Statistics of Daily Area Specific Discharge ($ls^{-1}km^{-2}$) Oct 2002-Sept 2003

Variable	N	N*	Mean	SE	St Dev	Minimum	Median	Maximum
DGC	335	30	39.37	2.27	41.54	0	23.48	202.74
UNG	355	10	23.417	0.941	17.734	4.6	15.38	92.19
NGC	355	10	36.75	0.767	14.457	21.18	31.14	102.51
UGC	343	21	31.88	1.11	20.47	7.65	23.73	111.91
RC	354	11	23.14	1.29	24.25	0	13.23	105.49
WC	360	5	24.75	1.23	23.28	0	15.35	107.26

Table 7.3: Ashop Catchments Annual Statistics of Daily Area Specific Discharge ($ls^{-1}km^{-2}$) Oct 2003-Sept 2004

Variable	N	N*	Mean	SE	St Dev	Minimum	Median	Maximum
DGC	366	0	33.72	2.11	40.43	0	18.58	244.02
UNG	366	0	33.366	0.998	19.091	6.73	28.79	118.41
NGC	348	18	42.997	0.831	15.495	27.2	38.015	126.82
UGC	MISSING OR PROBLEM DATA							
RC	365	1	37.24	1.18	22.46	4.53	33.65	160.83
WC	366	0	24.68	1.04	19.91	0	18.52	134.73

Table 7.4: Ashop Catchments Annual Statistics of Daily Area Specific Discharge ($ls^{-1}km^{-2}$) Oct 2004-Sept 2005

Variable	N	N*	Mean	SE	St Dev	Minimum	Median	Maximum
DGC	332	33	36.68	2.18	39.76	0	23.45	328.24
UNG	363	2	27.249	0.928	17.68	7.64	21.45	145.65
NGC	354	11	38.399	0.658	12.38	24.91	34.365	144.75
UGC	MISSING OR PROBLEM DATA							
RC	365	0	26.74	1.08	20.59	0.42	22.33	162.11
WC	341	24	19.028	0.953	17.597	0	13.86	136.46

Table 7.5: Ashop Catchments Annual Statistics of Daily Area Specific Discharge ($ls^{-1}km^{-2}$) Oct 2005-Sept 2006

Variable	N	N*	Mean	SE	St Dev	Minimum	Median	Maximum
DGC	MISSING OR PROBLEM DATA							
UNG	358	6	34.555	0.974	18.425	11.29	27.81	113.92
NGC	333	31	38.801	0.861	15.709	24.14	33.51	187.26
UGC	MISSING OR PROBLEM DATA							
RC	364	0	32.95	1.16	22.21	2.84	28.75	147.43
WC	330	34	27.92	1.21	22	0	25.78	124.36

KEY

DGC = Doctors Gate Clough
UNG = Upper North Grain
NGC = Nether Gate Clough
UGC = Upper Gate Clough
RC = Red Clough
WC = Within Clough

ASQ = Area Specific Discharge
N = number of days with data
N* = number of days with missing data

Figure 7.1: Ashop Catchments Annual Mean of Daily Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006

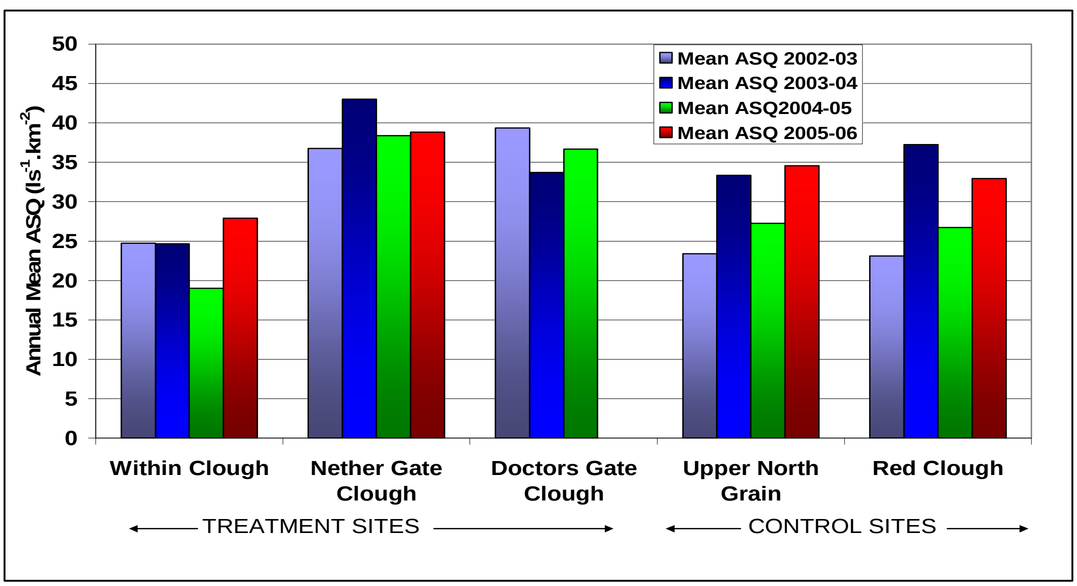
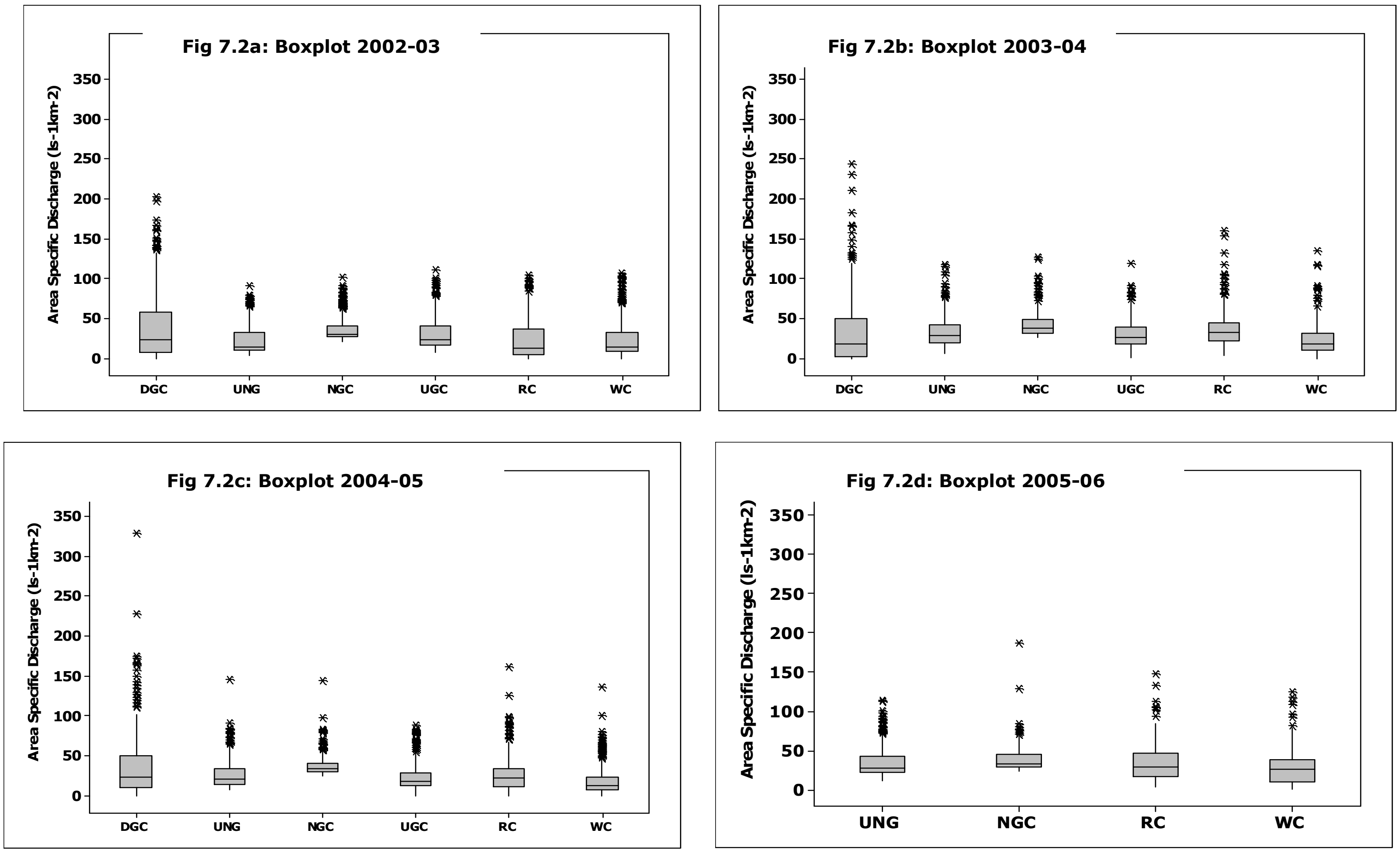


Figure 7.1 demonstrates the temporal and spatial range of annual mean runoff from the catchments and suggests that ASQ increased at Nether Gate Clough, Upper North

Grain and Red Clough in the second year, decreased in the third year and increased again in the fourth year. However, annual runoff at Within Clough (gullies blocked) was similar in the first and second year, before decreasing in the third year and increasing in the fourth year. At Doctors Gate Clough (removal of grazing) the runoff appeared to have decreased in the second year and then increased in the third year. This pattern of annual data may be too simplistic when trying to determine changes which may have been caused by land management manipulation, therefore daily and monthly ASQ were examined and are discussed in Sections 7.2.3 and 7.2.5. The box plots in Figures 7.2a-d demonstrate the range of mean ASQ for each study site with Doctors Gate Clough clearly having the largest range of ASQ in each water year and Nether Gate Clough the smallest range of ASQ. All the catchments had a number of outliers indicating high ASQ and rapid response on days associated with storm events.

Figure 7.2a-d: Ashop Catchments Boxplots of Daily Mean Area Specific Discharge ($ls^{-1}.km^{2}$) Oct 2002 – Sept 2006



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

TC = True Colour

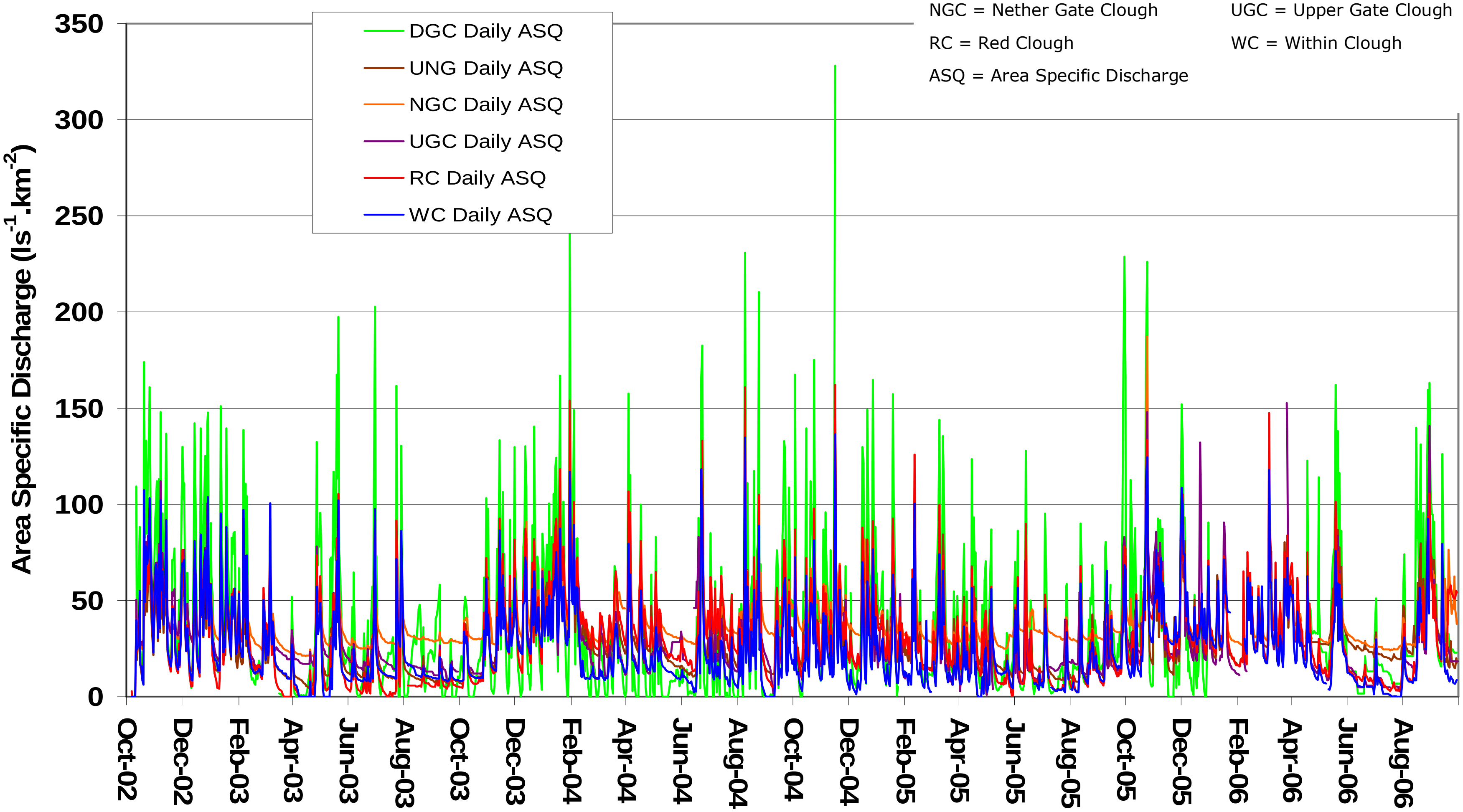
7.2.3 Daily Area Specific Discharge

Figure 7.3 presents daily ASQ and shows that all the catchments had a rapid discharge response to rainfall events resulting in a typical "flashy" hydrograph with steep rising and falling limbs. In addition, there was a clear temporal pattern in ASQ with a rise during the autumn/winter months caused by the rewetting of the catchments, increased rainfall and subsequent rise in runoff through both surface and sub-surface flow. During spring/summer there was a general reduction in ASQ when rainfall was lower in magnitude, resulting in a lowering of the water table and a change in hydrological processes that contributed to the ASQ, for example, an increase in the percentage contribution of baseflow to the total flow as water slowly drained from the catchment as the soils dried out.

Figure 7.3 also shows the spatial range of ASQ in response to each rainfall event. For example, Doctors Gate Clough had higher peaks than the other catchments, suggesting that there was relatively little water being stored on Doctors Gate Clough during these events. The maximum ASQ at Doctors Gate Clough was 244 $ls^{-1}.km^{-2}$ during the second water year Oct 2003-Sept 2004, compared to the much larger catchments of Upper North Grain and Within Clough where the maximum ASQ was 118 $ls^{-1}.km^{-2}$ and 135 $ls^{-1}.km^{-2}$ for the same period.

There were also differences in the spatial and temporal distribution of daily ASQ between water years. Figures 7.4a–d show the daily ASQ distribution for each catchment between the water years Oct 2002-Sept 2006 and show the data are generally not normally distributed. The figures demonstrate the frequency of low ASQ which caused a skewed distribution on all the catchments. This is not unusual in an upland catchment as the majority of ASQ will be made up of baseflow and discharge from small storm events with only a small percentage of daily flows exceeding the mean (Vogel *et al* 2003). However, the distribution at Doctors Gate Clough (removal of grazing) was less skewed indicating the greater range and frequency of high ASQ during each water year. Nether Gate Clough (cessation of burning) had a negatively skewed frequency distribution with a predominance of ASQ at a range of 30-35 $ls^{-1}.km^{-2}$. This was likely to be the ASQ rate during baseflow conditions which continued to be higher than the remaining catchments, particularly during the periods of low rainfall, for example, Mar-Apr 2003, and reflects the stage levels maintained in the pool area of the stream throughout the year.

Figure 7.3: Ashop Catchments Daily Area Specific Discharge ($ls^{-1}km^{-2}$) Oct 2002-Sept 2006



KEY

DGC = Doctors Gate Clough

NGC = Nether Gate Clough

RC = Red Clough

ASQ = Area Specific Discharge

UNG = Upper North Grain

UGC = Upper Gate Clough

WC = Within Clough

Figure 7.4a-d: Daily ASQ ($ls^{-1}km^{-2}$) Distribution Oct 2002–Sept 2006

Fig 7.4a: Daily ASQ ($ls^{-1}km^{-2}$) Distribution 2002-03

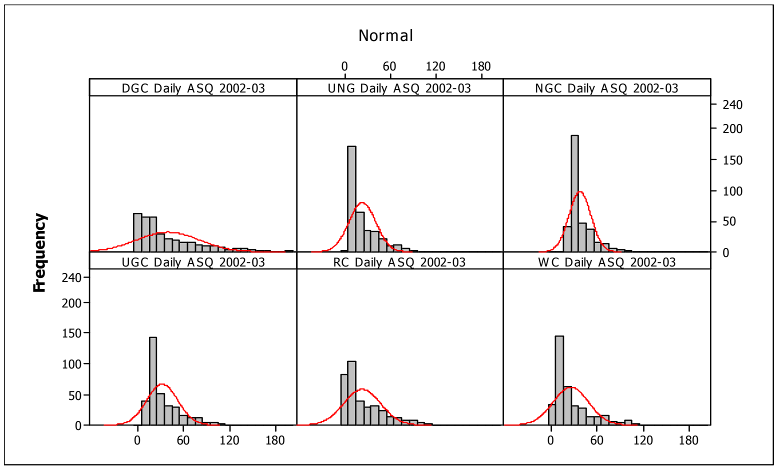


Fig 7.4b: Daily ASQ ($ls^{-1}km^{-2}$) Distribution 2003-04

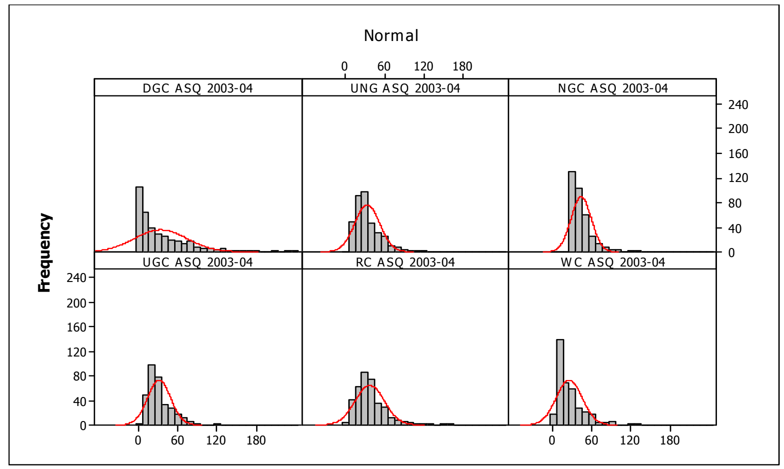


Fig 7.4c: Daily ASQ ($ls^{-1}km^{-2}$) Distribution 2004-05

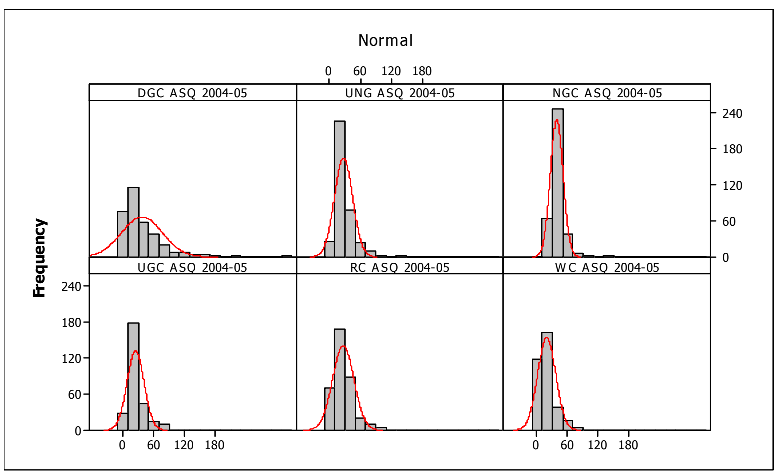
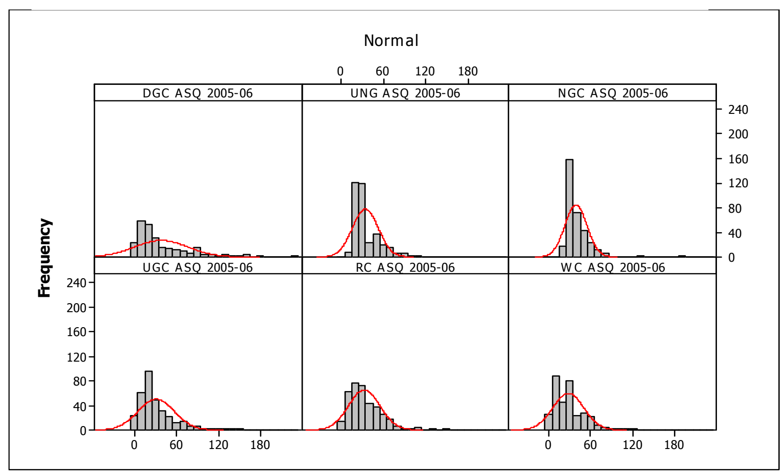


Fig 7.4d: Daily ASQ ($ls^{-1}km^{-2}$) Distribution 2005-06



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

ASQ = Area Specific Discharge

Statistical analysis of daily ASQ ($ls^{-1}.km^{-2}$) data was completed to determine if the character or distribution of the ASQ had changed as a result of the management changes. Mann Whitney U and Kolmogorov Smirnov tests were chosen to compare the medians and distributions of the annual datasets of years 2, 3 and 4 with year 1 for each catchment, that is, the pre-management calibration period (year 1) against each post-management year. A one-way ANOVA was used to test the differences in the variance of discharge between the water years at each site. The results are presented in Table 7.6 and discussed in Sections 7.2.3.1-7.2.3.4.

Table 7.6: Statistical Analysis of Daily Mean Area Specific Discharge ($ls^{-1}km^{-2}$) Ashop Catchments Oct 2002-Sept 2006 (comparison of subsequent years with control year 2002-03)

Variable	N	Median	Mean	Mann Whitney U Probability p value	Kolmogorov Smirnov Probability p value	ANOVA p value	F value
DGC ASQ ($ls^{-1}km^2$) 2002 -03	335	23.48	39.37				
DGC ASQ ($ls^{-1}km^2$) 2003-04	366	18.58	33.72	0.011*	<0.01**	0.069	3.32
DGC ASQ ($ls^{-1}km^2$) 2004-05	332	23.45	36.68	0.888	<0.01**	0.394	0.73
DGC ASQ ($ls^{-1}km^2$) 2005-06	256	23.86	38.27	MISSING OR PROBLEM DATA			
UNG ASQ ($ls^{-1}km^2$) 2002-03	355	15.38	23.42				
UNG ASQ ($ls^{-1}km^2$) 2003-04	366	28.79	33.37	<0.01**	<0.01**	<0.01**	52.48
UNG ASQ ($ls^{-1}km^2$) 2004-05	363	21.45	27.25	<0.01**	<0.01**	0.004**	8.4
UNG ASQ ($ls^{-1}km^2$) 2005-06	330	25.78	34.55	0.037*		<0.01**	67.61
NGC ASQ ($ls^{-1}km^2$) 2002-03	355	31.4	36.75				
NGC ASQ ($ls^{-1}km^2$) 2003-04	348	38.02	43.0	<0.01**	<0.01**	<0.01**	30.56
NGC ASQ ($ls^{-1}km^2$) 2004-05	354	34.37	38.4	<0.01**	<0.01**	0.103	2.66
NGC ASQ ($ls^{-1}km^2$) 2005-06	333	33.51	38.8	0.0061**	<0.01**	0.075	3.18
UGC ASQ ($ls^{-1}km^2$) 2002-03	343	23.73	31.88				
UGC ASQ ($ls^{-1}km^2$) 2003-04	326	27.25	31.27	MISSING OR PROBLEM DATA			
UGC ASQ ($ls^{-1}km^2$) 2004-05	277	18.35	24.22	MISSING OR PROBLEM DATA			
UGC ASQ ($ls^{-1}km^2$) 2005-06	327	23.58	31.13	MISSING OR PROBLEM DATA			
RC ASQ ($ls^{-1}km^2$) 2002-03	354	13.23	23.14				
RC ASQ ($ls^{-1}km^2$) 2003-04	365	33.65	37.24	<0.01**	<0.01**	<0.01**	65.5
RC ASQ ($ls^{-1}km^2$) 2004-05	365	22.33	26.74	<0.01**	<0.01**	0.032*	4.62
RC ASQ ($ls^{-1}km^2$) 2005-06	364	28.75	32.95	<0.01**	<0.01**	<0.01**	31.99
WC ASQ ($ls^{-1}km^2$) 2002-03	360	15.35	24.75				
WC ASQ ($ls^{-1}km^2$) 2003-04	366	18.52	24.68	0.118	<0.01**	0.964	0
WC ASQ ($ls^{-1}km^2$) 2004-05	341	13.86	19.03	0.002*	<0.01**	<0.01**	13.39
WC ASQ ($ls^{-1}km^2$) 2005-06	330	25.76	27.92	0.0079**	<0.01**	0.067	3.36

** indicates significance p <0.01   * indicates significance p <0.05

KEY

DGC = Doctors Gate Clough
UGC = Upper Gate Clough
UNG = Upper North Grain
RC = Red Clough
NGC = Nether Gate Clough
WC = Within Clough

ASQ = Area Specific Discharge

7.2.3.1 Control Catchments and Daily ASQ

The differences in the median, mean of daily ASQ ($ls^{-1}.km^{-2}$) at Upper North Grain (control) and Red Clough (control) were highly significant between the first water year (2002-03) and the subsequent water years, 2003-04, 2004-05 and 2005-06 ($p < 0.001$). These changes are likely to have resulted from changing rainfall patterns between year 1 and the subsequent years and show that there was a large increase in 2003-04 and 2005-06, but a smaller increase in 2004-05. The observed changes in ASQ between each water year at both sites were outside the accepted error so represent 'real' changes likely to have resulted from changes in climate as land management remained unaltered on these sites throughout the study. The changes in year 2 and year 3 were larger than those observed at the treatment sites.

7.2.3.2 Within Clough (Gullies Blocked) and Daily ASQ

At Within Clough (where gullies were blocked in Dec 2003) the mean ASQ was very similar in year 2 to the calibration year (~25 $ls^{-1}.km^{-2}$) and the difference was statistically insignificant ($p = 0.964$) despite the catchment being subject to the same climatic conditions as the control catchments where ASQ increased significantly. The results suggest that the gully blocking had successfully retained water on the catchment in the second year. In the subsequent years, year 3 (2004-05) and year 4 (2005-06) there were significant differences from year 1 ASQ at Within Clough as the ASQ firstly significantly decreased in the third year and then increased in the final year. This may have been caused by changing hydrological conditions and runoff regime on the catchment by the gully-blocking which succeeded in raising water table levels and subsequently increased the surface and sub-surface flow from the catchment, thereby raising ASQ levels once again. These changes were statistically significant (see Table 7.6) and the observed changes in daily ASQ were a decrease of ~6 $ls^{-1}.km^{-2}$ (2003-04 to 2004-05) and an increase of ~9 $ls^{-1}.km^{-2}$ (2004-05 to 2005-06). These values are not within the accepted error of 5.36 $ls^{-1}.km^{-2}$ (see Table 7.1) and this suggests the change was a real effect and likely to have resulted from the gully-blocking and not just change in climate conditions between years. The consequences of these changes in terms of water yield and DOC flux are discussed in Chapter 9.

7.2.3.3 Nether Gate Clough (Cessation of Burning) and Daily ASQ

Nether Gate Clough (where the normal burning regime was changed in autumn 2003) also showed a significant difference in median ASQ between year 1 and year 2 (2002-03 and 2003-04) ($p < 0.01$) which was likely to have been influenced by the climatic changes already discussed. The differences in the mean discharges for the subsequent years were more complex with differences in year 3 not significant and year 4 only very weakly significant ($p = 0.075$). The difference between year 1 and year 4 amounted to an observed increase in ASQ of ~ 2 $ls^{-1}.km^{-2}$. This falls within the accepted error level of 6.6 $ls^{-1}.km^{-2}$ (see Table 7.1) and therefore it is difficult to infer whether this is a real change. The fact that flow did not increase, as it did on the control catchments means that this may reflect a significant change as a result of land management. The consequences of such changes are discussed in Chapter 9.

7.2.3.4 Doctors Gate Clough (Removal of Grazing) and Daily ASQ

A reduction in runoff in year 2 at Doctors Gate Clough appeared to have occurred because of prolonged periods of low flow when water stage levels were particularly low. A change in stage of 0.01 m at this catchment equates to a change in discharge of 2.99 ls^{-1} (ASQ 16.49 $ls^{-1}.km^{-2}$) (see Table 7.1). On the removal of grazing, the difference in median ASQ between year 1 and 2 (2002-03 and 2003-04) was found to be statistically significant ($p = 0.011$) but the reduction in daily mean discharge was only from 7.28 ls^{-1}-6.24 ls^{-1}, and equated to a reduction in ASQ of 5.65 $ls^{-1}.km^{-2}$. Therefore, because of the potential error of 0.01 m in water stage levels on this catchment, it was difficult to determine if the reduction in ASQ resulted from the change in land management or from a mechanical error during the logging of stage levels.

In addition, the differences in discharge in subsequent years (Year 3 and year 4 when compared to year 1) may have resulted from different sample numbers between the years and the amount of missing data represented as N*. For example, Doctors Gate Clough had 108 days when no data were recorded in year four (2005-06) which occurred during one block period between Jan-Apr 2006 as a result of equipment failure and a prolonged period of no access to the site due to road closures in poor weather. Therefore it is difficult to infer that differences may have resulted from changes in land management. To minimise the effects of these periods of missing data, the monthly mean ASQ for each catchment was considered and is discussed in the next section.

7.2.4 Relationship between Daily True Colour and Daily Area Specific Discharge

The relationship between daily true colour (°H) and daily ASQ ($ls^{-1}km^{-2}$) was examined to identify changes between pre and post-management manipulation on individual catchments and also any differences between the treated sites and the control sites. Table 7.7 shows the correlation (Pearson's r), level of significance and r^2 between daily true colour and ASQ at each site for each water year.

The analysis indicates that there was a strong positive relationship between true colour and ASQ at Within Clough (gullies blocked), Nether Gate Clough (cessation of burning) and Upper North Grain (control) which remained highly significant

($p < 0.001$) throughout the study period. In contrast the relationships between the variables at Doctors Gate Clough (removal of grazing) and Red Clough (control) were poor negative correlations in 2002-03, 2004-05 and 2005-06 which suggest that water colour was generally higher when ASQ levels were low.

Table 7.7 Relationship between Daily True Colour (°H) and Daily Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006

Variable	N	Pearsons r	p	r^2
DGC TC & ASQ 2002-03	241	-0.052	0.442	0.0027
DGC TC & ASQ 2003-04	238	0.093	0.151	0.009
DGC TC & ASQ 2004-05	232	-0.084	0.228	0.007
DGC TC & ASQ 2005-06	251	-0.017	0.851	0
UNG TC & ASQ 2002-03	273	0.533	<0.001**	0.284
UNGTC & ASQ 2003-04	252	0.385	<0.001**	0.148
UNG TC & ASQ 2004-05	243	0.317	<0.001**	0.101
UNG TC & ASQ 2005-06	226	0.457	<0.001**	0.209
NGC TC & ASQ 2002-03	309	0.64	<0.001**	0.409
NGC TC & ASQ 2003-04	265	0.424	<0.001**	0.18
NGC TC & ASQ 2004-05	267	0.387	<0.001**	0.15
NGC TC & ASQ 2005-06	286	0.514	<0.001**	0.264
RC TC & ASQ 2002-03	282	0.117	0.05	0.014
RC TC & ASQ 2003-04	255	0.089	0.159	0.008
RC TC & ASQ 2004-05	255	-0.216	<0.001**	0.046
RC TC & ASQ 2005-06	201	-0.094	0.185	0.009
WCTC & ASQ 2002-03	322	0.578	<0.001**	0.335
WC TC & ASQ 2003-04	241	0.27	<0.001**	0.073
WC TC & ASQ 2004-05	260	0.294	<0.001**	0.086
WC TC & ASQ 2005-06	262	0.507	<0.001**	0.257

** indicates significance $p < 0.01$ * indicates significance $p < 0.05$

Figures 7.5a-e illustrate the similarity between daily true colour and ASQ at each site, that is, daily true colour generally mirrored the short-term peaks in discharge associated with storm events, but also demonstrated a seasonal pattern of colour, with higher levels occurring during autumn/winter at Within Clough, Nether Gate Clough and Upper North Grain. Figures 7.6a and 7.6d show that the pattern at Doctors Gate Clough and Red Clough was different with high colour levels also occurring during periods of low discharge, particularly during the spring/summer and additional spikes of high colour in autumn/winter with higher discharge levels. This suggests that colour was being generated from two distinct sources at Doctors Gate Clough and Red Clough and supports previous findings of high colour associated with iron oxidation in spring/summer and dissolved organic matter discolouring water in the autumn/winter (see Section 6.3).

Figures 7.5ae: Ashop Catchments Daily True Colour (°H) and Daily Mean ASQ ($ls^{-1}.km^{-2}$)

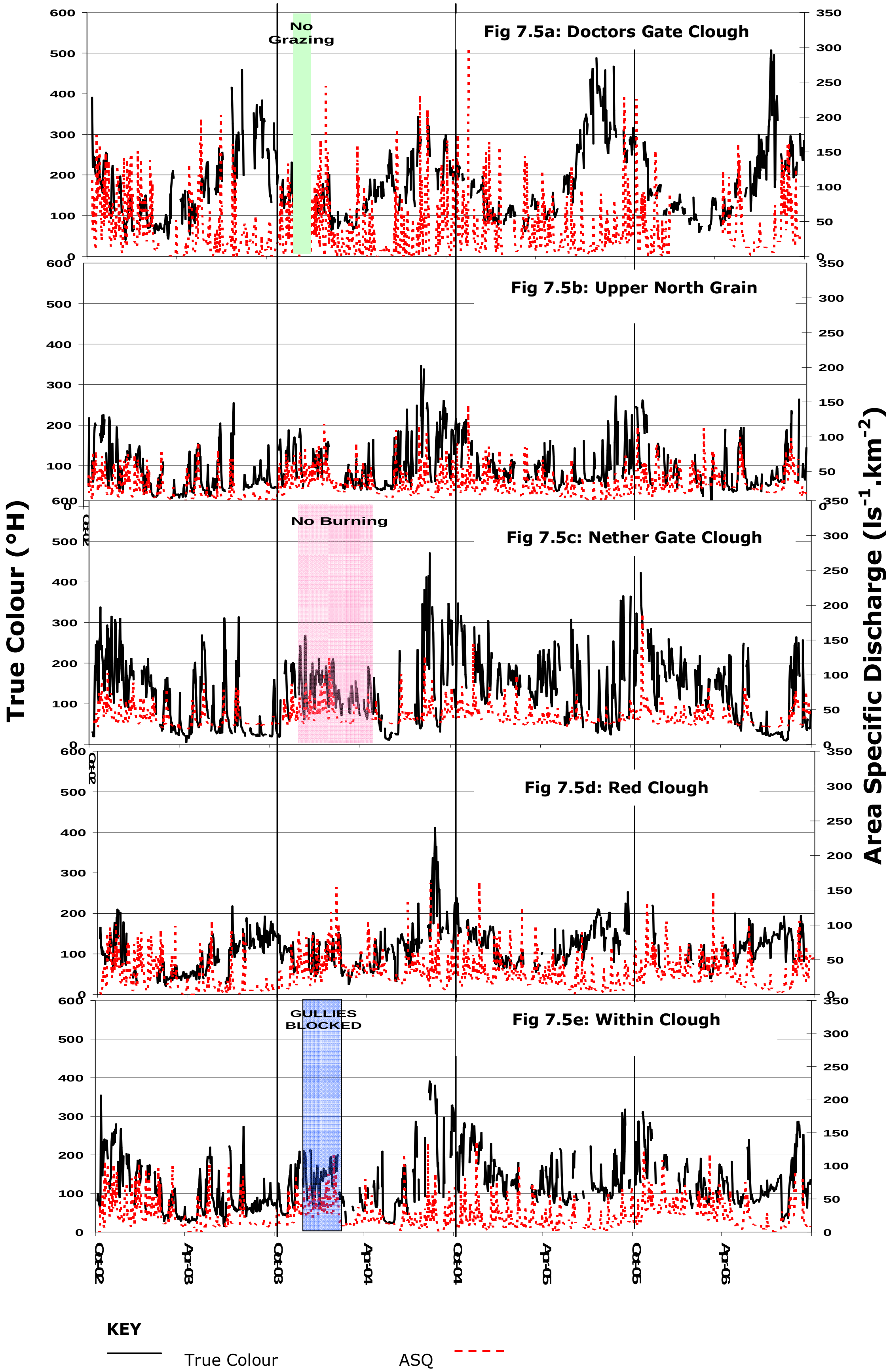
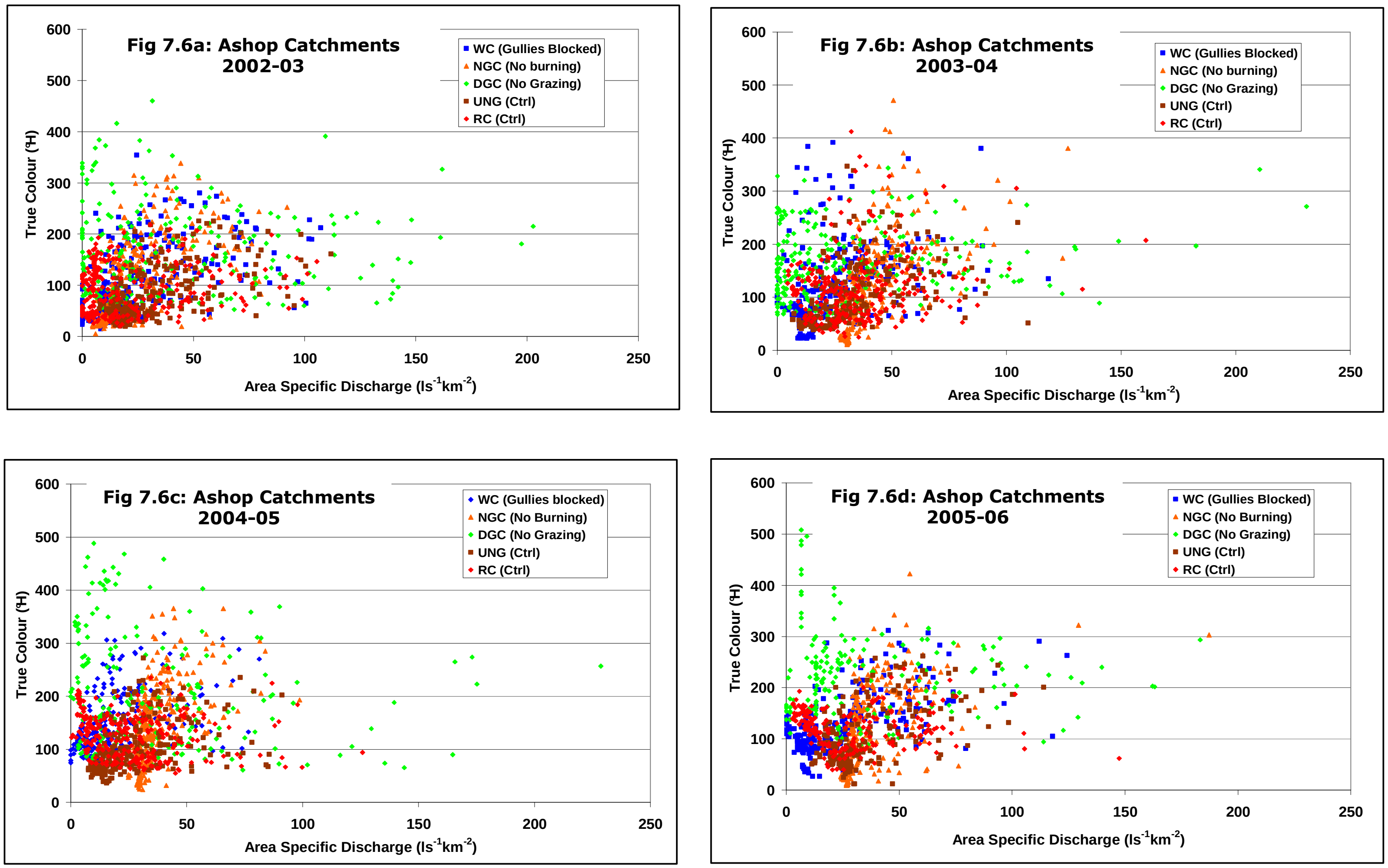


Figure 7.6a-d: Ashop Catchments Relationship between True Colour (°H) and Area Specific Discharge ($ls^{-1}.km^{-2}$)



KEY

DGC = Doctors Gate Clough

UNG = Upper North Grain

NGC = Nether Gate Clough

UGC = Upper Gate Clough

RC = Red Clough

WC = Within Clough

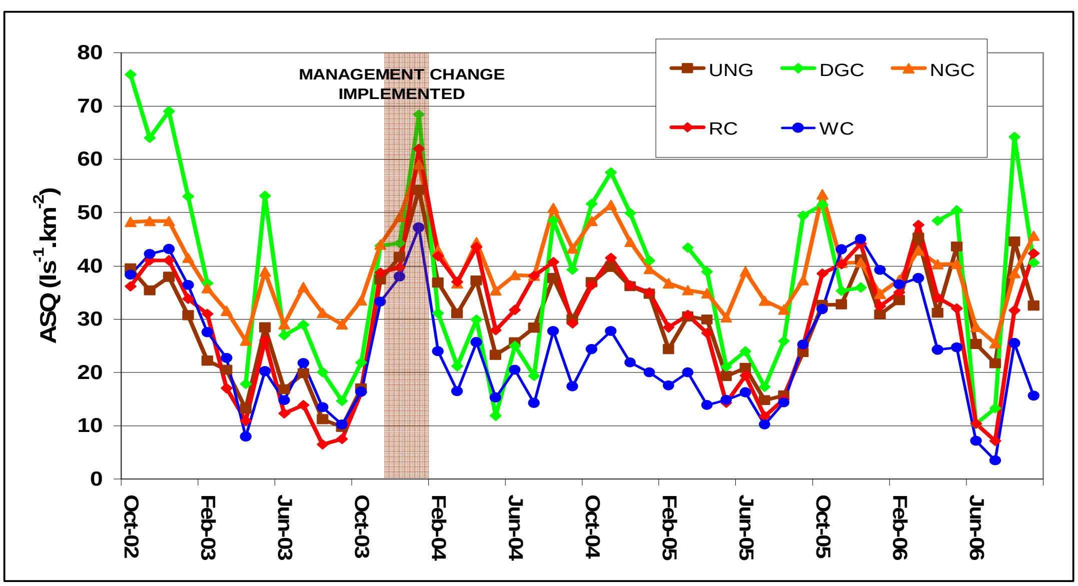
ASQ = Area Specific Discharge

Although many of the relationships are significant because of the large samples sizes, the low r^2 values indicate the relationships between true colour and ASQ were generally not linear and were complicated by the varying climatic response times of the hydrological, chemical and biological processes which generated water colour. Figures 7.6a-d show the daily data for each year and to avoid confusion of short-term responses the monthly mean data for each catchment were analysed and are discussed in Section 7.2.5.

7.2.5 Monthly Mean Area Specific Discharge

The monthly mean ASQ ($ls^{-1}\cdot km^{-2}$) for each catchment in the study area was examined to determine any temporal pattern of change pre and post management intervention and spatial change between catchments during the study period. Figure 7.7 shows the monthly mean ASQ ($ls^{-1}.km^{-2}$) and demonstrates the temporal and spatial differences in discharge per unit area from Oct 2002-Sept 2006. It shows the higher ASQ at Within Clough in the first water year Oct 2002-Sept 2003 compared to the noticeable change in ASQ in Jan 2004 when the runoff was impeded by the series of dams installed in the headwaters of the catchment. Within Clough clearly had the lowest ASQ for a period of approximately 14 months post gully-blocking, but showed a recovery in ASQ during winter 2005-06 when runoff was once again similar to that at Upper North Grain. This indicates a successful rewetting of the catchment and subsequent increase in runoff primarily through surface and sub-surface flow, but clearly affected the water yield of the catchment for some time.

Figure 7.7: Ashop Catchments Monthly Mean of Daily ASQ ($ls^{-1}km^{-2}$) Oct 2002-Sept 2006



KEY

DGC = Doctors Gate Clough UNG = Upper North Grain NGC = Nether Gate Clough
RC = Red Clough WC = Within Clough ASQ = Area Specific Discharge

The remaining catchments showed a seasonal pattern of ASQ with a general rise in ASQ during the autumn/winter caused by an increase in rainfall and a reduced discharge during spring/summer when rainfall magnitude was lower, water tables fell and a range of hydrological processes operated dependent on antecedent climatic conditions. Figures 7.8a-e show the monthly mean ASQ for each individual catchment and clearly illustrate the variability of ASQ at Doctors Gate Clough (removal of grazing) and changing pattern in ASQ at Within Clough (gullies blocked).

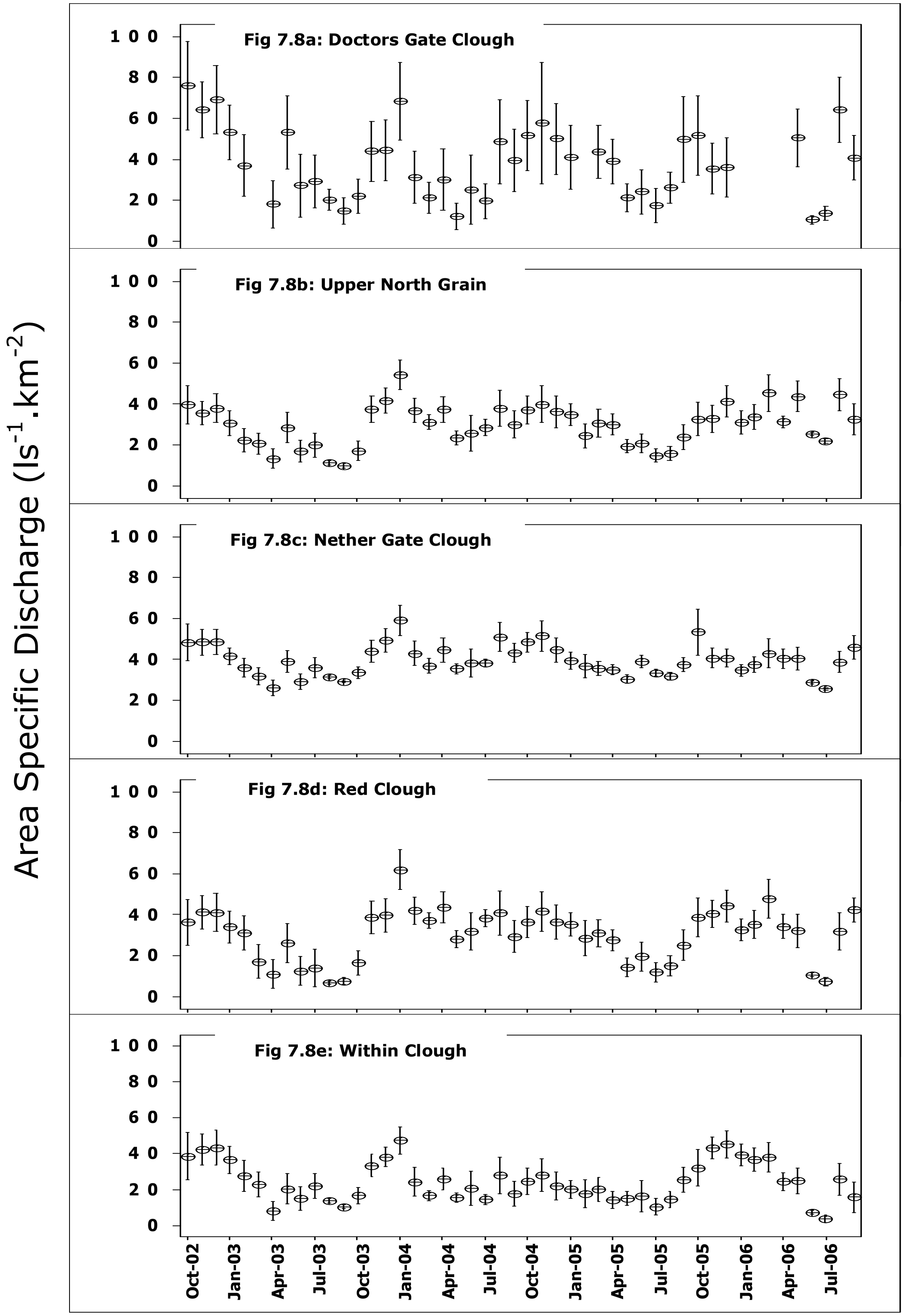
Table 7.8 presents the results of the statistical analysis using the non-parametric tests Mann Whitney U to test differences in the median, Kolmogorov Smirnov to test differences in the distribution of the data sets and the parametric one-way ANOVA to test differences in the variance. The results are discussed in Sections 7.2.5.1-7.2.5.4.

Table 7.8: Statistical Analysis Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Ashop Catchments Oct 2002-Sept 2006 (comparison of the control year 2002-03 with each subsequent year)

Variable	N	Median	Mean	Mann Whitney U Probability	Kolmogorov Smirnov Probability	ANOVA	F
DGC ASQ ($ls^{-1}km^{-2}$) 2002 -03	11	36.74	41.85				
DGC ASQ ($ls^{-1}km^{-2}$) 2003-04	12	30.54	33.71	0.479	0.408	0.317	1.05
DGC ASQ ($ls^{-1}km^{-2}$)2004-05	11	40.94	38.2	0.694	0.461	0.647	0.22
DGC ASQ ($ls^{-1}km^{-2}$) 2005-06	9	40.59	38.9	MISSING OR PROBLEM DATA			
UNG ASQ ($ls^{-1}km^{-2}$)2002-03	12	21.36	23.79				
UNG ASQ ($ls^{-1}km^{-2}$) 2003-04	12	33.95	33.38	0.0531	0.1	0.03*	5.42
UNG ASQ ($ls^{-1}km^{-2}$)2004-05	12	27.15	27.22	0.403	0.847	0.389	0.77
UNG ASQ($ls^{-1}km^{-2}$)2005-06	12	32.7	34.6	0.014*	0.034*	0.008**	8.46
NGC ASQ ($ls^{-1}km^{-2}$) 2002-03	12	35.92	37.01				
NGC ASQ ($ls^{-1}km^{-2}$)) 2003-04	12	43.07	42.98	0.078	0.249	0.073	3.55
NGC ASQ ($ls^{-1}km^{-2}$) 2004-05	12	37.01	38.55	0.525	0.518	0.615	0.26
NGC ASQ ($ls^{-1}km^{-2}$) 2005-06	12	40.35	39.05	0.583	0.518	0.525	0.42
UGC ASQ ($ls^{-1}km^{-2}$) 2002-03	12	27.94	31.99				
UGC ASQ ($ls^{-1}km^{-2}$) 2003-04	11	27.73	30.14	MISSING OR PROBLEM DATA			
UGC ASQ ($ls^{-1}km^{-2}$) 2004-05	9	24.39	24.18	MISSING OR PROBLEM DATA			
UGC ASQ ($ls^{-1}km^{-2}$) 2005-06	12	31.17	30.91	MISSING OR PROBLEM DATA			
RC ASQ ($ls^{-1}km^{-2}$) 2002-03	12	21.51	23.09				
RC ASQ ($ls^{-1}km^{-2}$)2003-04	12	38.44	37.23	0.019*	0.1	0.009**	8.19
RC ASQ ($ls^{-1}km^{-2}$) 2004-05	12	27.91	26.77	0.403	0.518	0.447	0.6
RC ASQ ($ls^{-1}km^{-2}$) 2005-06	12	34.55	32.98	0.099	0.1	0.072	3.58
WC ASQ ($ls^{-1}km^{-2}$)2002-03	12	22.22	24.9				
WC ASQ ($ls^{-1}km^{-2}$) 2003-04	12	22.24	24.67	0.885	0.847	0.963	0
WC ASQ ($ls^{-1}km^{-2}$) 2004-05	12	18.76	18.85	0.341	0.518	0.138	2.37
WC ASQ ($ls^{-1}km^{-2}$)2005-06	12	28.69	27.84	0.507	0.518	0.587	0.3

** indicates significance $p < 0.01$ * indicates significance $p < 0.05$

Figures 7.86a-e: Ashop Catchments Monthly Mean of Daily Area Specific Discharge ($ls^{-1}km^{-2}$) Oct 2002-Sept 2006.



7.2.5.1 *Control Catchments and Monthly ASQ*

The control sites (Upper North Grain and Red Clough) had a statistically significant increase in mean ASQ between year 1 calibration year (Oct 2002-03) and year 2 post management manipulation (Oct 2003-04) (ANOVA $p = 0.03$ and $p = 0.009$ respectively). The difference in monthly ASQ between year 1 and year 4 (2005-06) was also statistically significant at Upper North Grain (ANOVA $p = 0.008$). The change in ASQ between each of the water years on the control catchments was much larger than seen on the treatment sites and was greater than the accepted error suggesting that the change was not caused by mechanical error. However, Figures 7.8b and 7.8d illustrate that both catchments demonstrated a seasonal change in runoff from the catchments with increases generally observed during the autumn/winter and decreases during the spring/summer. It is likely therefore that these changes in ASQ were caused by climatic conditions, particularly as the management remained unaltered at the sites throughout the study.

7.2.5.2 *Within Clough (Gullies Blocked) and Monthly ASQ*

The statistical results were similar to the tests for daily ASQ in that the difference in monthly ASQ at Within Clough was highly insignificant between year 1 and year 2 (ANOVA $p = 0.963$) with the mean of monthly mean ASQ between the years decreasing by only 0.23 $ls^{-1}.km^{-2}$. This suggests that the gully blocking was successful in retaining water on the catchment in the second year so affecting the volume of runoff from the catchment. The changes in year 3 and year 4 when compared to year 1 at Within Clough were also not statistically significant despite the ASQ decreasing in year 3 and then increasing in year 4 suggesting some stability of hydrological conditions on site.

7.2.5.3 *Nether Gate Clough (Cessation of Burning) and Monthly ASQ*

The difference in the median and mean ASQ between year 1 and year 2 was weakly significant ($p = 0.073$ and $p = 0.075$) and amounted to a small increase in ASQ of 5.97 $ls^{-1}.km^{-2}$. This volume of discharge per unit area was within the accepted error of 6.6 $ls^{-1}.km^{-2}$ (see Table 7.1 and Section 7.2.1) of variation in ASQ between each water year and in years 3 and 4 the difference between the calibration period and the final two years was less and statistically insignificant. The fact that this is different from the pattern on the control catchment suggests that the cessation of burning may, in effect, have reduced monthly ASQ from what would have been expected if there had been no manipulation of landuse.

7.2.5.4 Doctors Gate Clough (Removal of Grazing) and Monthly ASQ

Doctors Gate Clough had the highest ASQ rates for each year with the exception of 2003-04 and the response from rainfall events appeared to have been higher compared to the remaining catchments suggesting that relatively little water was being stored on the catchments from these events and that the catchment was already wet. This may result from a legacy of intensive grazing which previous researchers have found to result in soil compaction, short vegetation or its entire removal, increase in exposure of bare earth and erosion, all of which would contribute to an increase or maintenance of high runoff (e.g. Evans 1997, 2005).

The differences in the mean ASQ between each year were not statistically significant despite the decrease in ASQ each year compared to year 1. In terms of percentage runoff this amounts to a small reduction of 0.9% and 1.9% reduction in runoff between year 1 and year 3 and year 1 and year 4 with very little change in the discharge observed on the catchment in the final two years post-management manipulation.

The control catchments suggest that ASQ, compared to year 2002-03, should have increased in all three treatment years. The changes at Doctors Gate Clough however, seem to suggest that more water was being retained on the catchment than would have been expected.

7.3 Changes in Land Management and the Effect on DOC Flux

The export of DOC in the fluvial carbon flux from peatland environments has until recently been largely ignored, but mounting interest in current and potential climate changes and their likely impact on upland soil carbon store has raised awareness of the need to understand DOC losses, particularly when considering future climate change and targets for carbon sequestration. This section discusses the changes in DOC flux during the study and the temporal and spatial changes in DOC flux across the catchments and the potential influence of land management manipulation. See Section 4.4.3 for DOC methodology and Equations 4.8-4.13 used to determine DOC (mgl^{-1}) from true colour (°H). See Appendix XII for monthly descriptive statistics of DOC flux.

7.3.1 Annual DOC Flux

The annual DOC flux was calculated by multiplying the daily mean DOC and daily mean discharge by 365 (years 2002-03, 2004-05 and 2005-06) and 366 (year 2003-04) to represent the annual flux, whilst the areal export of DOC from each site accounted for the catchment size to enable sites to be directly compared. A summary of the annual DOC for each water year (Oct-Sept) is presented in Table 7.9 which shows statistics for the mean and standard deviation of DOC and areal export of

DOC on each of the six catchments in the study. N* represents the number of missing days in a water year and were generally greater than the number of missing days for either daily water colour or discharge as data were only available when both these variables were recorded. Although every effort was made to maximise the sample data, battery exhaustion, sampler malfunction or extreme weather conditions largely dictated the number of samples collected and therefore varied between each catchment.

Figure 7.9 presents the annual mean DOC ($C.mgl^{-1}$) for the catchments. Upper Gate Clough was excluded because of problem or missing discharge data (see Section 7.2). It shows that the annual DOC flux was consistently higher at Upper North Grain (control) and Within Clough (gullies blocked), the two largest catchments (1.26 km^2 and 1.138 km^2) compared to the remaining catchments with the spatial magnitude of DOC flux varying in relation to catchment size (Red Clough 0.555 km^{-2}, Nether Gate Clough 0.305 km^2 and Doctors Gate Clough 0.185 km^2).

Figure 7.9: Ashop Catchments Annual DOC Flux ($Ctyr^{-1}$) Oct 2002-Sept 2006

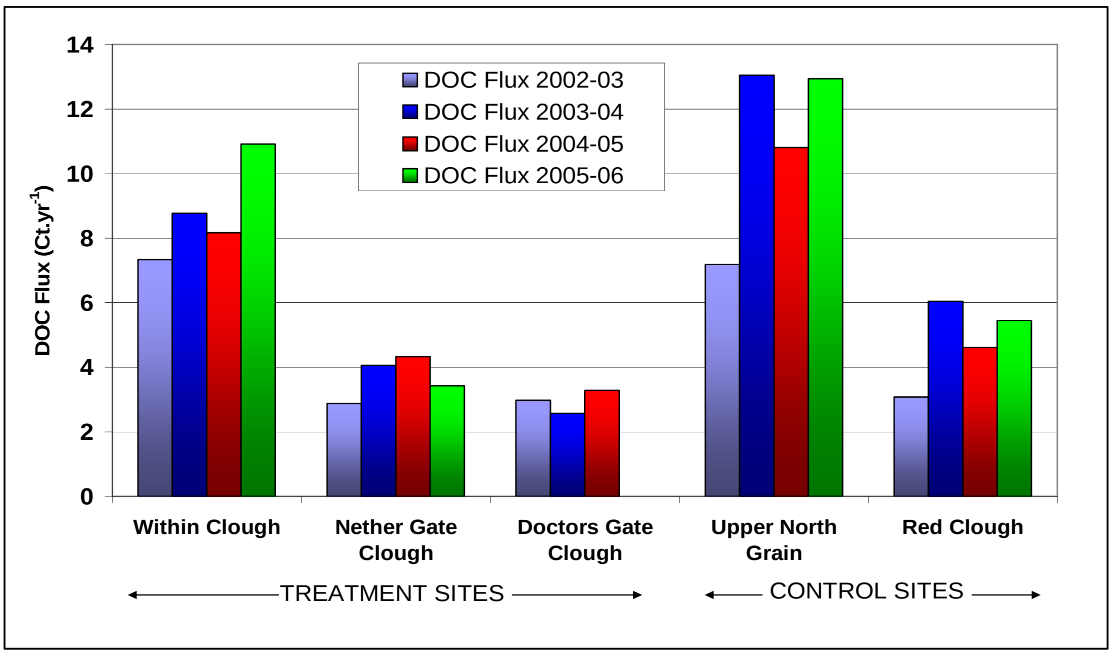


Figure 7.9 also shows that the temporal pattern of annual DOC flux was similar at three catchments, namely, Upper North Grain (control), Red Clough (control), but also at Within Clough where the gullies were blocked after the first year calibration period (Oct 2002-Dec 2003). Although the annual difference in DOC flux was comparatively small at Nether Gate Clough (cessation of burning) and Doctors Gate Clough (removal of grazing), the pattern of annual change at both sites differed from the other catchments and this may have been influenced by changes in management manipulation after the first year. The changes are, however, complex: Nether Gate Clough appeared to have increased flux 2004-05, but decreased in 2005-06, whereas Doctors Gate Clough had less DOC flux than expected in 2003-04. The reduction

at Doctors Gate Clough in 2003-04 is likely to have been because of the decrease in ASQ in that year, but it is unclear whether this was related to equipment failure or change in landuse (see Section 7.2.2).

Figure 7.10 shows the annual areal export of DOC ($C.tyr^{-1}.km^{-2}$) for each catchment and so accounts for the effect of catchment size. It demonstrates that although they had the lowest absolute flux, Nether Gate Clough and Doctors Gate Clough exported a higher level of DOC per unit area compared to the three sites. The two control sites (Upper North Grain and Red Clough) had a similar pattern of areal DOC flux over the four years, whilst at Within Clough (gullies blocked) the areal DOC was higher than the control sites in the first year, but lower in the three years post gully-blocking which suggests at this annual level, gully blocking may have decreased the volume of DOC being discharged from the site. However, the variation in the number of days of missing data between the years and the periods when no variables were recorded on each catchment may have had an influence on the changing pattern of DOC flux. To overcome the difficulties caused by periods of missing data, the differences between the monthly data are discussed in Section 7.3.2.

Figure 7.10: Ashop Catchments Annual Areal Export of DOC Flux ($Ctyr^{-1}.km^{-2}$) Oct 2002-Sept 2006

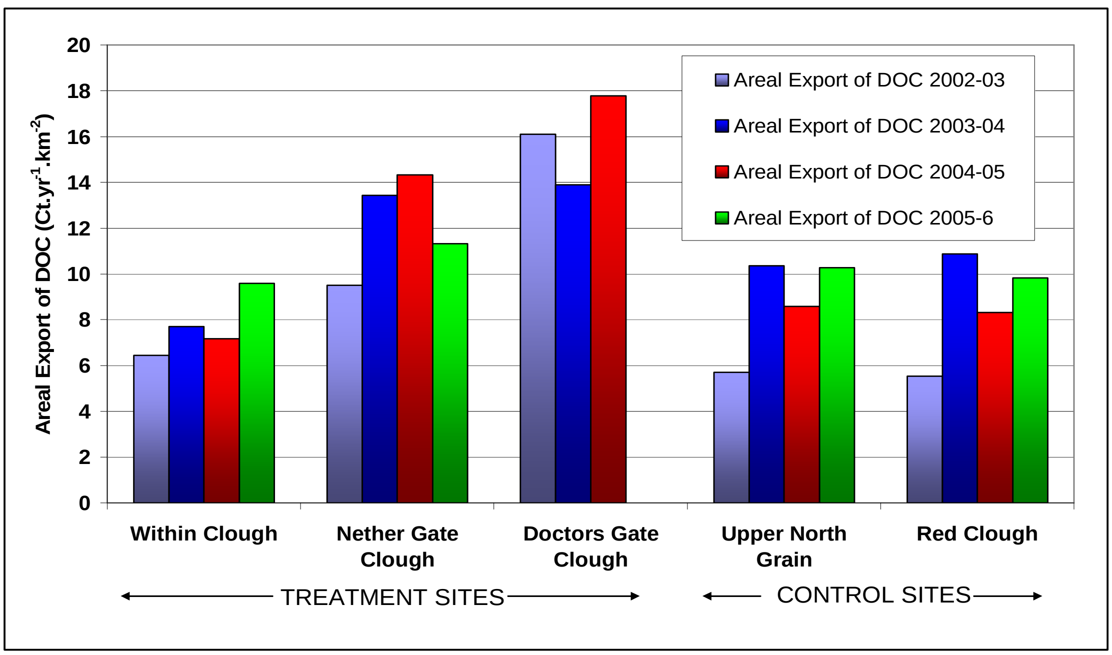


Table 7.9: Ashop Catchments Annual DOC Flux from Daily Mean Oct 2002-2006

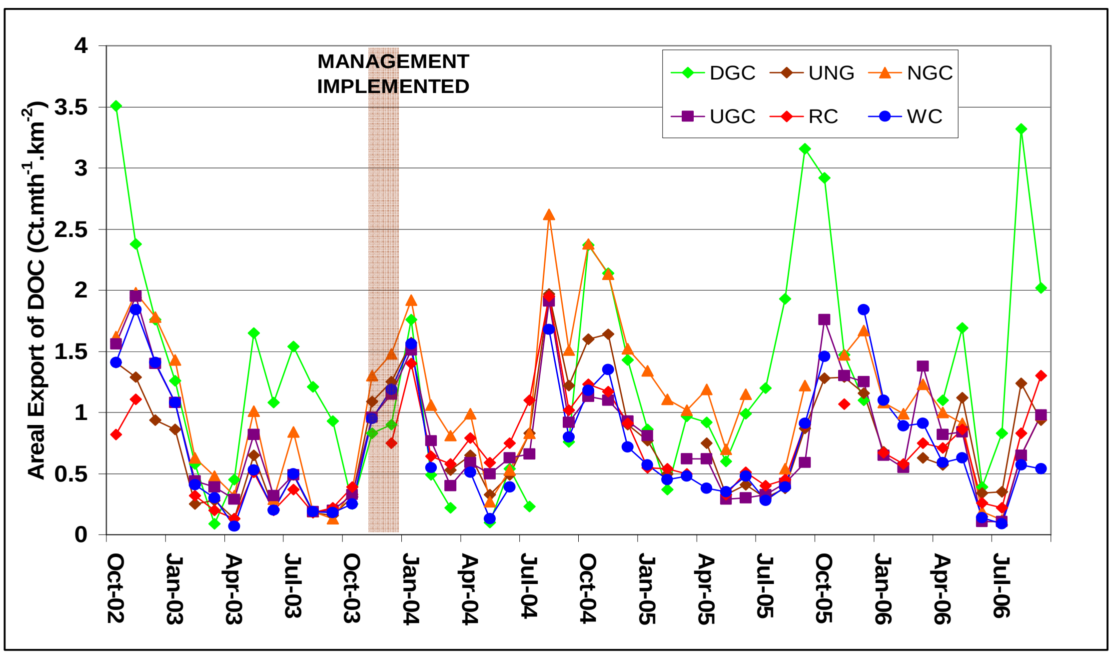
Year	Site	N	N*	Mean DOC (mgl^{-1})	DOC St Dev	Mean Daily Q (ls^{-1})	Q St Dev	DOC flux/day (mg $C.day^{-1}$)	DOC Flux ($C.t.yr^{-1}$)	Areal Export of DOC ($Ct.yr^{-1}.km^{-2}$)
2002-03	Doctors Gate Clough	365	124	12.99	6.33	7.283	7.684	8173973.1	2.98	16.11
	Upper North Grain	365	92	7.72	4.97	29.51	22.34	19683406	7.18	5.70
	Nether Gate Clough	365	56	8.2	6.57	11.099	4.366	7863419.5	2.87	9.41
	Upper Gate Clough	365	58	7.94	4.34	17.437	11.196	11962061	4.37	8.02
	Red Clough	365	83	7.59	3.23	12.842	13.457	8421475.4	3.07	5.53
	Within Clough	365	43	8.25	5.27	28.17	26.5	20079576	7.33	6.44
Year	**Site**	**N**	**N***	**Mean DOC (mgl^{-1})**	**DOC St Dev**	**Mean Daily Q (ls^{-1})**	**Q St Dev**	**DOC flux/day (mg $C.day^{-1}$)**	**DOC Flux ($C.t.yr^{-1}$)**	**Areal Export of DOC ($Ct.yr^{-1}.km^{-2}$)**
2003-04	Doctors Gate Clough	366	128	13.07	4.57	6.238	7.479	7044249	2.57	13.89
	Upper North Grain	366	113	9.84	5.71	42.04	24.05	35741399	13.05	10.36
	Nether Gate Clough	366	100	9.92	6.89	12.985	4.679	11129288	4.06	13.31
	Upper Gate Clough	366	129	10	5.62	17.107	9.71	14780448	5.39	9.89
	Red Clough	366	110	9.27	4.39	20.669	12.468	16554381	6.04	10.88
	Within Clough	366	124	9.9	6.25	28.09	22.65	24027062	8.77	7.71
Year	**Site**	**N**	**N***	**Mean DOC (mgl^{-1})**	**DOC St Dev**	**Mean Daily Q (ls^{-1})**	**Q St Dev**	**DOC flux/day (mg $C.day^{-1}$)**	**DOC Flux ($C.t.yr^{-1}$)**	**Areal Export of DOC ($Ct.yr^{-1}.km^{-2}$)**
2004-05	Doctors Gate Clough	365	132	15.37	7.68	6.786	7.355	9011590.8	3.29	17.78
	Upper North Grain	365	121	9.87	4.58	34.73	22.43	29616633	10.81	8.58
	Nether Gate Clough	365	97	11.84	6.17	11.596	3.739	11862430	4.33	14.20
	Upper Gate Clough	365	129	9.53	3.87	13.248	9.097	10908297	3.98	7.30
	Red Clough	365	115	9.87	2.85	14.84	11.427	12655077	4.62	8.32
	Within Clough	365	105	11.96	4.59	21.65	20.03	22371898	8.17	7.18
Year	**Site**	**N**	**N***	**Mean DOC (mgl^{-1})**	**DOC St Dev**	**Mean Daily Q (ls^{-1})**	**Q St Dev**	**DOC flux/day (mg $C.day^{-1}$)**	**DOC Flux ($C.t.yr^{-1}$)**	**Areal Export of DOC ($Ct.yr^{-1}.km^{-2}$)**
2005-06	Doctors Gate clough	365	113	14.79	6.44	7.054	7.005	9013996.2	3.29	17.78
	Upper North Grain	365	138	9.43	5.54	43.54	23.22	35474302	12.94	10.27
	Nether Gate Clough	365	78	9.26	6.54	11.718	4.744	9375150	3.42	11.21
	Upper Gate Clough	365	125	9.14	4.64	17.027	14.18	13446154	4.91	9.01
	Red Clough	365	164	9.46	2.54	18.287	12.325	14946770	5.45	9.82
	Within Clough	365	102	10.89	4.9	31.78	25.04	29901675	10.91	9.59

7.3.2 Monthly DOC Flux

The monthly mean areal export of DOC ($Ctkm^{-2}$) for each catchment in the study area was examined to determine any temporal pattern of change pre and post management intervention and spatial change between catchments during the study period. Tables 7.10-7.13 present the annual statistics of monthly mean areal export of DOC ($Ctkm^{-2}$) for each water year (Oct-Sept) for each catchment. Data for Upper Gate Clough is not presented because of missing or problem data (see Section 7.2) and similarly at Doctors Gate Clough for year 4.

The Tables and Figure 7.11 show the monthly mean DOC flux ($Ctkm^{-2}$) and demonstrate the temporal and spatial differences in DOC per unit area from Oct 2002-Sept 2006. Figure 7.11 shows a seasonal pattern of DOC flux on all catchments with a general rise during the autumn/winter caused by an increase in rainfall and discharge and flushing out of DOC/water colour, and a reduced flux during spring/summer when rainfall magnitude was lower, water tables fell and a range of hydrological processes operated dependent on antecedent climatic conditions. Figures 7.12a-e show the mean monthly areal export of DOC ($Ctkm^{-2}$) at each site and emphasises the similarity in the pattern of DOC flux at each site month by month

Figure 7.11: Monthly Mean of Daily Areal Export of DOC Flux Oct 2002-Sept 2006



KEY

DGC = Doctors Gate Clough	UNG = Upper North Grain	NGC = Nether Gate Clough
UGC = Upper Gate Clough	RC = Red Clough	WC = Within Clough

Table 7.10: Ashop Catchments Annual Statistics of Monthly Mean Areal Export of DOC ($Ctkm^{-2}$) Oct 2002-Sept 2003

Variable	N	N*	Mean	SE	StDev	Minimum	Median	Maximum
DGC	12	0	1.37	0.265	0.919	0.09	1.235	3.51
UNG	12	0	0.571	0.132	0.456	0.13	0.385	1.41
NGC	12	0	0.892	0.191	0.661	0.13	0.735	1.98
UGC	MISSING OR PROBLEM DATA							
RC	10	2	0.406	0.102	0.322	0.13	0.27	1.11
WC	12	0	0.677	0.173	0.598	0.07	0.455	1.84

Table 7.11: Ashop Catchments Annual Statistics of Monthly Mean Areal Export of DOC ($Ctkm^{-2}$) Oct 2003-Sept 2004

Variable	N	N*	Mean	SE	StDev	Minimum	Median	Maximum
DGC	10	2	0.608	0.156	0.492	0.1	0.515	1.76
UNG	11	1	0.931	0.162	0.538	0.31	0.83	1.97
NGC	12	0	1.141	0.195	0.676	0.27	1.025	2.62
UGC	MISSING OR PROBLEM DATA							
RC	11	1	0.905	0.134	0.446	0.39	0.75	1.95
WC	10	2	0.801	0.17	0.537	0.13	0.675	1.68

Table 7.12: Ashop Catchments Annual Statistics of Monthly Mean Areal Export of DOC ($Ctkm^{-2}$) Oct 2004-Sept 2005

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Median	Maximum
DGC	12	0	1.412	0.238	0.825	0.37	1.095	3.16
UNG	11	1	0.768	0.143	0.474	0.3	0.75	1.64
NGC	11	1	1.3	0.165	0.548	0.54	1.19	2.38
UGC	MISSING OR PROBLEM DATA							
RC	11	1	0.6809	0.0951	0.3155	0.33	0.54	1.23
WC	12	0	0.628	0.0996	0.345	0.28	0.48	1.35

Table 7.13: Ashop Catchments Annual Statistics of Monthly Mean Areal Export of DOC ($Ctkm^{-2}$) Oct 2005-Sept 2006

Variable	N	N*	Mean	SE	StDev	Minimum	Median	Maximum
DGC	MISSING OR PROBLEM DATA							
UNG	11	1	0.873	0.112	0.37	0.34	0.94	1.29
NGC	11	1	0.935	0.143	0.474	0.12	0.99	1.67
UGC	MISSING OR PROBLEM DATA							
RC	10	2	0.725	0.104	0.329	0.22	0.73	1.3
WC	11	1	0.796	0.158	0.525	0.09	0.63	1.84

KEY

DGC = Doctors Gate Clough
UNG = Upper North Grain
NGC = Nether Gate Clough
UGC = Upper Gate Clough
RC = Red Clough
WC = Within Clough

N = number of days with data
N* = number of days with missing data

Table 7.14 presents the results of the statistical analysis using the non-parametric tests Mann Whitney U to test differences in the median, Kolmogorov Smirnov to test differences in the distribution of the data sets and the parametric one-way ANOVA to test differences in the variance. The results of the analysis are discussed in Sections 7.3.2.1-7.3.2.4.

Table 7.14: Statistical Analysis Monthly Mean Areal Export of DOC ($Ctmth^{-1}.km^{-2}$) Ashop Catchments Oct 2002-Sept 2006 (comparison of control year 2002-03 with each subsequent year)

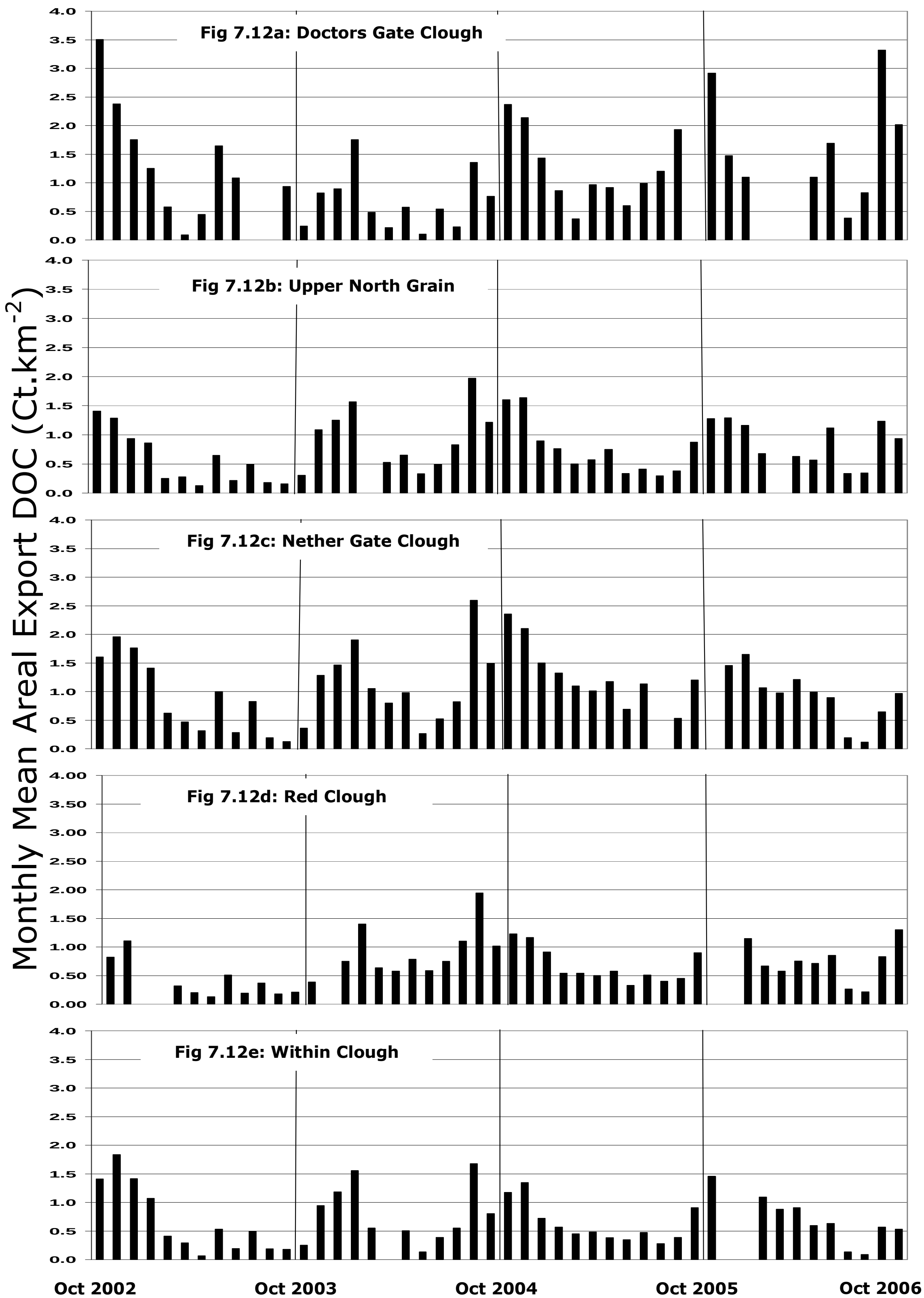
Variable	N	Median	Mean	Mann Whitney U Probability	Kolmogorov Smirnov Probability	ANOVA	F
DGC DOC ($Ctkm^{-2}$) 2002 -03	12	1.24	1.37				
DGC DOC ($Ctkm^{-2}$) 2003-04	10	0.52	0.61	0.03*	0.02*	0.029*	5.52
DGC DOC ($Ctkm^{-2}$)2004-05	12	1.1	1.41	0.97	0.41	0.98	0.01
DGC DOC ($Ctkm^{-2}$) 2005-06				MISSING OR PROBLEM DATA			
UNG DOC ($Ctkm^{-2}$)2002-03	12		0.57				
UNG DOC ($Ctkm^{-2}$) 2003-04	11	0.83	0.93	0.08	0.113	0.097	3.02
UNG DOC ($Ctkm^{-2}$)2004-05	11	0.75	0.77	0.16	0.113	0.32	1.04
UNG DOC ($Ctkm^{-2}$)2005-06	11	0.94	0.87	0.09	0.113	0.098	3.0
NGC DOC ($Ctkm^{-2}$) 2002-03	12	0.74	0.89				
NGC DOC ($Ctkm^{-2}$) 2003-04	12	1.03	1.14	0.4	0.85	0.37	0.83
NGC DOC ($Ctkm^{-2}$) 2004-05	11	1.19	1.3	0.12	0.135	0.12	2.57
NGC DOC ($Ctkm^{-2}$) 2005-06	11	0.99	0.94	0.81	0.61	0.86	0.03
UGC DOC ($Ctkm^{-2}$) 2002-03							
UGC DOC ($Ctkm^{-2}$) 2003-04				MISSING OR PROBLEM DATA			
UGC DOC ($Ctkm^{-2}$) 2004-05				MISSING OR PROBLEM DATA			
UGC DOC ($Ctkm^{-2}$) 2005-06				MISSING OR PROBLEM DATA			
RC DOC ($Ctkm^{-2}$) 2002-03	10	0.27	0.41				
RC DOC ($Ctkm^{-2}$)2003-04	11	0.75	0.91	<0.01**	0.01**	<0.01**	8.49
RC DOC ($Ctkm^{-2}$) 2004-05	11	0.54	0.68	0.02**	0.041*	0.063	3.9
RC DOC ($Ctkm^{-2}$) 2005-06	10	0.73	0.73	0.03*	0.06	0.042*	4.8
WC DOC ($Ctkm^{-2}$)2002-03	12	0.46	0.68				
WC DOC ($Ctkm^{-2}$) 2003-04	10	0.68	0.8	0.45	0.77	0.62	0.26
WC DOC ($Ctkm^{-2}$) 2004-05	12	0.48	0.63	0.71	0.52	0.81	0.06
WC DOC ($Ctkm^{-2}$)2005-06	11	0.63	0.8	0.36	0.14	0.62	0.26

** indicates significance p <0.01   * indicates significance p <0.05

KEY

DGC = Doctors Gate Clough   UNG = Upper North Grain   NGC = Nether Gate Clough
UGC = Upper Gate Clough   RC = Red Clough   WC = Within Clough

Figure 7.12a-e: Ashop Catchments Monthly Mean Areal Export of DOC (Ctkm^{-2}) Oct 2002-Sept 2006



7.3.2.1 Control Catchments and Monthly Areal Export of DOC

Monthly areal DOC flux increased on both control catchments after year 1 (2002-03). Red Clough had a statistically significant difference between mean areal export of DOC in year 1 (calibration period) and year 2 and year 4 (ANOVA $p < 0.01$ and $p = 0.04$) whilst the variance at Upper North Grain was weakly significant for the same years (ANOVA $p = 0.097$ and 0.098). Statistical tests for monthly true colour (°H) for the same years were not significant, but tests for monthly ASQ were significant and the change in ASQ on the control catchments was much larger than observed on the treatment sites. The differences in ASQ were likely to have caused the statistical significance in areal DOC flux on the two control sites with DOC flux ranging from 0.27-0.51 $Ct.km^{-2}$ at Red Clough and 0.2-0.36 $Ct.km^{-2}$ at Upper North Grain. It is likely that the changes in areal export of DOC may have been caused by climatic conditions, particularly as the management remained unaltered at the sites throughout the study.

7.3.2.2 Within Clough (Gullies Blocked) and Monthly Areal Export of DOC

Figure 7.12e shows that Within Clough had a generally lower rate of monthly DOC flux after winter 2003 (when gully blocking was completed) compared to the remainder of the sites. However, the differences between year 1 (prior to gully-blocking) and each year following gully-blocking were not statistically significant (ANOVA $p = 0.62$, 0.81 and 0.62 between year 1 and comparison with year 2, year 3 and year 4 during the post-manipulation period). The changes in mean areal export of DOC flux before and following gully-blocking were generally low, ranging from an increase in DOC export between year 1 and year 2 of 0.12 $Ctkm^{-2}$ to a decrease between year 1 and year 3 of 0.05 $Ct.km^{-2}$. This suggests more stability and fewer extremes of colour export from the catchment. The consequences of such changes are discussed in Chapter 9.

7.3.2.3 Nether Gate Clough (Cessation of Burning) and Monthly Areal Export of DOC

Nether Gate Clough (cessation of burning) responded differently when compared to the control catchments (Upper North Grain and Red Clough). Whereas, both control catchments had a similar pattern of DOC flux that appears to have been largely climate driven, Nether Gate Clough DOC flux was high in winter 2002-03 (prior to change in management). This pattern continued during the post-manipulation period when high levels of DOC flux were observed following the late summer storms of 2004, continued into winter 2004-05 and were higher than other catchments (with the exception of Doctors Gate Clough) in winter 2005-06. However, the differences in the variance of monthly DOC flux between year 1 and the subsequent years were not statistically significant (ANOVA $P = 0.37$, 0.12, 0.86 respectively). The changes in mean areal export of DOC flux before and following the cessation of burning were generally low, ranging from an increase in DOC export between year 1 and year 3 of 0.4 $Ctkm^{-2}$ and 0.05 $Ctkm^{-2}$ between year 1 and year 4

7.3.2.4 Doctors Gate Clough (Removal of Grazing) and Monthly Areal Export of DOC

Although the areal export of DOC at Doctors Gate Clough (removal of grazing) was higher in winter 2002-03 and summer 2005 and 2006, the same seasonal pattern was also observed on the other sites to a lesser extent. This was reflected in this catchment having the highest mean areal DOC flux in year 1 and year 3 (year 4 data were not presented because of missing data). Table 7.14 shows year 2 mean areal DOC flux decreased significantly by 0.76 $Ctkm^{-2}$ (ANOVA $p = 0.029$). However, the remainder of the sites had an increase in areal DOC flux between year 1 and year 2 and the decrease at Doctors Gate Clough may have been caused by the prolonged periods of low flow when water stage levels were particularly low in the second year (see Section 7.2.3.3). Although the land management was manipulated in year 2 it is unlikely that the response in areal DOC flux would have been so immediate, for example, the impacts of intensive sheep grazing such as soil compaction, short vegetation and increased erosion would be unlikely to recover within 12 months of the sheep having been removed.

The control catchments suggest that DOC flux should have increased in all three treatment years and therefore the changes at Doctors Gate Clough seem to suggest that more DOC was being retained on the catchment than would have been expected. The evidence of monthly DOC flux suggests that manipulation of land management may help stabilise and control the level of carbon discharged from sites. However, it should be noted that it is unclear whether the reduction in ASQ at this site in 2003-04 was caused by equipment failure or changes in landuse and therefore the findings should be treated with caution although the possibility of real change occurring cannot be dismissed. These findings and their implications are discussed further in Chapter 9.

7.4 Summary

All catchments responded rapidly to rainfall events with a rapid rise in ASQ and DOC flux. Seasonal changes in ASQ and DOC were observed with a general rise in ASQ and DOC during the autumn/winter months when catchments rewet and rainfall events were greater, causing the colour to be flushed from the catchments. There was a general reduction in ASQ and DOC flux in spring/summer as rainfall was less and hydrological processes contributing to ASQ and DOC changed.

The processes and observed changes in ASQ and DOC flux between each water year were complex with a seasonal climatic component clearly affecting the temporal and spatial changes on each catchment. This is further complicated by the non-stationarity of catchment response, for example in a period of rising colour in response to drought which is difficult to separate from other factors that may affect colour response or discharge such as changes in land management. In order to remove the impact on non-stationarity a paired catchment model was used to compare the changes in catchment response to true colour, ASQ and DOC flux, the results of which are discussed in Chapter 8.

8 MODELLING MONTHLY COLOUR, RUNOFF AND DISSOLVED ORGANIC CARBON FLUX USING A PAIRED CATCHMENT APPROACH

8.1 Introduction

Whilst the prediction of such variables as water colour and ASQ may be possible using climatic variables such as temperature, hours of sunshine, rainfall etc, it is acknowledged that a number of problems have been identified in using this approach (Naden and McDonald 1989, Kalbitz *et al* 2000). The non-stationarity of catchment response, for example in a period of rising colour in response to drought is difficult to distinguish from other factors that may affect colour response or discharge.

In terms of understanding the natural chemical, biological and physical processes generating water colour/DOC, further complicated by their interaction with past and present climatic conditions and the additional anthropogenic influences of land management and atmospheric pollution, it is difficult to disentangle the cause and effect processes in the short and longer-term. For example, a period of monitoring may show short-term fluctuations, but this may be interpreted very differently from the longer-term trends and therefore there may be great variability at different time-scales.

In order to remove the impact on non-stationarity a paired catchment approach was used to compare the changes in catchment response to true colour, ASQ and DOC flux whereby two catchments were monitored for a calibration period, that is, the period prior to any changes in land management, to establish a degree of similarity (see Section 4.2.1)

This chapter discusses the relationships between the catchments, the predictive equations established and the subsequent comparison of changes in catchment response to true colour, ASQ and DOC flux. Statistical analysis of the differences between the calibration and treatment period was undertaken to determine if the changes in land management were associated with significant changes that might be replicated more broadly. The analysis concentrated on the responses to monthly mean variables only because of difficulties of using daily data to detect differences between catchments (see Section 8.2). The use of monthly data therefore enabled changes at the study sites to be more readily analysed.

8.2 Daily vs Monthly Data Regression Modelling

The use of daily independent variables to predict true colour, ASQ and DOC flux at each study site was considered, but a number of difficulties were identified in using such data. These are summarised as follows:

- The data sets all had periods of missing data due to failure of equipment and adverse weather conditions and the number of missing samples varied from year to year at each study site (approximately one third). Statistical analysis of annual daily data could have implied significant differences between the water years which may have only occurred because of data loss, but could have been misinterpreted as being significant due to changes in land management. The use of mean monthly data limited the influence of the periods of missing data whilst still enabling statistical analysis to be used in predicting monthly true colour, runoff and DOC flux post-management intervention on those catchments where land management had been manipulated.

- The daily data sets included a number of extremes where "outliers" of variables occurred which were considered to be outside the normal range for a variable or population and although the outliers were real and were likely to have occurred on the study site due to the nature of the environment and extremes in climate, potentially occurring during storm events; they could affect statistical analysis by increasing the error variance and power of statistical tests. By using the monthly mean, the "outliers" were not excluded as they were likely to have occurred legitimately, and analysis identified significant differences in datasets that had not resulted merely from the inclusion of several outliers.

8.3 Catchment Pairings: Prediction of Colour, Runoff, DOC Flux

Catchments found to be similar in hydrology, pedology, geology, topography and vegetation were paired together after the calibration period (Oct 2002-Dec 2003) (see Section 4.3.1 and Table 4.2). Table 4.5 shows the original catchment pairings of treatment and control catchment selected from the cluster analysis with Red Clough acting as an additional control. During the study however, a number of observations were made which no longer made these catchment pairings appropriate:

- Doctors Gate Clough and Red Clough discharged a high volume of discoloured water associated with iron which was not observed on the remaining sites;

- Upper Gate Clough stage logger malfunctioned for part of the time resulting in data loss or unreliable data.

The pairings were therefore reassessed and appropriate pairings selected through correlation analysis for the calibration period (Oct 2002–Dec 2003). Table 8.1 shows the revised catchment pairings and the paired catchment analysis to predict water colour, runoff and DOC flux are discussed in the following sections.

Table 8.1: Original Catchment Pairings from Cluster Analysis

TREATMENT SITE	PAIRED CONTROL SITE (water colour)	PAIRED CONTROL SITE (ASQ & DOC flux)
Within Clough	Upper North Grain	Upper North Grain
Nether Gate Clough	Upper North Grain	Upper North Grain
Doctors Gate Clough	Red Clough	Upper North Grain

8.3.1 Catchment Pairings for Prediction of Monthly Mean True Colour

Analysis of similarities in monthly mean true colour between catchments was completed using the Pearson's correlation co-efficient in SPSS v.15. Table 8.3 shows that a number of sites were highly correlated. For example, Doctors Gate Clough and Red Clough were highly correlated (Pearson's $r = 0.872$, $p < 0.001$) and were not significantly correlated with any other sites and so provided an obvious pairing. Nether Gate Clough was highly correlated with Upper Gate Clough (Pearson's $r = 0.954$, $p < 0.001$) and Upper North Grain (Pearson's $r = 0.866$, $p < 0.001$) whilst Within Clough was also highly correlated with these sites: Upper Gate Clough (Pearson's $r = 0.979$, $p < 0.001$) and Upper North Grain (Pearson's $r = 0.959$, $p < 0.001$). All the correlations were good and provided an acceptable relationship between the pairs in order to predict changes in monthly mean true colour.

Table 8.3: Correlations of Monthly Mean True Colour (°H) At Study Sites

		DGCMTC	UNGMTC	NGCMTC	UGCMTC	RCMTC	WCMTC
DGCMTC	Pearson Correlation	1	.152	-.293	-.056	.872**	.078
	Sig. (2-tailed)		.605	.310	.849	.000	.801
	N	14	14	14	14	12	13
UNGMTC	Pearson Correlation	.152	1	.866**	.949**	.550	.958**
	Sig. (2-tailed)	.605		.000	.000	.064	.000
	N	14	14	14	14	12	13
NGCMTC	Pearson Correlation	-.293	.866**	1	.954**	.007	.931**
	Sig. (2-tailed)	.310	.000		.000	.981	.000
	N	14	14	15	15	13	14
UGCMTC	Pearson Correlation	-.056	.949**	.954**	1	.264	.979**
	Sig. (2-tailed)	.849	.000	.000		.383	.000
	N	14	14	15	15	13	14
RCMTC	Pearson Correlation	.872**	.550	.007	.264	1	.315
	Sig. (2-tailed)	.000	.064	.981	.383		.295
	N	12	12	13	13	13	13
WCMTC	Pearson Correlation	.078	.958**	.931**	.979**	.315	1
	Sig. (2-tailed)	.801	.000	.000	.000	.295	
	N	13	13	14	14	13	14

** indicates significance $p < 0.01$ * indicates significance $p < 0.05$

8.3.1.1 Upper Gate Clough (Control Catchment): Prediction of Monthly Mean True Colour using Paired Control Catchment (Upper North Grain)

In order to determine if changes in monthly mean true colour could be attributed to land management manipulation, two of the control catchments (Upper Gate Clough and Upper North Grain) were compared. Whilst acknowledging that the management on these two sites differed (Upper North Grain was grazed, but had not been burnt for a period of at least 10 years compared to Upper Gate Clough which was actively burnt and grazed), both catchments had a similar topography and vegetation composition and had been subjected to the same climatic events during the study period. Figure 8.4a shows the relationship between Upper Gate Clough and Upper North Grain for the calibration period (Oct 2002 –Dec 2003) from which a predictive equation was determined to enable monthly mean true colour (°H) to be predicted post management manipulation (Equation 8.1).

$y = 1.0881x - 1.3001$ $r^2 = 0.9006$ **Equation 8.1**

Where y = Upper Gate Clough monthly mean true colour (°H)

x = Upper North Grain monthly mean true colour (°H) n = 14

Figure 8.1a: Relationship between Upper Gate Clough and Upper North Grain Monthly Mean True Colour (°H) Oct 2002-Dec 2003

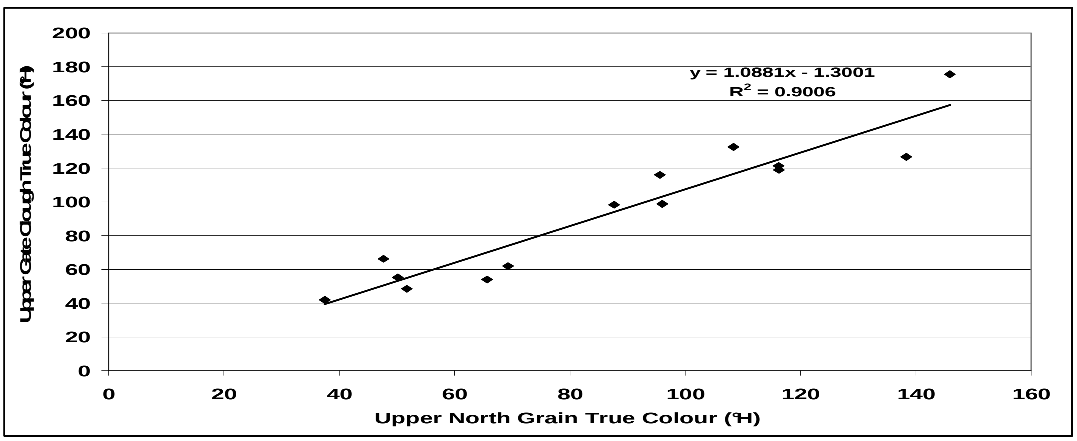
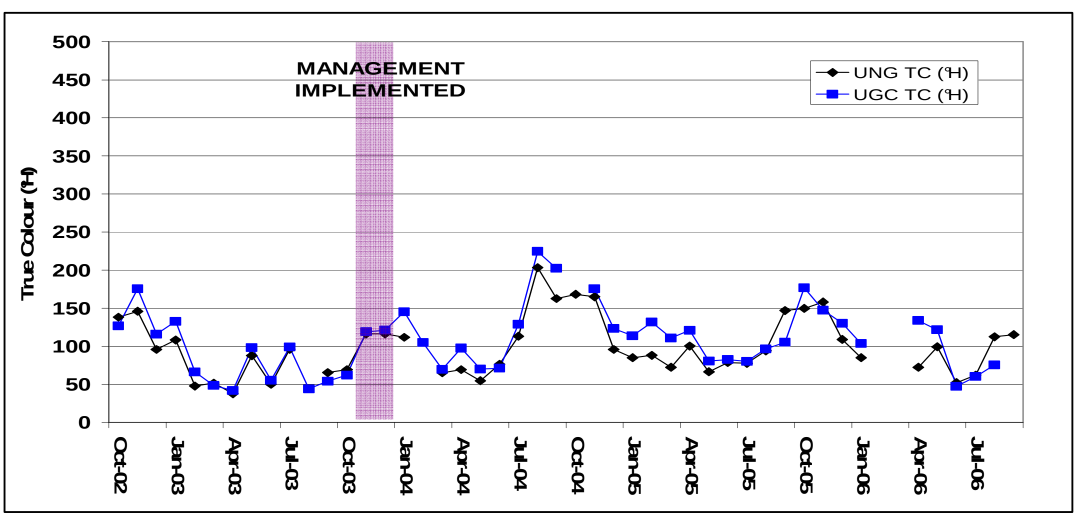


Figure 8.1b: Upper Gate Clough and Upper North Grain Observed Monthly Mean True Colour (°H) Oct 2002-Sept 2006



The observed and predicted monthly mean true colour (°H) for the period Oct 2002–Dec 2003 was good (r^2 = 0.9006) and the similarity in true colour values is shown in Figures 8.1c and 8.1d.

Figure 8.1c: Upper Gate Clough Observed and Predicted Monthly Mean True Colour (°H) Oct 2002-Sept 2006

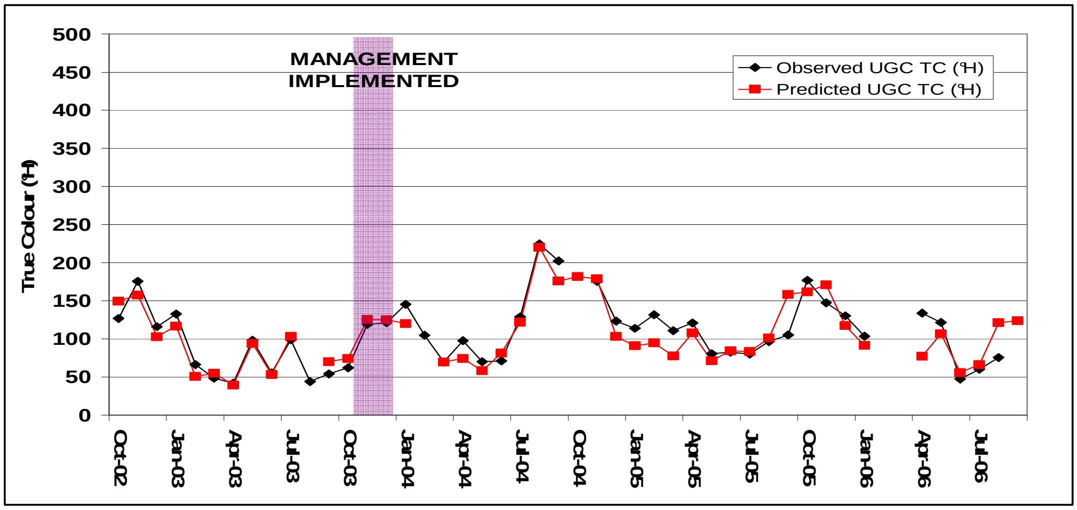


Figure 8.1d: Upper Gate Clough Monthly Mean True Colour (°H) Residuals of Observed minus Predicted Monthly Mean True Colour Oct 2002-Sept 2006

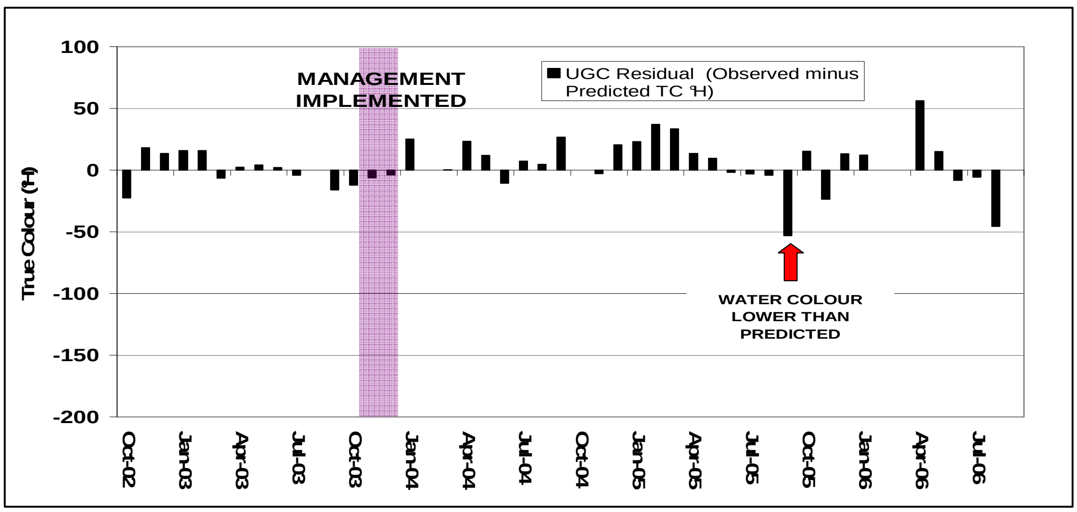


Table 8.4: Statistical Summary of Residuals of Monthly Mean True Colour (°H) Upper Gate Clough Pre and Post Management Manipulation (Observed minus Predicted from Paired Catchment)

Residuals of Monthly Mean True Colour	N	Median (°H)	Mean (°H)	Mann Whitney U Probability	ANOVA Probability	F
UGC pre mgt residuals (Oct 2002 – Dec 2003)	14	-0.9	-0.00			
UGC post mgt residuals (Jan 2004 – Sept 2006)	28	10.72	6.69	0.161	0.317	1.03

Table 8.4 presents a summary of the statistical analysis of differences in the residuals (Upper Gate Clough minus Upper North Grain monthly mean true colour) pre and post management manipulation. This indicates that no significant changes occurred during the study period, for example the difference in pre and post-management residual

mean increased by 7 °H and the median increased by 11 °H) (ANOVA $p = 0.32$, Mann Whitney U $p = 0.16$). The findings are summarised in Table 8.8.

8.3.1.2 Within Clough (Blocking of Gullies): Prediction of Monthly Mean True Colour using Paired Control Catchment (Upper North Grain)

Relationships between the treated catchment (Within Clough) and control catchments were analysed and the cluster analysis indicated that Upper Gate Clough was the closest pairing with Within Clough. A second alternative strong pairing with Upper North Grain was also identified through the correlation analysis ($r = 0.958$, see Table 8.3) and this was selected to enable the same pairing to be used for the analysis of area specific discharge (ASQ) and DOC flux at Within Clough post gully blocking. Upper Gate Clough was not suitable for this additional analysis due to missing or problem data at the site during the treatment period (see Chapters 3 and 7).

Figure 8.2a shows the relationship between Within Clough and Upper North Grain, from which a predictive equation was determined to enable prediction of monthly mean true colour (°H) post management manipulation (Equation 8.2). Figure 8.2b shows the similarity in the pattern of observed monthly true colour (°H) between the treated and control catchment during the calibration period and how the pattern changed between the two sites post management manipulation.

$$y = 1.3206x - 5.2391 \qquad r2 = 0.9173$$

Equation 8.2

Where y = Within Clough monthly mean true colour (°H)

x = Upper North Grain monthly mean true colour (°H) n = 13

Figure 8.2a: Relationship between Within Clough and Upper North Grain Monthly Mean True Colour (°H) for the Calibration Period Oct 2002 – Dec 2003

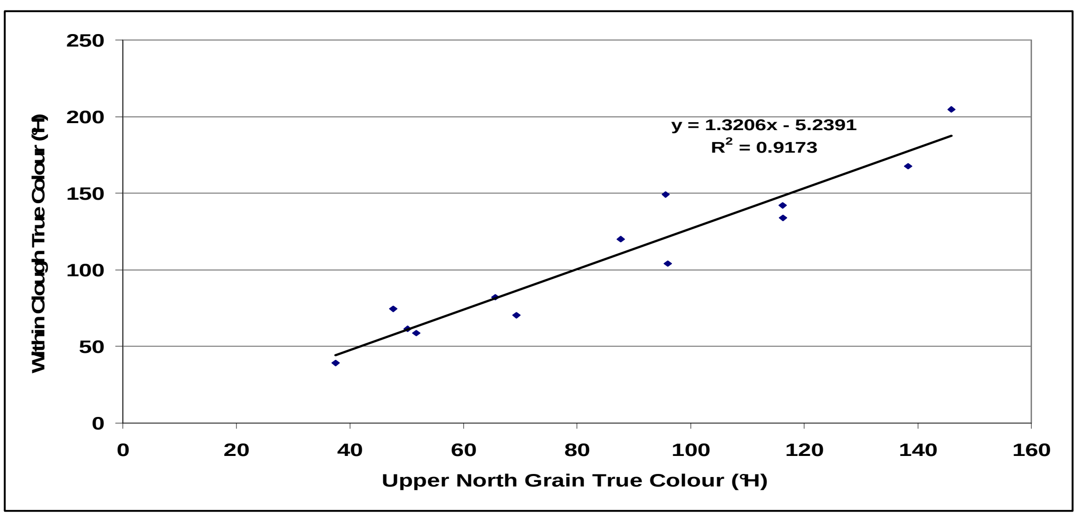
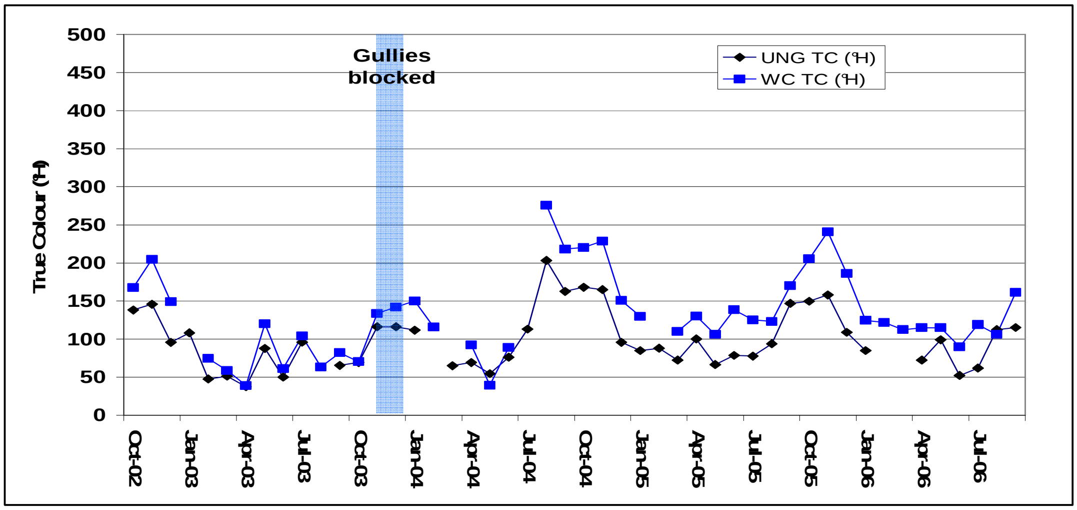


Figure 8.2b: Within Clough and Upper North Grain Observed Monthly Mean True Colour (°H) Oct 2002 - Sept 2006



The fit between the observed and predicted monthly mean true colour (°H) for the calibration period Oct 2002–Dec 2003 was good (r^2 = 0.9173). Figure 8.2c shows the observed (black) and predicted (red) lines closely followed the same pattern and the residuals were small, but from January 2004 and for the remainder of the monitoring period the differences between the observed and predicted true colour increased and the residuals were larger (see Figure 8.2d).

Figure 8.2c: Within Clough Observed and Predicted Monthly Mean True Colour (°H) Oct 2002-Sept 2006

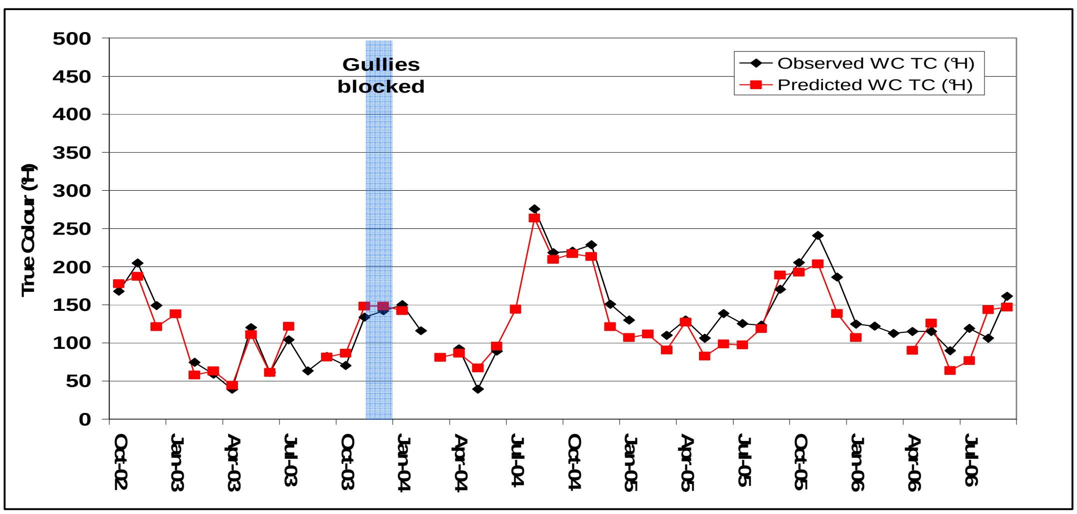


Figure 8.2d: Within Clough Monthly Mean True Colour (°H) Residuals of Observed minus Predicted Monthly Mean True Colour (Oct 2002 – Sept 2006)

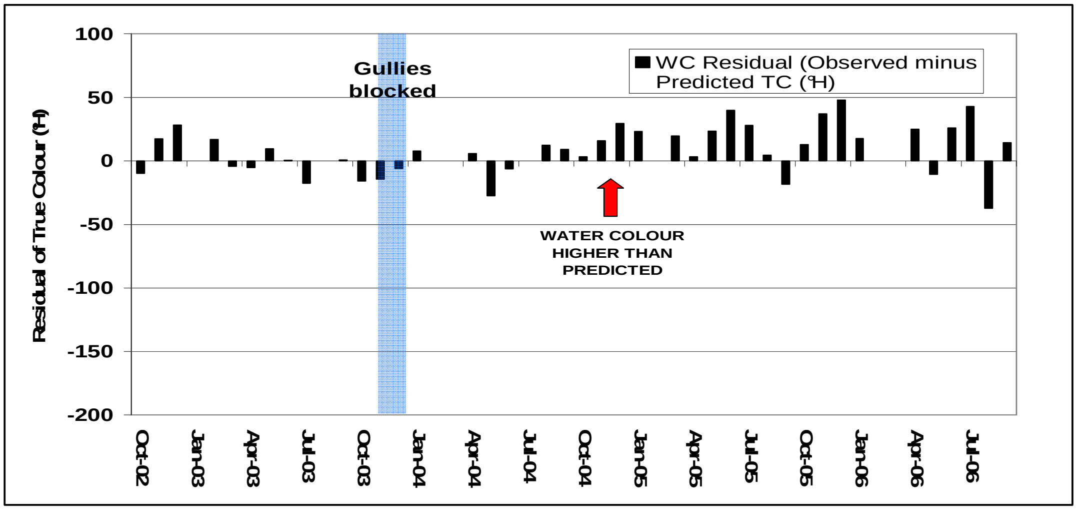


Table 8.5 presents a summary of the statistical analysis of the differences in residuals (observed minus predicted) of monthly mean true colour at Within Clough (predicted from Upper North Grain) during pre and post management manipulation. The main findings are summarised in Table 8.8.

Table 8.5: Statistical Summary of Residuals of Monthly Mean True Colour (°H) Within Clough Pre and Post Management Manipulation (observed minus predicted from paired catchment)

Residuals of Monthly Mean True Colour	N	Median (°H)	Mean (°H)	Mann Whitney U Probability	ANOVA Probability	F
WC pre mgt residuals (Oct 2002 – Dec 2003)	13	-4.31	-0.00			
WC post mgt residuals (Jan 2004 – Sept 2006)	25	12.9	10.58	0.061	0.091	3.02

** indicates significance p <0.01 * indicates significance p <0.05

8.3.1.3 *Nether Gate Clough (Cessation of Burning): Prediction of Monthly Mean True Colour using Paired Control Catchment (Upper North Grain)*

Relationships between the treated catchment (Nether Gate Clough) and control catchments were analysed and both the cluster analysis and the correlation analysis indicated that Nether Gate Clough was most closely paired with Upper Gate Clough. A second alternative pairing with Upper North Grain was also identified through the correlation analysis and was considered suitable as this pairing could also be used for the analysis of changes in area specific discharge (ASQ) and DOC flux following the cessation of burning rather than using Upper Gate Clough due to missing or problem data during the period post management manipulation.

Figure 8.2a shows the relationship between Nether Gate Clough and Upper North Grain from which a predictive equation was determined to enable monthly mean true colour (°H) to be predicted post management manipulation (Equation 8.3). Figure 8.2b shows the similarity in pattern of observed monthly true colour (°H) between the treated and control catchment during the calibration period and the change between the two sites post management manipulation.

$$y = 1.3636x - 5.3223 \qquad r^2 = 0.7506$$

Equation 8.3

Where y = Nether Gate Clough monthly mean true colour (°H)

x = Upper North Grain monthly mean true colour (°H) n = 14

Figure 8.3a: Relationship between Nether Gate Clough and Upper North Grain Monthly Mean True Colour (°H) for the Calibration Period Oct 2002-Dec 2003

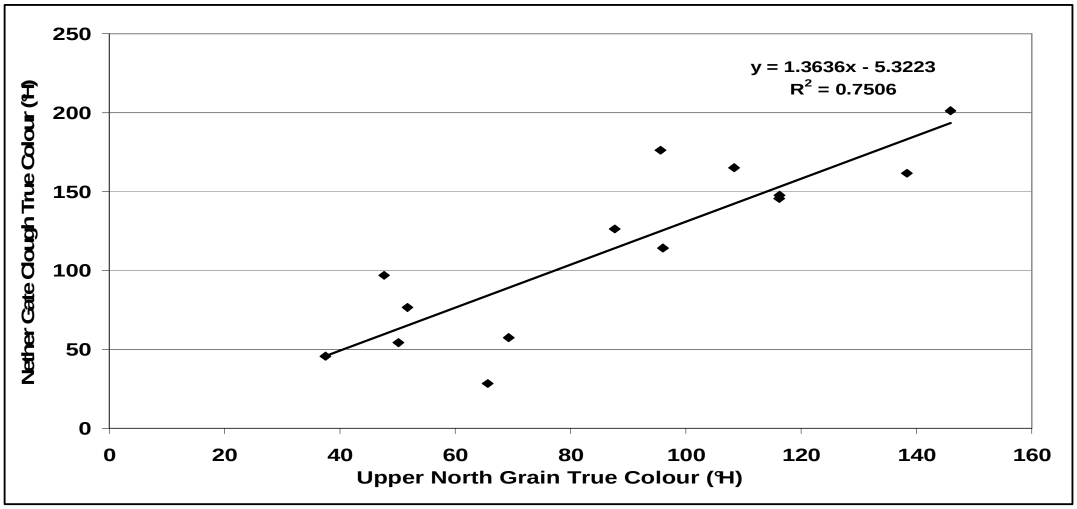
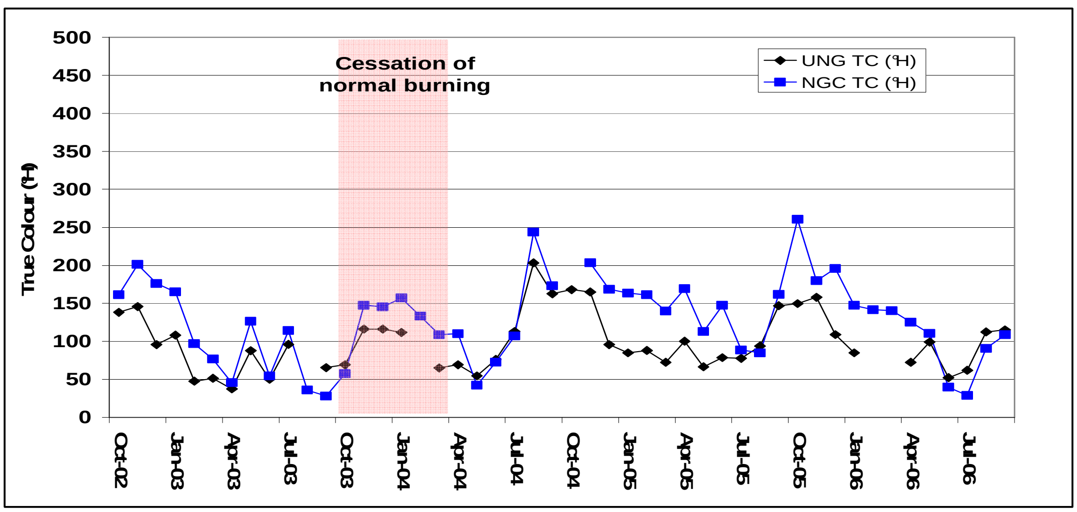


Figure 8.3b: Nether Gate Clough and Upper North Grain Observed Monthly Mean True Colour (°H) Oct 2002-Sept 2006



The observed and predicted monthly mean true colour (°H) for the calibration period Oct 2002–Dec 2003 was good (r^2 = 0.7506), but Figures 8.3c and 8.3d show there was a difference between the observed and predicted monthly mean true colour that throughout the study.

Figure 8.3c: Nether Gate Clough Observed and Predicted Monthly Mean True Colour (°H) Oct 2002-Sept 2006

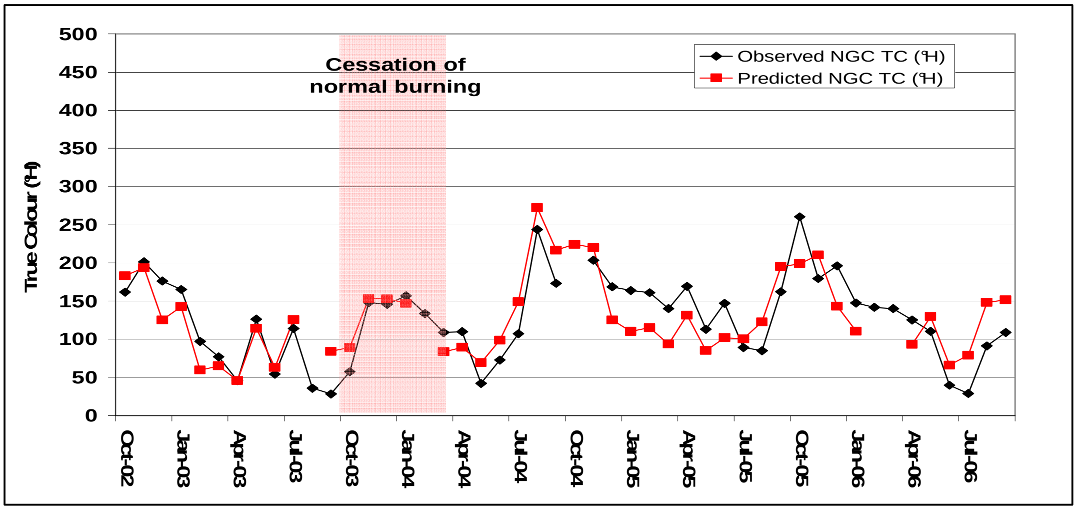


Figure 8.3d: Nether Clough Monthly Mean True Colour Residuals of Observed minus Predicted Monthly Mean True Colour (°H) Oct 2002-Sept 2006

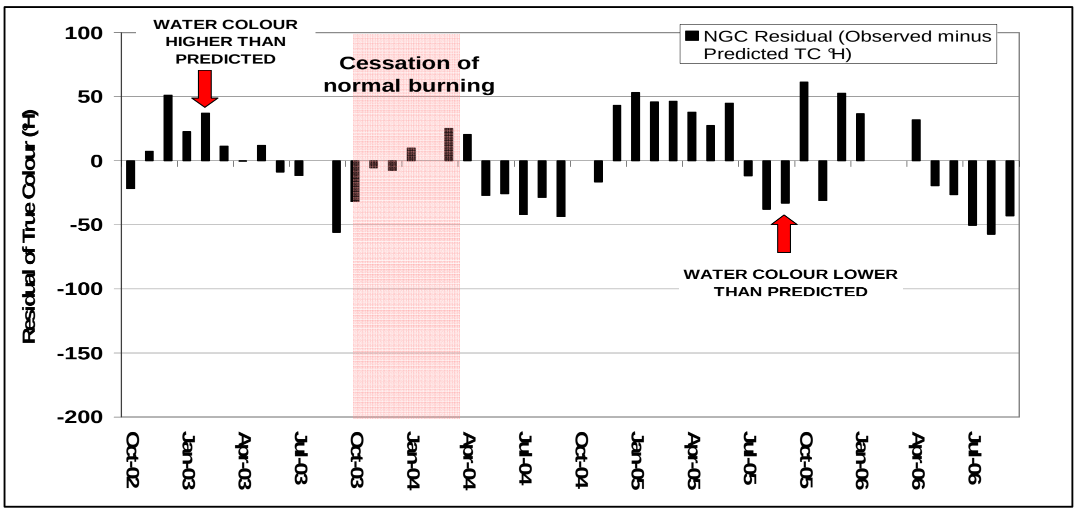


Table 8.6 presents a summary of the statistical analysis of differences in the residuals (observed minus predicted) monthly mean true colour at Nether Gate Clough (predicted from Upper North Grain) during pre and post management manipulation. The main findings are summarised in Table 8.8.

Table 8.6: Statistical Summary of Residuals in Monthly Mean True Colour (°H) Nether Gate Clough Pre and Post Management Manipulation (Observed minus Predicted from Paired Catchment)

Residuals of Monthly Mean True Colour	N	Median (°H)	Mean (°H)	Mann Whitney U Probability	ANOVA	F
NGC pre mgt residuals (Oct 2002 – Dec 2003)	14	-2.85	-0.00			
NGC post mgt residuals (Jan 2004 – Sept 2006)	28	-11.68	1.59	0.948	0.891	0.02

8.3.1.4 Doctors Gate Clough (Removal of Grazing): Prediction of Monthly Mean True Colour using Paired Control Catchment (Red Clough)

Relationships during the calibration period between Doctors Gate Clough and Red Clough were analysed for monthly mean true colour as this was found to be the only significant pairing with Doctors Gate Clough (see Table 8.3). Figure 8.4a shows the relationship between Doctors Gate Clough and Red Clough from which a predictive equation was determined to enable the monthly mean true colour to be predicted post management manipulation (Equation 8.4). Figure 8.4.b shows the similarity in pattern of observed monthly true colour (°H) between the treated and control catchment during the calibration period and how the pattern remains similar between the two sites post management manipulation.

$y = 1.7745x + 14.099$ $\qquad r^2 = 0.7605$

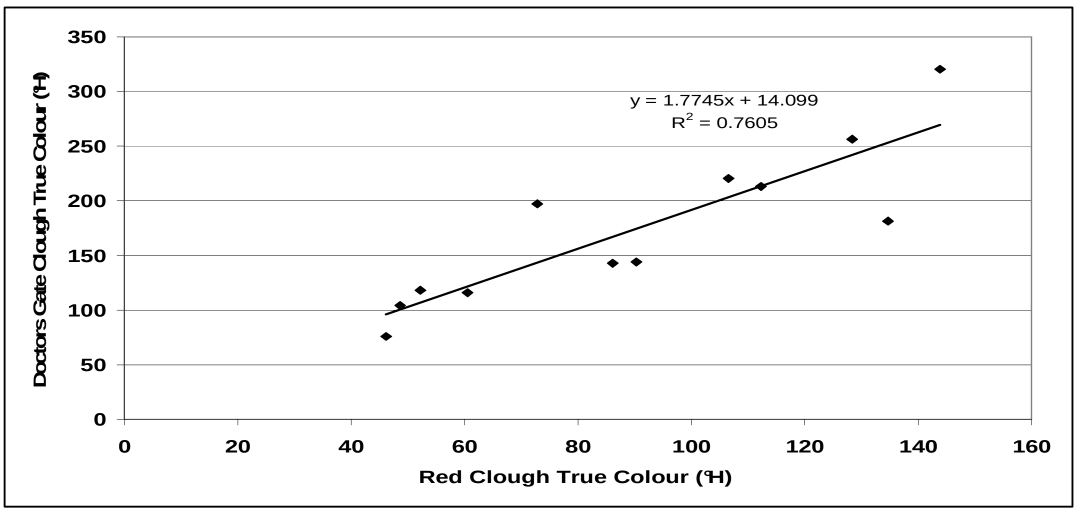
Equation 8.4

Where y = Doctors Gate Clough monthly mean true colour

x = Red Clough monthly mean true colour

n = 12

Figure 8.4a: Relationship between Doctors Gate Clough and Red Clough Monthly Mean True Colour (°H) Oct 2002-Dec 2003



The fit of observed and predicted monthly mean true colour for the calibration period Oct 2002–Dec 2003 was good ($r^2 = 0.7605$) and is shown in Figure 8.4c where the observed (black) and predicted (red) lines closely followed the same pattern and the residuals (shown in Figure 8.4d) were relatively small. However, from January 2004 and the remainder of the monitoring period the differences between the observed and predicted true colour increased and the residuals were much larger. This suggests that the relationship between Doctors Gate Clough and Red Clough weakened during the treatment period. This is illustrated in Figure 8.4b which shows the observed true colour at Doctors Gate Clough (black lines) and Red Clough (blue lines). It shows that whilst monthly mean true colour decreased at Doctors Gate Clough during summer 2004, the colour at Red Clough increased during the same period and was similar to that at Doctors Gate Clough. This flush was short-lived and during summer 2005 and 2006 the true colour at Red Clough decreased and differences in observed colour between the two sites was much greater than in summer 2004.

Figure 8.4b: Doctors Gate Clough and Red Clough Observed Monthly Mean True Colour (°H) Oct 2002-Sept 2006

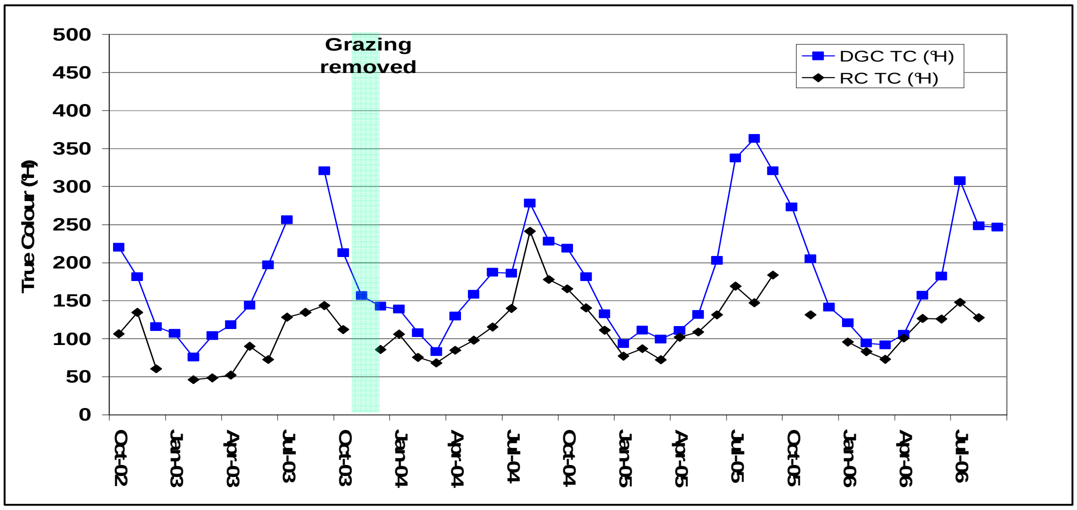


Figure 8.4c: Doctors Gate Clough Observed and Predicted Monthly Mean True Colour (°H) Oct 2002 – Sept 2006

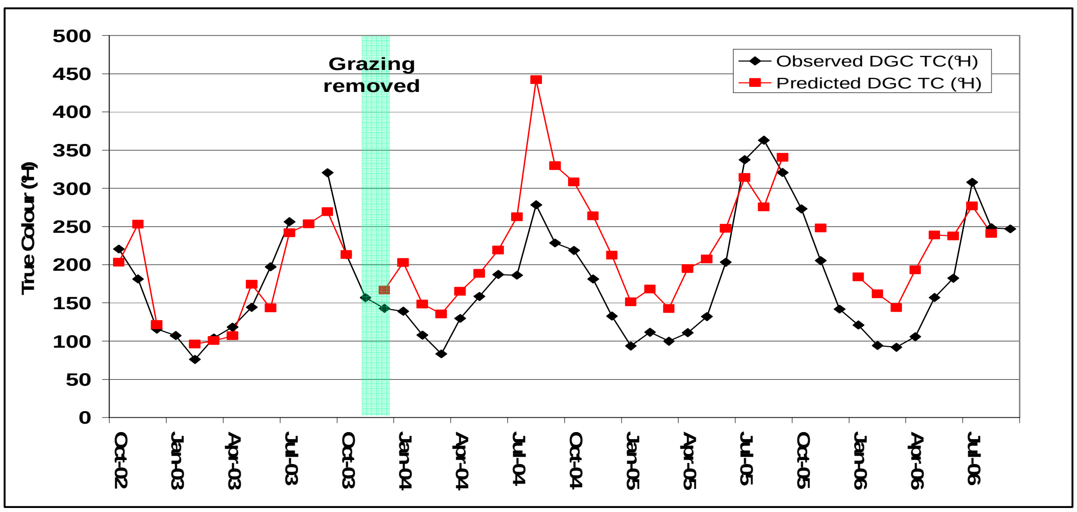
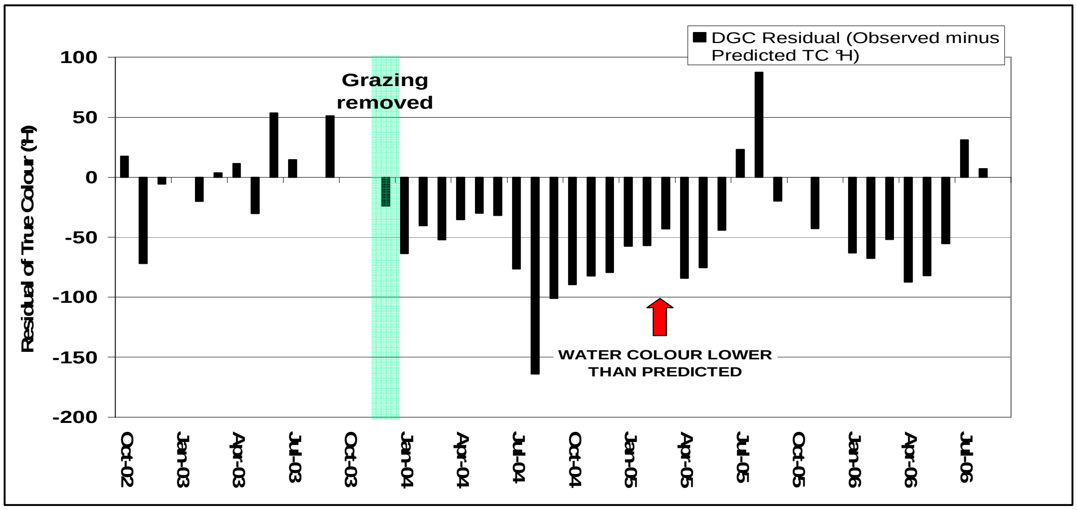


Figure 8.4d shows that following the change in management manipulation there was a step change in true colour. Despite being elevated at both sites, it was over-predicted at Doctors Gate Clough, that is, the expected colour should have been higher when using Red Clough to predict colour (where management had remained unchanged). It should be emphasised however, that although the changes in water colour coincided with the change in management (removal of grazing) this may not necessarily have been a direct causative effect.

Figure 8.4d: Doctors Gate Clough Monthly Mean True Colour (°H) Residuals of Actual minus Predicted Monthly Mean True Colour (Oct 2002-Sept 2006)



The paired catchment model generally over-predicted the true colour at Doctors Gate Clough throughout the remainder of the study post management manipulation, with the exception of Jul-Aug 2005 and Jul-Aug 2006 when warm, dry conditions prevailed and the colour levels at Doctors Gate Clough escalated. The model did partially account for the elevation in true colour during the summer, particularly in the first and second year post manipulation, as this pattern was also observed at the control site. However, it should be noted that the production of organic colour was heavily influenced by iron (see Section 6.3) which was observed during the second year of study at both sites.

Table 8.7 presents a summary of the statistical analysis of differences in the residuals (monthly mean true colour at Doctors Gate Clough minus predicted from Red Clough) pre and post management manipulation. The main findings are summarised in Table 8.8.

Table 8.7: Statistical Summary of Residuals in Monthly Mean True Colour (°H) Doctors Gate Clough Pre and Post Management Manipulation (Observed minus Predicted from Paired Catchment)

Residuals of Monthly Mean True Colour	N	Median (°H)	Mean (°H)	Mann Whitney U Probability	ANOVA	F
DGC pre mgt residuals (Oct 2002 – Dec 2003)	12	1.84	0.00			
DGC post mgt residuals (Jan 2004 – Sept 2006)	30	-56.09	-50.94	0.0008**	0.001**	11.98

** indicates significance p <0.01   * indicates significance p <0.05

8.3.2 Summary of Prediction of True Colour using Paired Catchment Model

Table 8.8 presents a summary of the main findings for the prediction of true colour at the sites.

Table 8.8: Summary of Prediction of True Colour (°H) using Paired Catchment Model

Site	Calibration Period Oct 2002-Dec 2003		Treatment Period Jan 2004-Sept 2006	
	Observed Colour	**Predicted Colour**	**Observed Colour**	**Predicted Colour**
Upper Gate Clough (CONTROL) paired with Upper North Grain	Flush of true colour winter 2002-03	Regression equation good fit (r^2 = 0.9) General under prediction in winter and over prediction during summer	Flush in winter 2003-04 lower than in 2002-03 Flush in winter 2004-05 higher than 2002-03 Flush winter 2005-06 similar to 2002-03	Generally very small over prediction of colour with under prediction in Aug 05, Dec 05 and Aug 06. Residuals small and differences not statistically significant Prediction of 7°H rise over colour expected
Within Clough (gullies blocked) paired with Upper North Grain	Flush of true colour winter 2002-03	Regression equation good fit (r^2 = 0.917) General under prediction in winter and over prediction during summer	Flush in winter 2003-04 lower than in 2002-03 Flush in winter 2004-05 higher than in 2002-03 Flush in winter 2005-06 similar to 2002-03 Increase of 25 °H between calibration period and final year	General under prediction with over prediction in May 04, Jul 05, May 06, Aug 06 Difference in residuals (observed minus predicted) between calibration and treatment period was an increase of 11 °H and weakly statistically significant p = 0.09).
Nether Gate Clough (cessation of burning) paired with Upper North Grain	Flush of true colour winter 2002-03	Regression equation good fit (r^2 = 0.715) General under prediction in winter and over prediction during summer	Flush in winter 2003-04 lower than in 2002-03 Flush in winter 2004-05 higher than in 2002-03 Flush in winter 2005-06 higher than in 2002-03 Increase of 14 °H between calibration period and final year	Continued seasonal influence of under prediction in winters 2002-03, 2004-05 and 2005-06 and over prediction in summers 2004, 2005 and 2006 Differences in residuals (observed minus predicted) between calibration and treatment period increase of 2 °H and not statistically significant
Doctors Gate Clough (removal of grazing) paired with Red Clough	Flush of true colour winter 2002-03 Flush of true colour in summer 2003	Regression equation good fit (r^2 = 0.761) Individual months over predicted (Nov 02, Jan 03, May 03) and remainder under predicted, particularly Jun 03 and Sept 03.	Flush in summer 2004 lower than summer 2003 Flush in summer 2005 higher than summer 2003 Flush summer 2006 lower than summer 2003 Increase of 14 °H between calibration period and final year	Generally over prediction of colour from Dec 03, peaking in Aug 04 and under prediction of colour Aug 05 and Aug 06 Difference in residuals (observed minus predicted) between calibration and treatment period was decrease 51 °H from colour expected and statistically significant

8.3.3 Catchment Pairings and Prediction of Monthly Mean ASQ

Analysis of similarities in monthly mean area specific discharge (ASQ) between catchments was completed using the Pearson's correlation co-efficient in SPSS v.15. Table 8.9 shows the analysis of correlations and a number of sites are highly correlated. All treated catchments where management had been manipulated were highly correlated with the control catchments. Upper Gate Clough was not selected as an appropriate pairing for ASQ on any of the treated catchments because of problems with data loss and unreliable data from stage loggers particularly in the second and third year of the study (discussed in Chapters 3 and 7). Doctors Gate Clough was highly correlated with Red Clough (Pearson's $r = 0.837$, $p < 0.001$) and Upper North Grain (Pearson's $r = 0.839$, $p < 0.001$). Nether Gate Clough was highly correlated with Red Clough (Pearson's $r = 0.933$, $p < 0.001$) and Upper North Grain (Pearson's $r = 0.96$, $p < 0.001$). Within Clough was also highly correlated with Red Clough (Pearson's $r = 0.948$, $p < 0.001$) and Upper North Grain (Pearson's $r = 0.928$, $p < 0.001$). All the correlations were good and provided an acceptable relationship between the pairs in order to predict changes in monthly mean ASQ. Upper North Grain was the site with the most complete data and therefore was selected to be an appropriate control catchment by which the effects of land management manipulation upon ASQ could be analysed.

Table 8.9: Correlations of Monthly Mean ASQ ($ls^{-1}.km^{-2}$) at Ashop Study Sites

		DGC MASQ	UNG MASQ	NGC MASQ	UGC MASQ	RC MASQ	WC MASQ
DGCMASQ	Pearson Correlation	1	.839**	.875**	.896**	.837**	DGCMAS
	Sig. (2-tailed)		.000	.000	.000	.000	
	N	15	15	15	14	15	
UNGMASQ	Pearson Correlation	.839**	1	.960**	.940**	.955**	UNGMAS
	Sig. (2-tailed)	.000		.000	.000	.000	
	N	15	15	15	14	15	
NGCMASQ	Pearson Correlation	.875**	.960**	1	.910**	.933**	NGCMAS
	Sig. (2-tailed)	.000	.000		.000	.000	
	N	15	15	15	14	15	
UGCASQ	Pearson Correlation	.896**	.940**	.910**	1	.925**	UGCASQ
	Sig. (2-tailed)	.000	.000	.000		.000	
	N	14	14	14	14	14	
RCASQ	Pearson Correlation	.837**	.955**	.933**	.925**	1	RCASQ
	Sig. (2-tailed)	.000	.000	.000	.000		
	N	15	15	15	14	15	
WCASQ	Pearson Correlation	.824**	.928**	.950**	.909**	.948**	WCASQ
	Sig. (2-tailed)	.000	.000	.000	.000	.000	
	N	15	15	15	14	15	

** indicates significance $p < 0.01$ * indicates significance $p < 0.05$

8.3.3.1 *Control Catchment (Red Clough): Prediction of Monthly Mean Area Specific Discharge using Paired Catchment Upper North Grain*

In order to determine if changes in monthly mean ASQ could be attributed to land management manipulation, two of the control catchments (Red Clough and Upper North Grain) were compared. Whilst acknowledging that the management on these two sites differed (Upper North Grain was grazed, but had not been burnt for a period of at least 10 years compared to Red Clough which was actively burnt and grazed), both catchments had a similar topography, vegetation composition and had been subjected to the same climatic events during the study period. Figures 8.5a and 8.5b show the relationship between Red Clough and Upper North Grain from which a predictive equation was determined to enable monthly mean ASQ to be predicted post management manipulation (Equation 8.5).

$$y = 1.1391x - 4.1903 \qquad r^2 = 0.9119$$

Equation 8.5

Where y = Red Clough monthly mean area specific discharge

x = Upper North Grain monthly mean area specific discharge n = 15

Figure 8.5a: Relationship between Red Clough and Upper North Grain Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Dec 2003

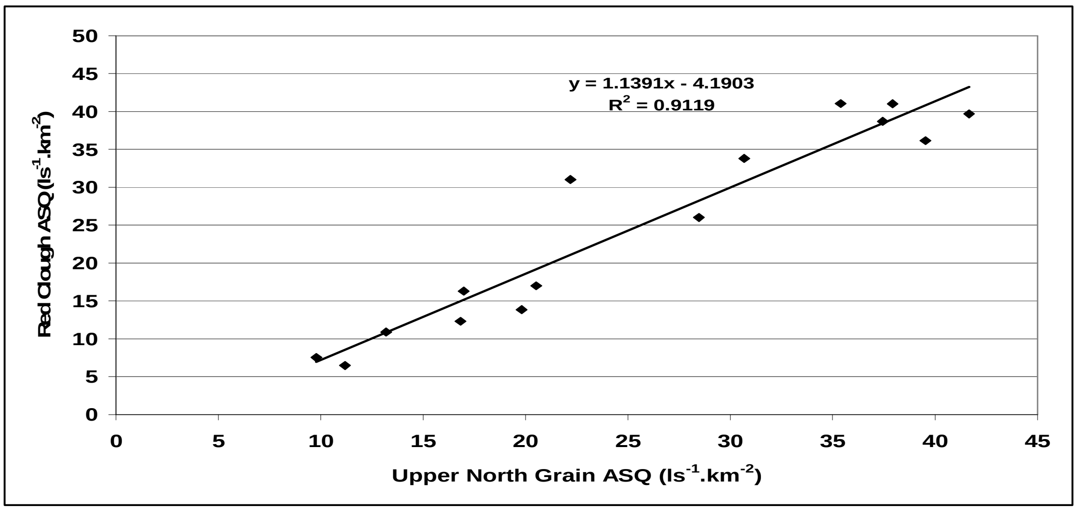
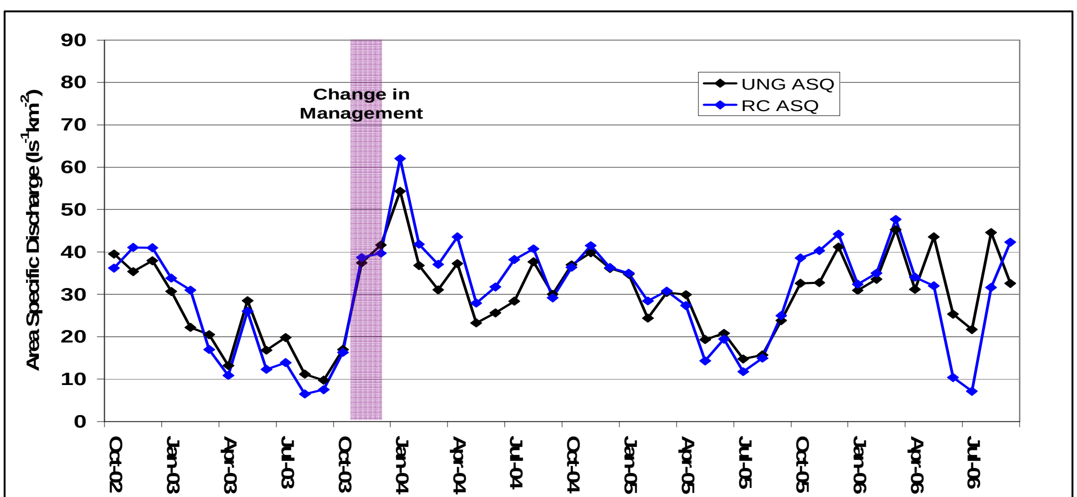


Figure 8.5b: Red Clough and Upper North Grain Observed Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006



The fit between the observed and predicted monthly mean ASQ for the period Oct 2002–Dec 2003 was good ($r^2 = 0.9119$) and is shown in Figures 8.5c and 8.5d. Throughout the period of study there were differences in the observed and predicted monthly mean ASQ at Red Clough, that is, both during the pre and the post management manipulation periods. During the calibration period the residuals followed a seasonal pattern whereby ASQ was lower than predicted during the spring/summer and was higher than predicted in winter. This seasonal pattern continued throughout the treatment period, although the differences between the observed and predicted ASQ at Red Clough were less in the second year post management manipulation. In the final year of the study there was a larger seasonal difference with an over-prediction of ASQ during the spring/summer.

Figure 8.5c: Red Clough Observed and Predicted Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 Predicted from Paired Catchment Upper North Grain

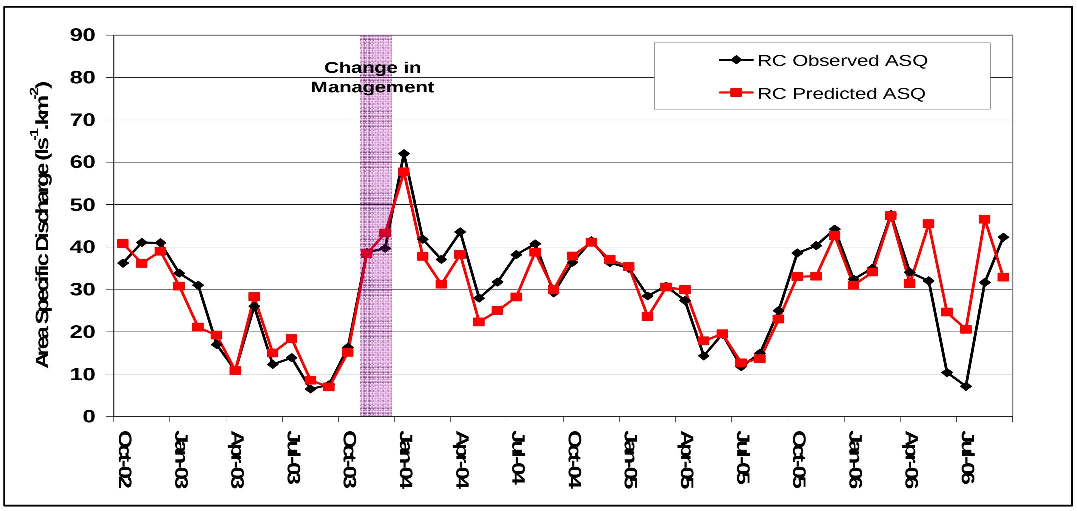


Figure 8.5d: Red Clough Residuals of Observed minus Predicted Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

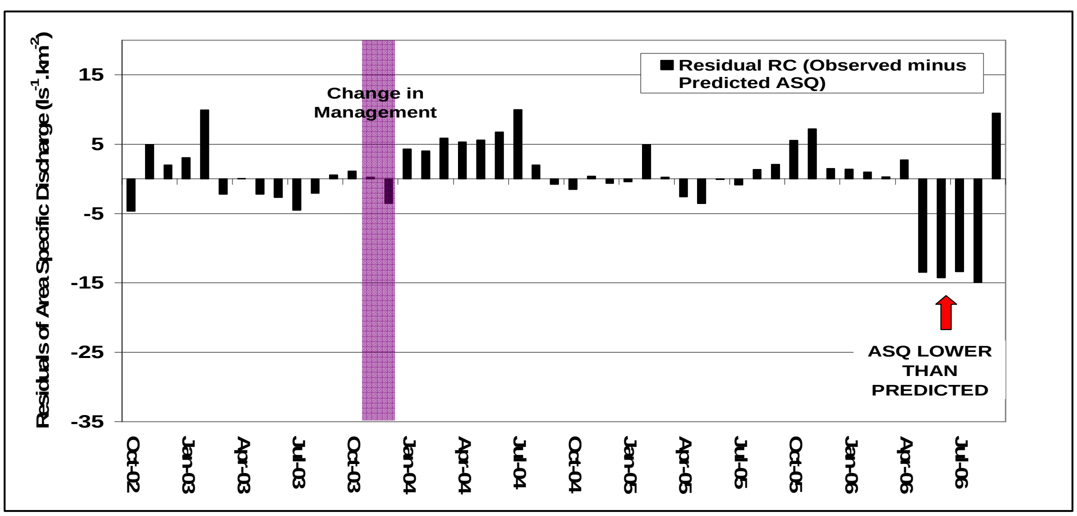


Table 8.10 presents a summary of the statistical analysis of differences in the residuals (Red Clough minus Upper North Grain monthly mean ASQ) pre and post management manipulation. These indicate that there was no significant change

during the treatment period (ANOVA p = 0.793, Mann Whitney U p = 0.197). These findings suggest that any significant changes observed on other catchments may have resulted from management manipulation.

Table 8.10: Statistical Summary of Residuals in Monthly Mean Area Specific Discharge ($ls^{-1}.km^{2}$) Red Clough Pre and Post Management Manipulation (Observed minus Predicted) using paired Catchment Upper North Grain

Residuals of ASQ	N	Median ($ls^{-1}.km^{-2}$)	Mean ($ls^{-1}.km^{-2}$)	Mann Whitney U Probability	ANOVA Probability	F
RC pre mgt residuals (Oct 2002 – Dec 2003)	15	0.05	0			
RC post mgt residuals (Jan 2004 – Sept 2006)	33	1.32	0.47	0.197	0.793	0.07

8.3.3.2 Within Clough (Blocking of Gullies): Prediction of Monthly Mean Area Specific Discharge using Paired Catchment Upper North Grain

Relationships for monthly mean area specific discharge (ASQ) during the calibration period between Within Clough and Upper North Grain were analysed. Figures 8.6a and 8.6b show the relationship between Within Clough and Upper North Grain from which a predictive equation was determined to enable the values of monthly mean true colour to be predicted post management manipulation (Equation 8.6).

$$y = 1.011x + 0.0165 \qquad r^2 = 0.8615$$ **Equation 8.6**

Where y = Within Clough monthly mean area specific discharge

x = Upper North Grain monthly mean discharge n = 15

Figure 8.6a: Relationship between Within Clough and Upper North Grain Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Dec 2003

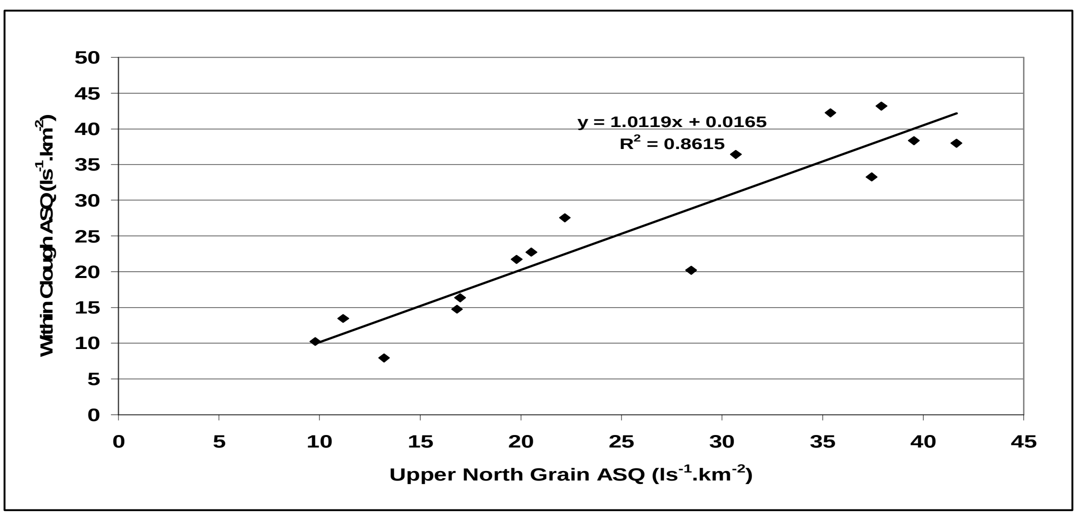
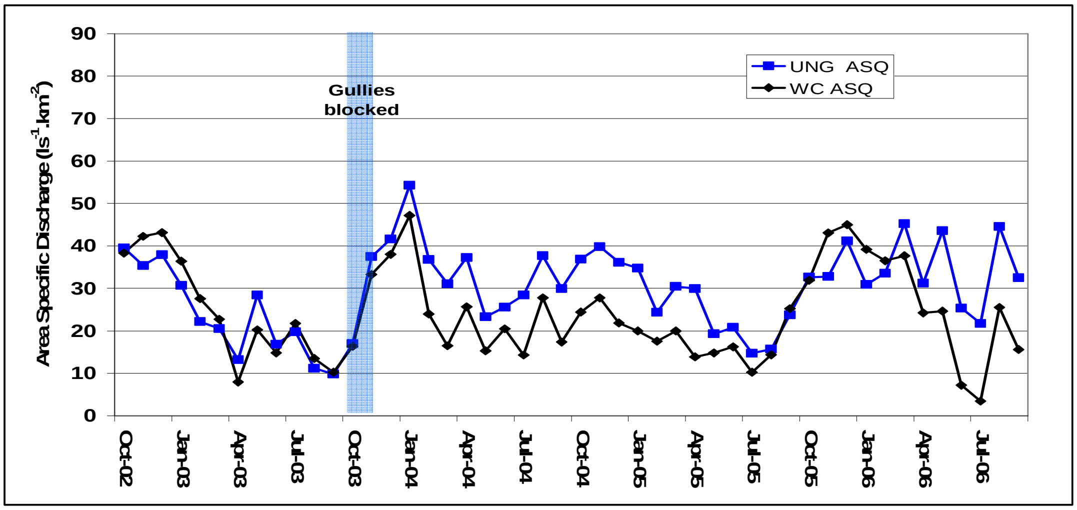


Figure 8.6b: Within Clough and Upper North Grain Observed Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006



The fit between observed and predicted monthly mean ASQ for the period Oct 2002–Dec 2003 was good (r^2 = 0.8615) and is shown in Figures 8.6c and 8.6d where the observed (black) and predicted (red) lines closely followed the same pattern and the residuals were small. In Nov-Dec 2003 (when the gully-blocking began) there was a slight over-prediction of ASQ at Within Clough, but from January 2004 there were large differences between the observed and predicted ASQ, particularly following the completion of the gully-blocking programme in December 2003. The ASQ was noticeably over-predicted from Jan 2004-Sep 2005. This effect was not seen on the other catchments where there was an under-prediction of ASQ for some of this period (with the exception of Doctors Gate Clough). The residuals indicate that less ASQ was flowing from the catchment than was expected and that more water was being retained on the site. It appears reasonable to consider that this may be a result of the gully-blocking as the over-prediction of ASQ commenced during and soon after completion of the gully-blocking programme.

During winter 2005-06 there appeared to be some recovery of ASQ as the rate increased in the winter period indicating that the site had rewet. In these circumstances ASQ may have largely been from surface runoff as the soil may have reached saturation point. ASQ for this period was generally under-predicted and there was more ASQ being discharged from the site than expected as predicted by the paired control catchment Upper North Grain where management had remained unaltered. During the spring/summer of the final year however, there was again an over-prediction of ASQ and this suggested that ASQ was lower than predicted and that more water was being retained on the catchment. The residuals were also larger during this period and indicated that more water was being retained at Within Clough during the drier conditions than expected from the relationship established previously during the calibration period.

Figure 8.6c: Within Clough Observed and Predicted Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 using paired Catchment Upper North Grain

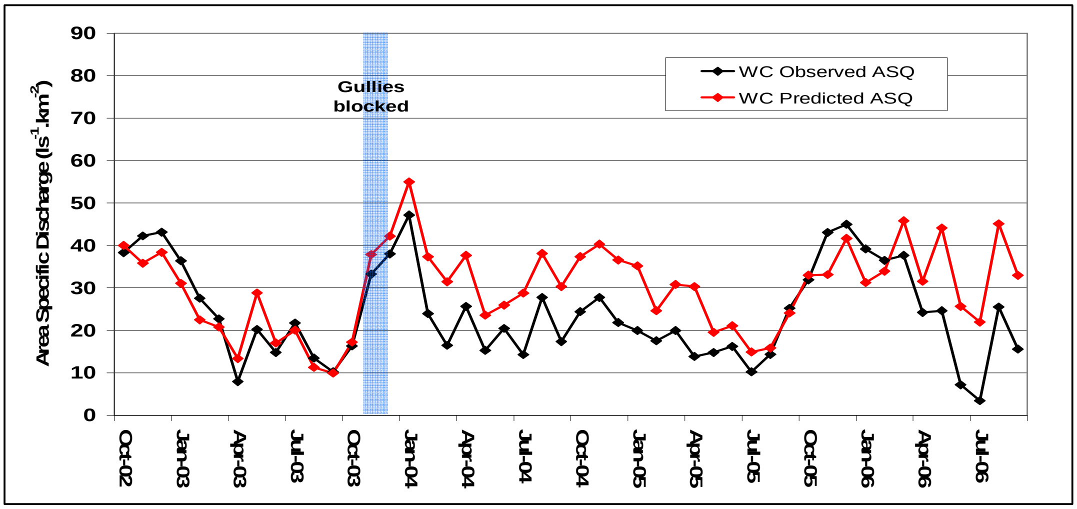


Figure 8.6d: Within Clough Residuals of Observed minus Predicted Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

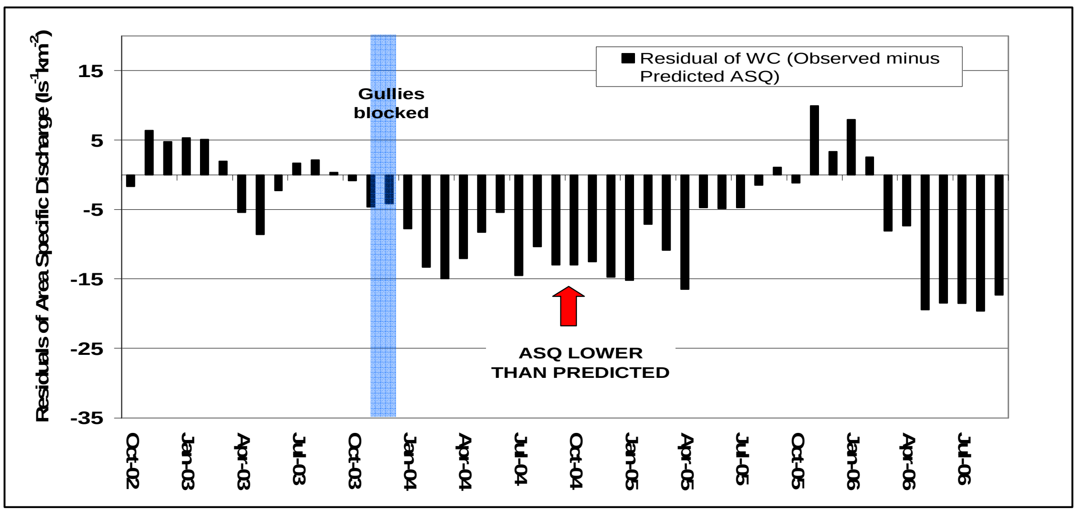


Table 8.11 presents a summary of the statistical analysis of differences in the residuals (monthly mean ASQ at Within Clough minus predicted ASQ from Upper North Grain) pre and post management manipulation. The main findings are summarised in Table 8.14.

Table 8.11: Statistical Summary of Residuals in Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Within Clough Pre and Post Management Manipulation using Paired Catchment Upper North Grain

Residuals of ASQ	N	Median ($ls^{-1}.km^{-2}$)	Mean ($ls^{-1}.km^{-2}$)	Mann Whitney U Probability	ANOVA Probability	F
WC pre mgt residuals (Oct 2002 – Dec 2003)	15	0.32	0.001			
WC post mgt residuals (Jan 2004 – Sept 2006)	33	-10.38	-8.81	<0.001**	<0.001**	16.38

** indicates significance p <0.01

8.3.3.3 *Nether Gate Clough (Cessation of Burning): Prediction of Monthly Mean Area Specific Discharge using Paired Catchment Upper North Grain*

Relationships during the calibration period between Nether Gate Clough and Upper North Grain were analysed for monthly mean area specific discharge (ASQ). Figures 8.7a and 8.7b show the relationship between Nether Gate Clough and Upper North Grain from which a predictive equation was determined to enable the values of monthly mean ASQ to be predicted post management manipulation (Equation 8.7).

$$y = 0.7058x + 20.102 \qquad r^2 = 0.9222$$

Equation 8.7

Where y = Nether Gate Clough monthly mean area specific discharge
x = Upper North Grain monthly mean area specific discharge n = 15

The fit between the observed and predicted monthly mean ASQ for the period Oct 2002–Dec 2003 was very good (r^2 = 0.9222). This is shown in Figure 8.7c where the observed (black) and predicted (red) lines followed a close pattern and the residuals (shown in Figure 8.7d) were relatively small. The predictive ability of the pairing continued well until summer 2005 when the differences between the observed and predicted ASQ increased and the residuals were much larger. This indicates that the relationship between Nether Gate Clough and Upper North Grain weakened during the post-management period and this is demonstrated in Figure 8.7b which shows the ASQ at Nether Gate Clough (black lines) decreased to a level similar to Upper North Grain (blue lines).

Figure 8.7a: Relationship between Nether Gate Clough and Upper North Grain Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Dec 2003

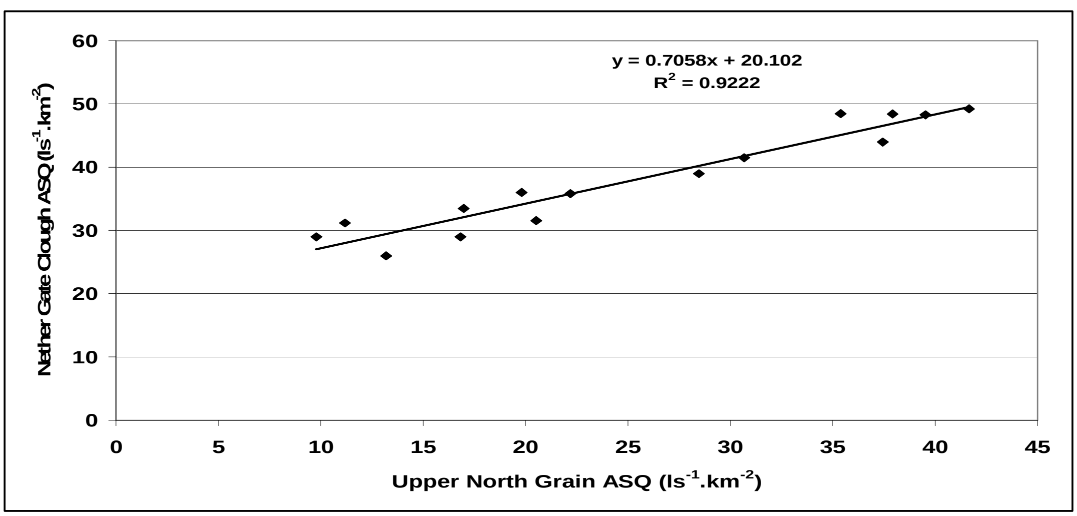
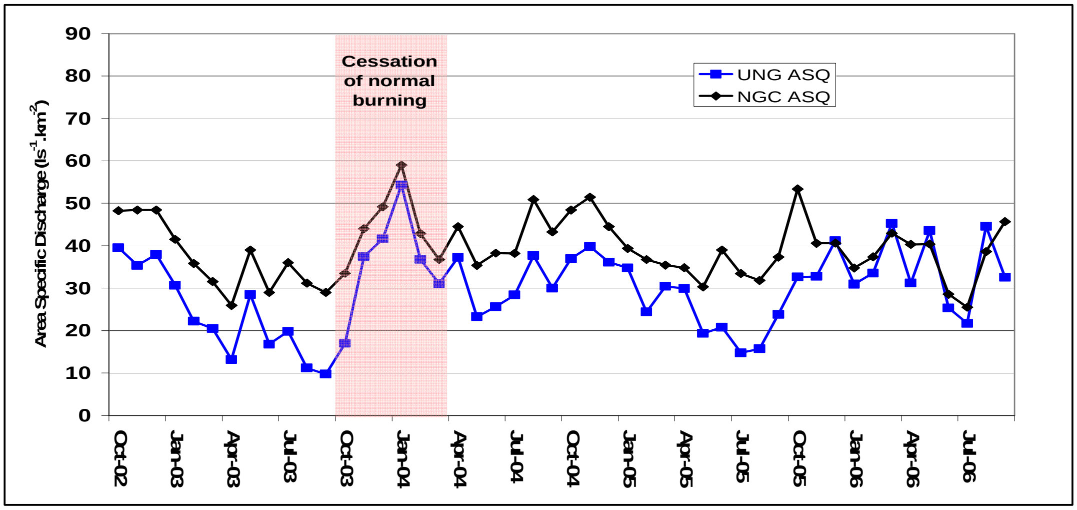


Figure 8.7b: Nether Gate Clough and Upper North Grain Observed Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006



During the calibration period the residuals followed a seasonal pattern whereby ASQ was slightly higher than predicted during the late summer/autumn and was lower than predicted in spring indicating that there was less water than expected being discharged from Nether Gate Clough in spring/early summer. This seasonal pattern continued throughout the treatment period, but there appeared to be a change in pattern with an increase in the residual difference during October 2005 when ASQ levels were higher than predicted, followed by a prolonged period during the summer when ASQ levels were lower than predicted.

Figure 8.7c: Nether Gate Clough Observed and Predicted Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

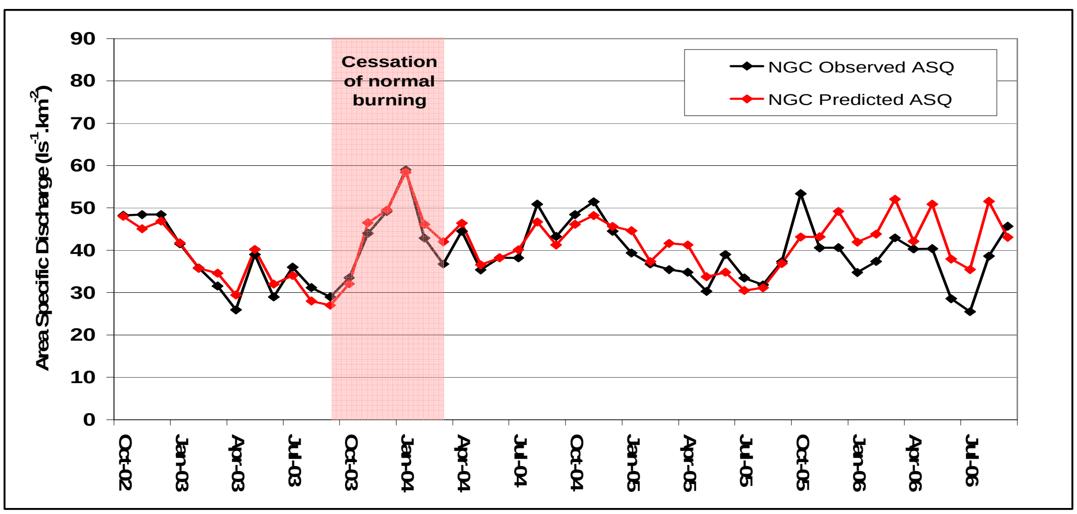


Figure 8.7d: Nether Gate Clough Residuals of Observed minus Predicted Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

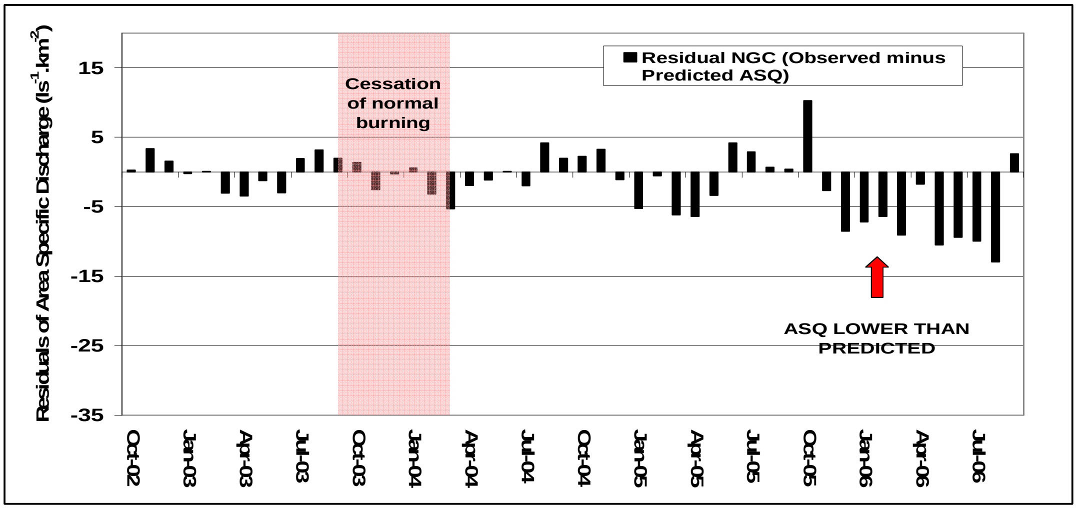


Table 8.12 presents a summary of the statistical analysis of differences in the residuals (monthly mean ASQ at Nether Gate Clough minus predicted ASQ from Upper North Grain) pre and post management manipulation. The main findings are summarised in Table 8.14.

Table 8.12: Statistical Summary of Residuals in Monthly Mean ASQ ($ls^{-1}.km^{-2}$) Nether Gate Clough Pre and Post Management Manipulation (Observed minus Predicted) using Paired Catchment Upper North Grain

Residuals of ASQ	N	Median ($ls^{-1}.km^{-2}$)	Mean ($ls^{-1}.km^{-2}$)	Mann Whitney U Probability	ANOVA Probability	F
NGC pre mgt residuals (Oct 2002 – Dec 2003)	15	0.08	0			
NGC post mgt residuals (Jan 2004 – Sept 2006)	33	-1.91	-2.47	0.12	0.085	3.09

8.3.3.4 Doctors Gate Clough (Removal of Grazing): Prediction of Monthly Mean Area Specific Discharge using Paired Catchment Upper North Grain

Relationships during the calibration period between Doctors Gate Clough and Upper North Grain were analysed for monthly mean area specific discharge (ASQ). Figures 8.8a and 8.8b show the relationship between Doctors Gate Clough and Upper North Grain from which a predictive equation was determined to enable the values of monthly mean ASQ to be predicted post management manipulation (Equation 8.8).

$y = 1.5566x + 0.5862$ $\quad\quad$ $r^2 = 0.7777$

Equation 8.8

Where $\quad$ y = Doctors Gate Clough monthly mean area specific discharge ($ls^{-1}.km^{-2}$)

x = Upper North Grain monthly mean area specific discharge ($ls^{-1}.km^{-2}$) $\quad$ n = 14

Figure 8.8a: Relationship between Doctors Gate Clough and Upper North Grain Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Dec 2003

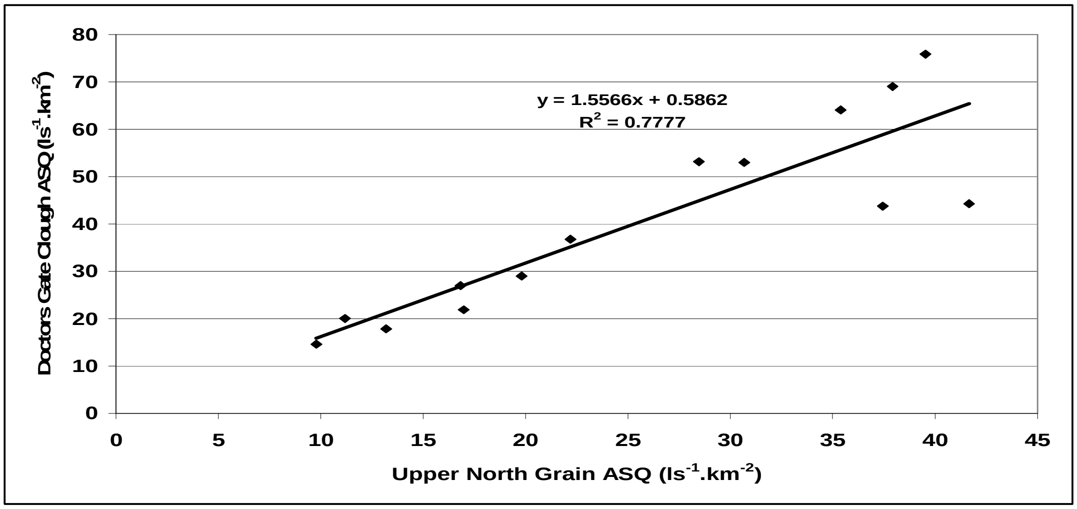
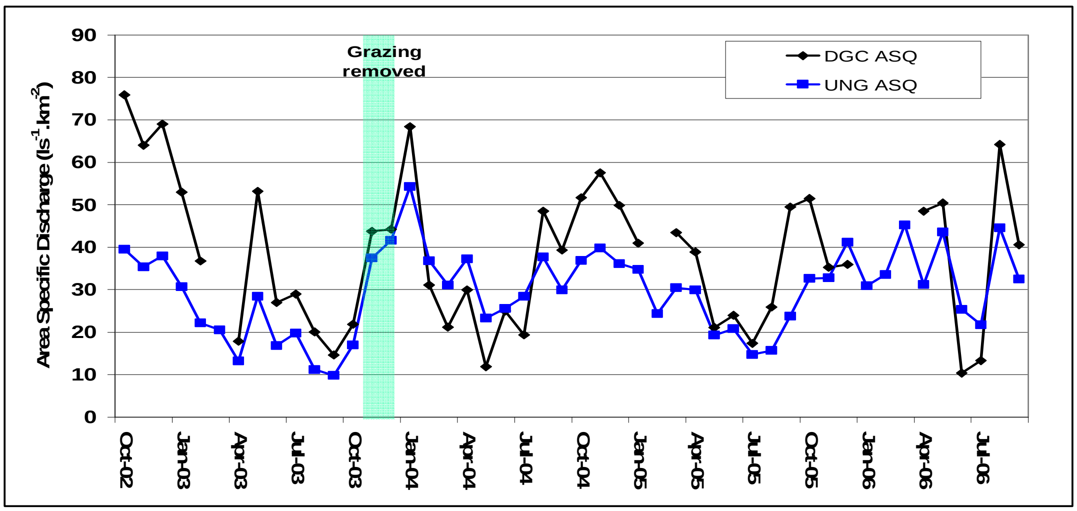


Figure 8.8b: Doctors Gate Clough and Upper North Grain Observed Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006



The fit between observed and predicted monthly mean ASQ for the period Oct 2002–Dec 2003 was good (r^2 = 0.7777) and is shown in Figure 8.8c where the observed (black) and predicted (red) lines followed the same pattern and the residuals (shown in Figure 8.8d) were relatively small. However, from January 2004 and for the remainder of the monitoring period the differences between the observed and predicted ASQ increased and the residuals were much larger. This indicated that the relationship between Doctors Gate Clough and Upper North Grain weakened during the post-management period and this is illustrated in Figure 8.8b which shows the ASQ at Doctors Gate Clough (black lines) and Upper North Grain (blue lines).

Figure 8.8c: Doctors Gate Clough Observed and Predicted Monthly Mean ASQ ($ls^{-1}.km^{-2}$) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

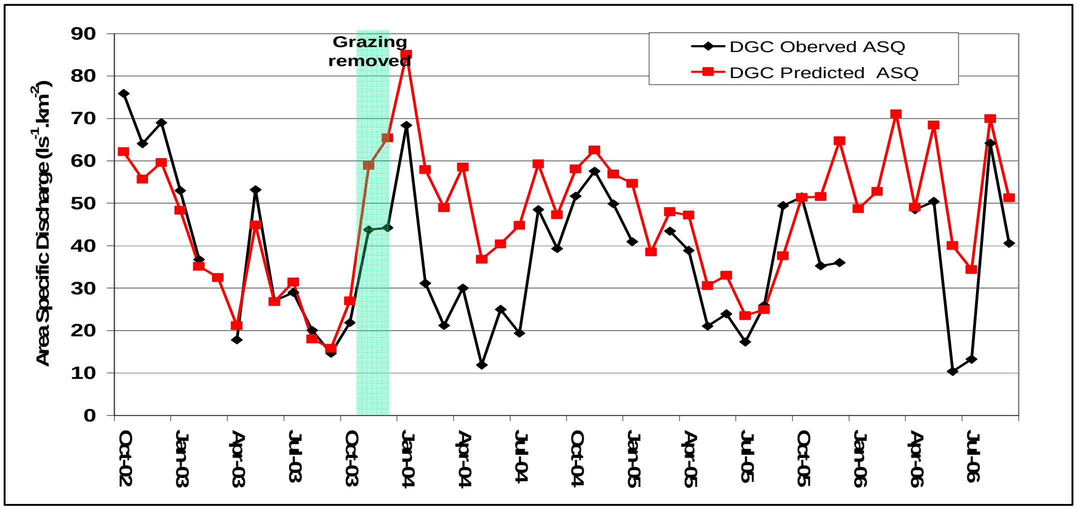
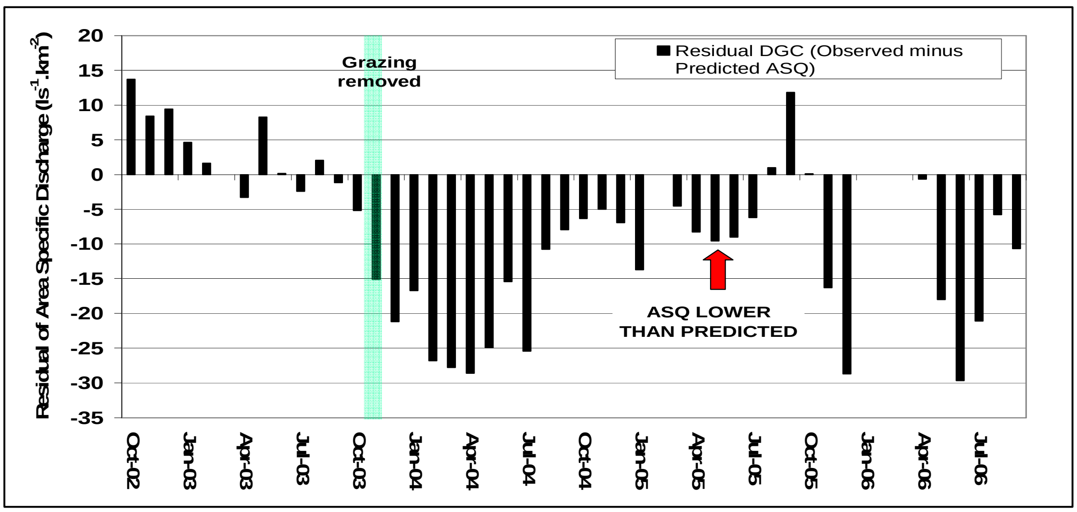


Figure 8.7d: Doctors Gate Clough Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Residuals of Observed minus Predicted (Oct 2002-Sept 2006) using Paired Catchment Upper North Grain



During the calibration period the residuals appeared to follow a seasonal pattern whereby ASQ was lower than predicted during the winter months, and was more variable during the summer months. Figure 8.8d shows that following the change in management manipulation there was a step change in ASQ on the treated catchment and despite being elevated at both sites, ASQ was less than predicted at Doctors Gate Clough. It should be emphasised that although the changes in ASQ coincide with the change in management, this may not have been a direct causative effect. This pattern was also similar to the monthly mean true colour predicted at Doctors Gate Clough by Red Clough (see Section 8.2.3.3) and indicates a complex change in processes generating both colour and discharge at Doctors Gate Clough.

The model generally over-predicted the ASQ at Doctors Gate Clough throughout the remainder of the study period post management manipulation, with the exception of Jul-Aug 2005 when total rainfall for each month was comparatively low (70.7 and

76.4 mm) and yet observed ASQ was higher than predicted. The data suggest that following the removal of grazing, Doctors Gate Clough was discharging a lower ASQ than predicted and this rewetting of the catchment may have contributed to the observed flushing out of iron during the summer and organic carbon in the winter following the recharge of previously aerobic soil in the acrotelm layer.

Table 8.13 presents a summary of the statistical analysis of differences in the residuals (monthly mean ASQ at Doctors Gate Clough minus predicted ASQ from Upper North Grain) pre and post management manipulation. The main findings are summarised in Table 8.14.

Table 8.13: Statistical Summary of Residuals in Monthly Mean Area Specific Discharge ($ls^{-1}.km^{-2}$) Doctors Gate Clough Pre and Post Management Manipulation (Observed minus Predicted) using Paired Catchment Upper North Grain

Residuals of ASQ	N	Median ($ls^{-1}.km^{-2}$)	Mean ($ls^{-1}.km^{-2}$)	Mann Whitney U Probability	ANOVA Probability	F
DGC pre mgt residuals (Oct 2002 – Dec 2003)	14	0.91	0			
DGC post mgt residuals (Jan 2004 – Sept 2006)	29	-10.65	-12.83	<0.001**	<0.001**	14.83

** indicates significance p <0.01 * indicates significance p <0.05

8.3.4 Summary of Prediction of Area Specific Discharge using Paired Catchment Model

Table 8.14 presents a summary of the main findings for the prediction of ASQ at the sites

Table 8.14: Summary of Prediction of Area Specific Discharge ($ls^{-1}.km^{-2}$) using Paired Catchment Model

Site	Calibration Period Oct 2002-Dec 2003		Treatment Period Jan 2004-Sept 2006	
	Observed ASQ	**Predicted ASQ**	**Observed ASQ**	**Predicted ASQ**
Red Clough (CONTROL) paired with Upper North Grain	Increased runoff winter 2002-03	Regression equation good fit (r^2 = 0.912) General under prediction in winter and over prediction in summer	Increased runoff winter 2003-04 higher than winter 2002-03 Increased runoff Aug 04 and winter 2004-05 – similar to 2002-nt Increased runoff winter 2005-06 – similar to winter 2002-03 Low runoff summer 2006	From Jan 04 general under prediction of ASQ to winter 2004-05 when small over prediction In winter 2005-06 residuals increased and greater under prediction of ASQ and larger over prediction of ASQ during summer 2006 Differences in residuals between calibration and treatment period increase in mean of 0.5 $ls^{-1}km^{-2}$and not statistically significant
Within Clough (gullies blocked) paired with Upper North Grain	Increased runoff winter 2002-03	Regression equation good fit (r^2 = 0.862) General under prediction in winter and over prediction in summer	Increased runoff winter 2003-04 followed by prolonged period of low runoff with no obvious increase during winter 2004-05 Increased runoff winter 2005-06 at similar level to winter 2002-03 Low runoff summer 2006	From Nov03-Jul 05 over prediction of ASQ following installation of gully-blocks Winter 2005-06 under prediction of ASQ, but residuals and over prediction of ASQ occurred during summer 2006 Differences in residuals between calibration and treatment period decrease in mean of 9 $ls^{-1}km^{-2}$ from that predicted and statistically significant Practical significant predicted reduction in total runoff of 278 $mmyr^{-1}$ (1 % of Ladybower reservoir capacity).

Site	Calibration Period Oct 2002-Dec 2003		Treatment Period Jan 2004-Sept 2006	
	Observed ASQ	**Predicted ASQ**	**Observed ASQ**	**Predicted ASQ**
Nether Gate Clough (cessation of burning) paired with Upper North Grain	Increased runoff winter 2002-03	Regression equation good fit (r^2 = 0.922) General under prediction in winter and over prediction in summer	Increased runoff winter 2003-04, higher than winter 2002-03 Increased runoff Aug 2004 and winter 2004-05 Increased runoff winter 2005-06 Low runoff summer 2006	Seasonal predictions continued but over prediction in winter and under prediction in summer. This pattern continued during summer 2004 and 2005 with over prediction in winter 2003-04, 2004-05 and 2005-06 During summer 2006 increase in residuals and over prediction of ASQ i.e. less runoff than predicted Differences in residuals between calibration and treatment period decrease in mean of 2.5 $ls^{-1}km^{-2}$ from that expected and weakly significant Practical significant increase in total runoff from that expected of 84 $mm.yr^{-1}$ (0.3% of Ladybower reservoir capacity).
Doctors Gate Clough (removal of grazing) paired with Upper North Grain	Increased runoff winter 2002-03	Regression equation good fit (r^2 = 0.778) General under prediction in winter and over prediction in summer	Increased runoff winter 2003-04 lower than winter 2002-03 Increased runoff Aug 2004 and winter 2004-05 Low runoff summer 2006	From Oct 03 general over prediction of runoff with increasing residuals peaking in winter 04, Dec 05 and Jun 06 Differences in residuals between calibration and treatment period decrease in mean of 13 $ls^{-1}km^{-2}$ from that expected and statistically significant Practically significant reduction in total runoff of 430 $mm.yr^{-1}$ from that expected (1.5% Ladybower reservoir capacity)

8.3.5 Catchment Pairings and Prediction of Monthly Mean Areal Export of Dissolved Organic Carbon

Analysis of similarities in monthly mean DOC flux between catchments was completed using the Pearson's correlation co-efficient in the statistical software SPSS v.15. DOC flux is considered an important concept in terms of contribution to increasing cost of water treatment. Table 8.15 shows the results of the correlations; a number of sites were highly correlated. All treated catchments where management had been manipulated were highly correlated with the control catchments. Upper Gate Clough has however been excluded from the analysis because of problems with data loss and unreliable data from stage loggers at this site particularly in the second and third year of the study as previously discussed in Chapters 3 and 7. Doctors Gate Clough was highly correlated with Red Clough (Pearson's r = 0.658, p = 0.008) and Upper North Grain (Pearson's r = 0.674, p = 0.006); Nether Gate Clough was highly correlated with Red Clough (Pearson's r = 0.929, p <0.001) and Upper North Grain (Pearson's r = 0.943, p <0.001) whilst Within Clough was also highly correlated with these sites: Red Clough (Pearson's r = 0.950, p <0.001) and Upper North Grain (Pearson's r = 0.940, p <0.001). All these correlations were good and provided an acceptable relationship between the pairs in order to predict changes in monthly mean DOC flux. Upper North Grain was the most complete data set and therefore was selected to be an appropriate control catchment by which the effects of land management manipulation could be analysed on the three treated catchments in terms of DOC flux and would then enable comparison of the relationship with Upper North Grain between the sites.

Table 8.15: Ashop Catchments Correlations of Monthly Mean DOC Flux (Ct.mth^{-1}.km^{-2})

		DGCDOC	UNGDOC	NGCDOC	RCDOC	WCDOC
DGCDOC	Pearson Correlation	1	.674**	.648**	.658**	.686**
	Sig. (2-tailed)		.006	.009	.008	.005
	N	15	15	15	15	15
UNGDOC	Pearson Correlation	.674**	1	.943**	.941**	.940**
	Sig. (2-tailed)	.006		.000	.000	.000
	N	15	15	15	15	15
NGCDOC	Pearson Correlation	.648**	.943**	1	.929**	.976**
	Sig. (2-tailed)	.009	.000		.000	.000
	N	15	15	15	15	15
RCDOC	Pearson Correlation	.658**	.941**	.929**	1	.950**
	Sig. (2-tailed)	.008	.000	.000		.000
	N	15	15	15	15	15
WCDOC	Pearson Correlation	.686**	.940**	.976**	.950**	1
	Sig. (2-tailed)	.005	.000	.000	.000	
	N	15	15	15	15	15

** indicates significance p <0.01 * indicates significance p <0.05

8.3.5.1 Control Catchments: Predicted Monthly Mean Areal Export of DOC using Paired Catchment Control Catchments

The areal export of DOC was calculated by multiplying DOC (Ct) and ASQ ($ls^{-1}.km^{-2}$) for each catchment. Missing or problem stage/discharge data at Upper Gate Clough (control) (see Chapter 3 and 7) meant the calculation of ASQ was not representative for the site and therefore was not used to calculate DOC flux for the catchment during the calibration and treatment period. Likewise, the use of Red Clough (control) as a second site by which to determine changes on treated catchments was questionable because of the large increases in true colour observed particularly during the treatment period (2003-2006) (see Section 6.3). Whilst it was possible to compare two control catchments to determine changes in true colour (Upper Gate Clough and Upper North Grain – not significant) and ASQ (Red Clough and Upper North Grain – not significant), it was not possible to compare two of the control sites for areal export of DOC because of the difficulties described. The subsequent sections therefore compare each treated catchment with the one control catchment (Upper North Grain) where management was not altered and from which an acceptable dataset was collected.

8.3.5.2 Within Clough (Gully Blocking): Predicted Monthly Mean Areal Export of DOC using Paired Catchment Upper North Grain

Relationships during the calibration period between Within Clough and Upper North Grain were analysed for monthly mean DOC flux. Figures 8.9a and 8.9b show the relationship between Within Clough and Upper North Grain from which a predictive equation was determined to enable the values of monthly mean DOC flux to be predicted post management manipulation (Equation 8.9).

$$y = 1.1389x - 0.0219 \qquad r^2 = 0.8842$$

Equation 8.9

Where y = Within Clough monthly mean area specific true colour load
x = Upper North Grain monthly mean area specific true colour load n = 15

The fit between the observed and predicted monthly mean DOC flux for the period Oct 2002–Dec 2003 was good (r^2 = 0.8842) and is shown in Figures 8.9c and 8.9d where the observed (black) and predicted (red) lines closely followed the same pattern and the residuals are small.

Figure 8.9a: Relationship between Within Clough and Upper North Grain Monthly Mean Areal Export of DOC ($Ct.mth^{-1}.km^{-2}$) Oct 2002-Dec 2003

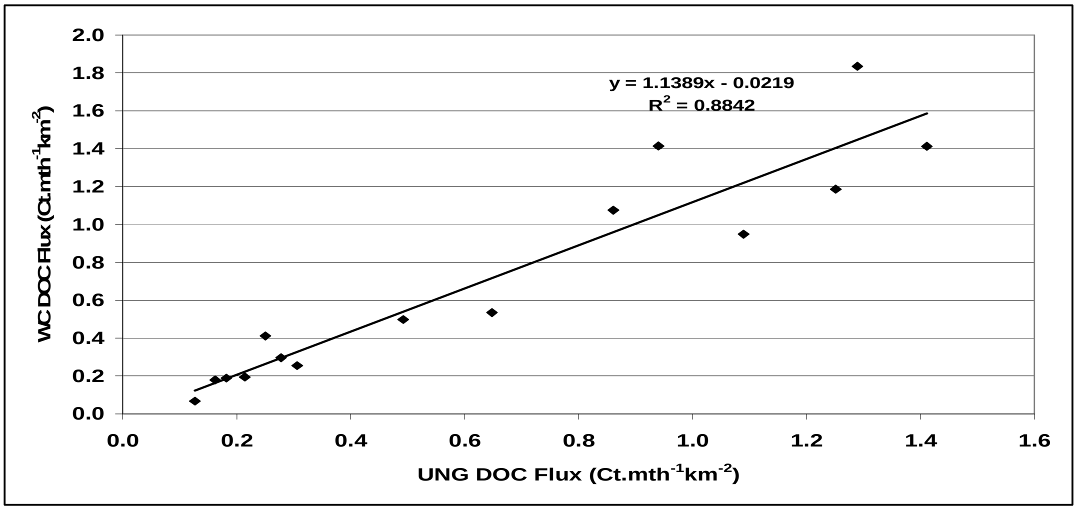
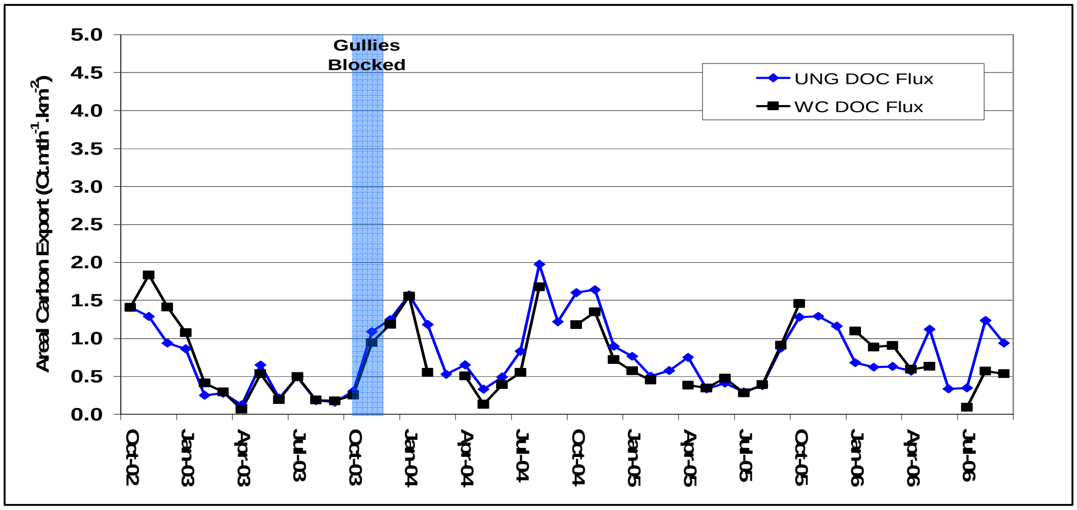


Figure 8.9b: Within Clough and Upper North Grain Observed Monthly Mean of Areal Export of DOC ($Ct.mth^{-1}.km^{-2}$) Oct 2002-Sept 2006



The areal export of DOC flux during the calibration period followed a seasonal pattern with an under-prediction of DOC flux during the winter and a smaller over-prediction during the spring/summer. In Nov-Dec 2003 there was a slight over-prediction of DOC flux, but from January 2004, on completion of the gully-blocking, there was a prolonged period to summer 2005 when the DOC flux was over-predicted and the observed DOC flux was less than would be expected to be discharged from the site. Figures 8.9c and 8.9d show the DOC flux was noticeably over-predicted from Jan 2004-Jul/Aug 2005.

The residuals suggest that less DOC flux was being discharged from the Within Clough catchment and more water was being retained on the site during this period. During Jan and Feb 2006 there appeared to be some recovery of DOC flux but during the spring/summer of the final year there was again an over-prediction of DOC flux and this indicates that DOC flux was lower than expected, suggesting that more water was once again being retained on the catchment.

Figure 8.9c: Within Clough Observed and Predicted Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Sept 2006

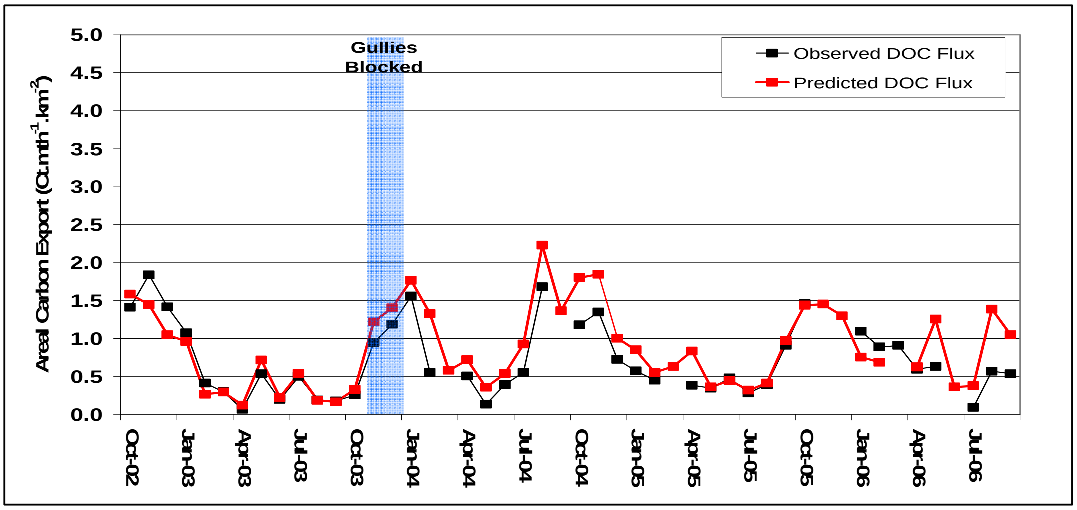


Figure 8.9d: Within Clough Monthly Mean True Colour Residuals (Observed minus Predicted) Monthly Mean Areal Export of DOC (Ct.mth^{-1}.km^{-2}) Oct 2002-Sept 2006 using paired Catchment Upper North Grain

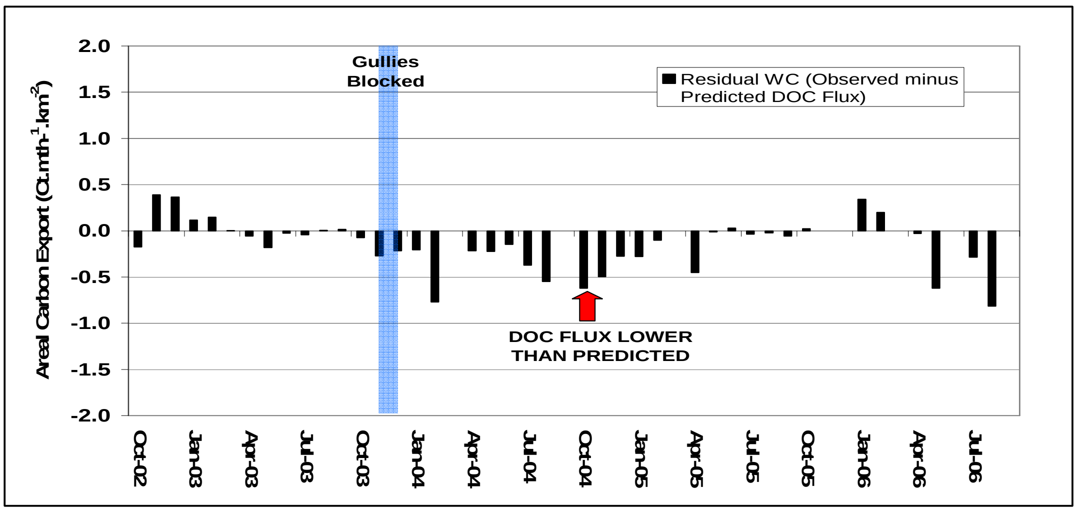


Table 8.16 presents a summary of the statistical analysis of differences in the residuals (monthly mean areal export of DOC at Within Clough minus predicted areal export of DOC from Upper North Grain) pre and post management manipulation. The main findings are summarised in Table 8.19.

Table 8.16: Statistical Summary of Residuals Monthly Mean Areal Export of DOC (Ct.mth^{-1}.km^{-2}) Within Clough Pre and Post Management Manipulation (Observed minus Predicted) using Paired Catchment Upper North Grain

Residuals of Areal Export of DOC	N	Median (Ct.mth^{-1}. km^{-2})	Mean (Ct.mth^{-1}. km^{-2})	Mann Whitney U Probability	ANOVA Probability	F
WC pre mgt residuals (Oct 2002 – Dec 2003)	15	-0.03	0.0007			
WC post mgt residuals (Jan 2004 – Sept 2006)	25	-0.22	-0.241	0.01**	<0.01**	8.09

**indicates significance <0.01 * indicates significance p <0.05

8.3.5.3 Nether Gate Clough (Cessation of Burning): Predicted Monthly Mean Areal Export of DOC using Paired Catchment Upper North Grain

Relationships during the calibration period between Nether Gate Clough and Upper North Grain have been analysed for monthly mean areal export of DOC. Figures 8.10a and 8.10b show the relationship between Nether Gate Clough and Upper North Grain from which a predictive equation was determined to enable the values of monthly mean true colour load to be predicted post management manipulation (Equation 8.10).

$y = 1.266x + 0.1113 \qquad r^2 = 0.8859$ **Equation 8.10**

Where y = Nether Gate Clough monthly mean area specific true colour load

x = Upper North Grain monthly mean area specific true colour load n = 15

Figure 8.10a: Relationship between Nether Gate Clough and Upper North Grain Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Dec 2003

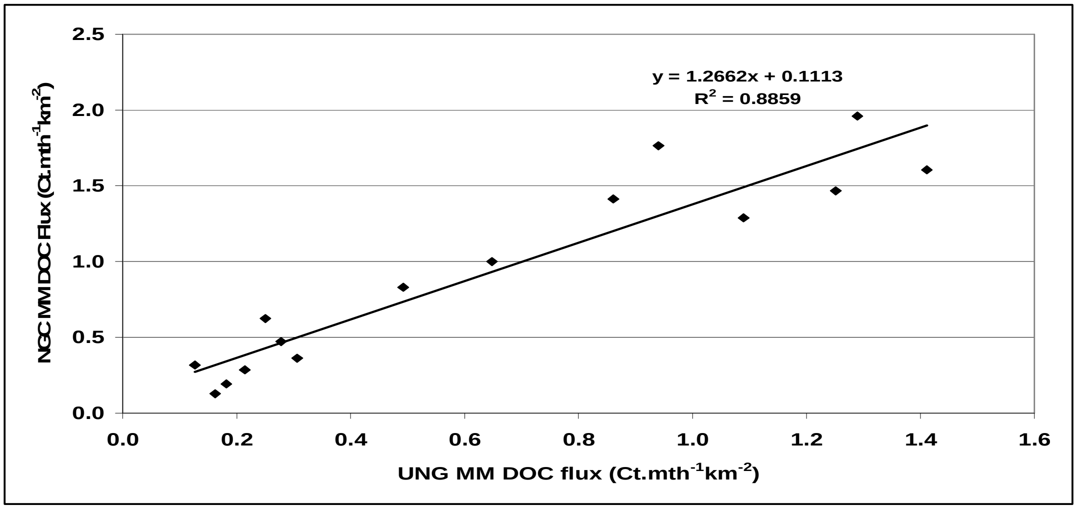
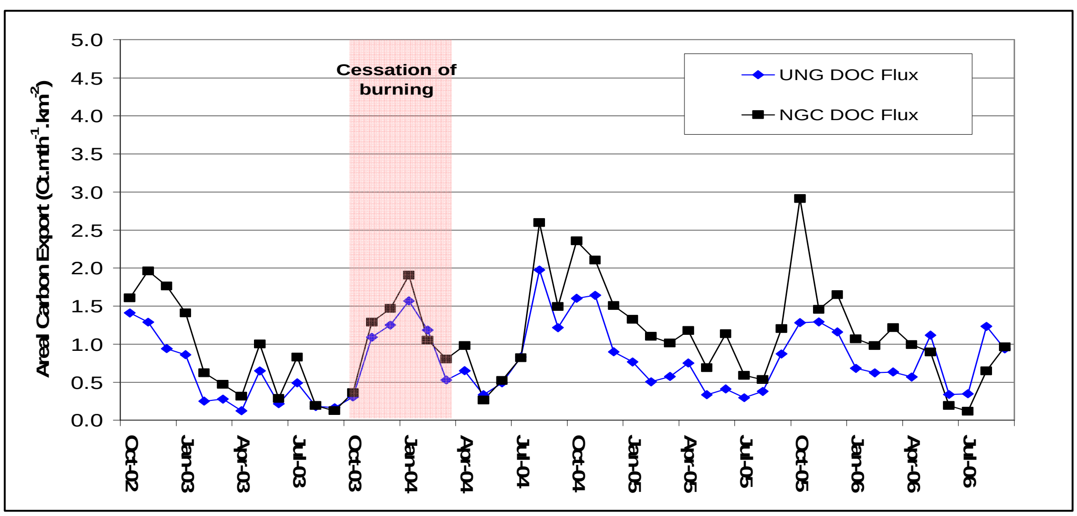


Figure 8.10b: Nether Gate Clough and Upper North Grain Observed Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Sept 2006



The fit between the observed and predicted monthly mean areal export of DOC for the period Oct 2002–Dec 2003 was good (r^2 = 0.8859). This is shown in Figures 8.10c where the observed (black) and predicted (red) lines followed a close pattern and the residuals (shown in Figure 8.10d) were relatively small. The good predictive ability of the pairing continued until summer 2005, after which the differences between the observed and predicted ASQ increased and the residuals were much larger. This indicates that the relationship between Nether Gate Clough and Upper North Grain weakened during the treatment period in the final year and this is illustrated in Figure 8.10b which shows the ASQ at Nether Gate Clough (black lines) and Upper North Grain (blue lines).

Figure 8.10c: Nether Gate Clough Observed and Predicted Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

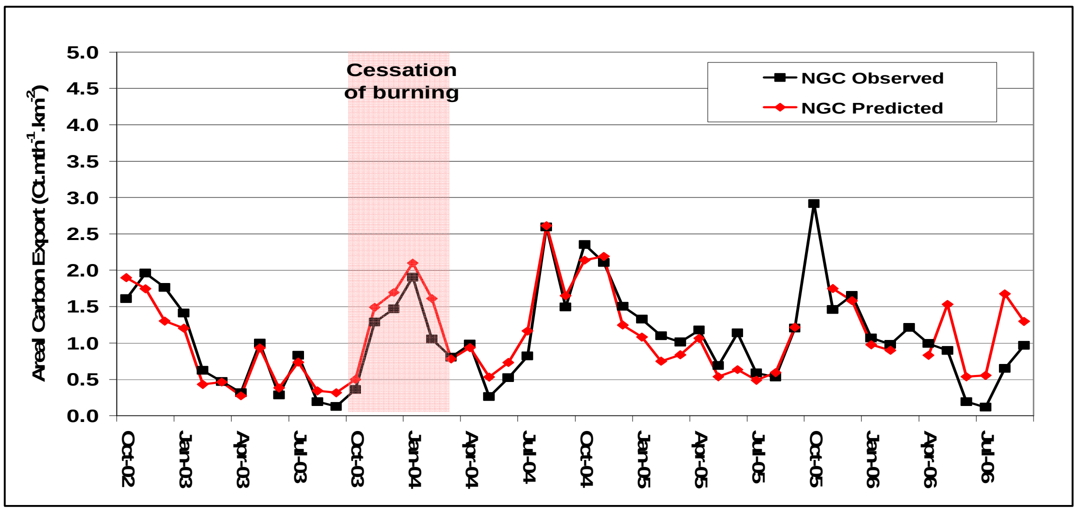
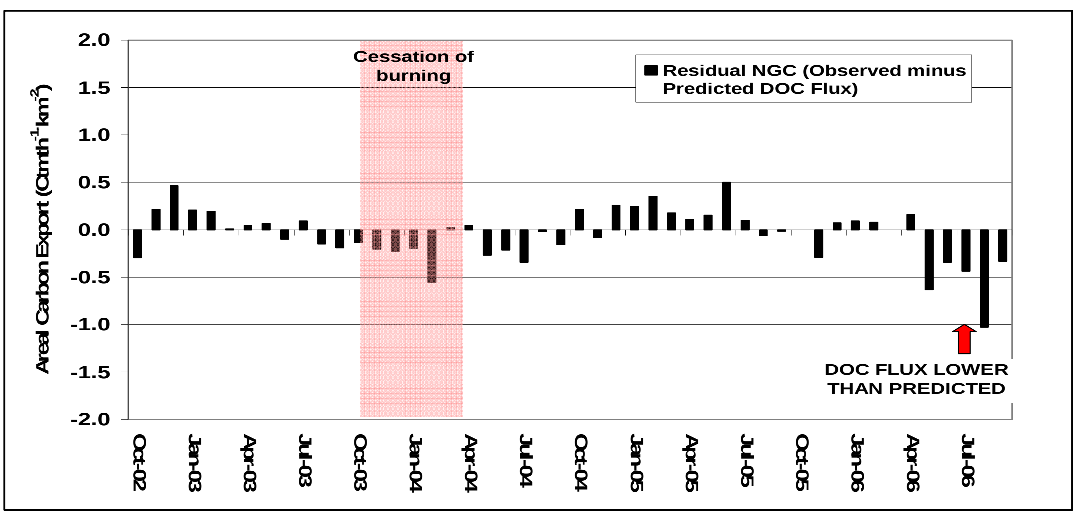


Figure 8.10d: Nether Clough Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Residuals (Observed minus Predicted) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain



During the calibration period the residuals followed a seasonal pattern whereby the observed areal export of DOC was higher than predicted during the winter and was lower than predicted in late summer/autumn indicating that there was less discoloured water than expected being discharged from the catchment during the drier summers. This seasonal pattern continued throughout the treatment period, but in the final year of study, the pattern continued with an increase in the residual difference, particularly in Oct 2005 when DOC flux was lower than predicted, followed by a prolonged period during the summer 2006 when DOC flux was also lower than predicted.

Table 8.17 presents a summary of the statistical analysis of differences in the residuals (Nether Gate Clough minus Upper North Grain monthly mean areal export of DOC) pre and post management manipulation. The main findings are summarised in Table 8.19.

Table 8.17: Statistical Summary of Residuals (Observed minus Predicted) in Monthly Mean Areal Export of DOC ($Ct.mth^{-1}km^{-2}$) Nether Gate Clough Pre and Post Management Manipulation using Paired Catchment Upper North Grain

Residuals of Areal Export of DOC	N	Median ($Ct.mth^{-1}.km^{-2}$)	Mean ($Ct.mth^{-1}.km^{-2}$)	Mann Whitney U Probability	ANOVA Probability	F
NGC pre mgt residuals (Oct 2002 – Dec 2003)	15	0.01	0			
NGC post mgt residuals (Jan 2004 – Sept 2006)	31	-0.01	-0.077	0.631	0.404	0.71

8.3.5.4 Doctors Gate Clough (Removal of Grazing): Predicted Monthly Mean Areal Export of DOC using Paired Catchment Upper North Grain

The sheep were removed from Doctors Gate Clough catchment during the autumn/winter 2002/03. For analytical purposes the calibration period was accepted as Oct 2002-Dec 2003 when the programme of removing the sheep and erection of fencing was completed. Regression relationships during the calibration period between Doctors Gate Clough and Upper North Grain and between Doctors Gate Clough and Red Clough were analysed for monthly mean areal export of DOC. Both pairings had a relatively poor linear relationship, but the pairing of Doctors Gate Clough and Upper North Grain was accepted because of the more complete data set post management manipulation. Figures 8.11a and 8.11b shows the relationship between Doctors Gate Clough and Upper North Grain from which a predictive equation was determined to enable the monthly mean areal export of DOC to be predicted post management manipulation (Equation 8.11).

$$y = 1.2699x + 0.4219 \qquad r^2 = 0.4545$$

Equation 8.11

Where y = Doctors Gate Clough monthly mean area specific true colour load

x = Upper North Grain monthly mean area specific true colour load n = 15

Figure 8.11a: Relationship between Doctors Gate Clough and Upper North Grain Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Dec 2003

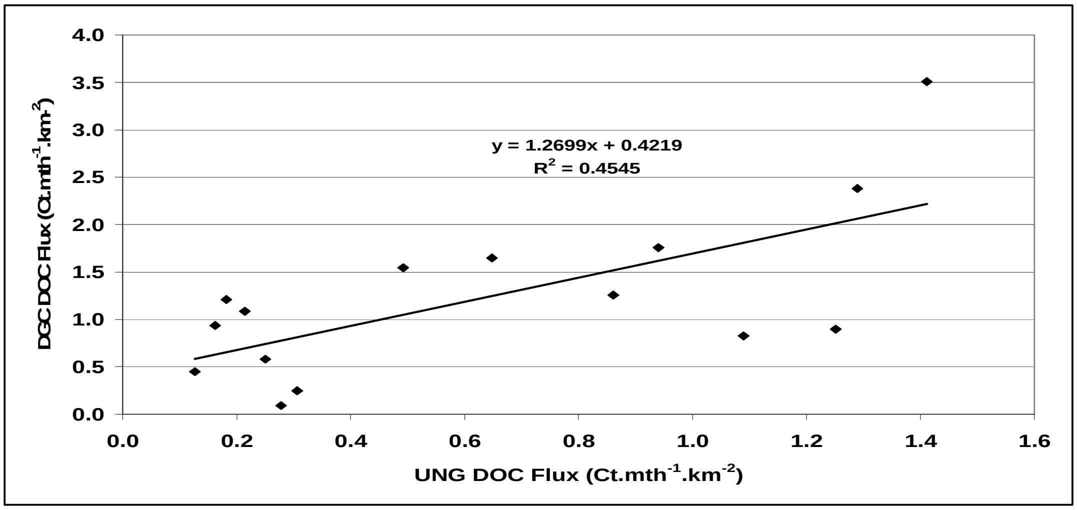
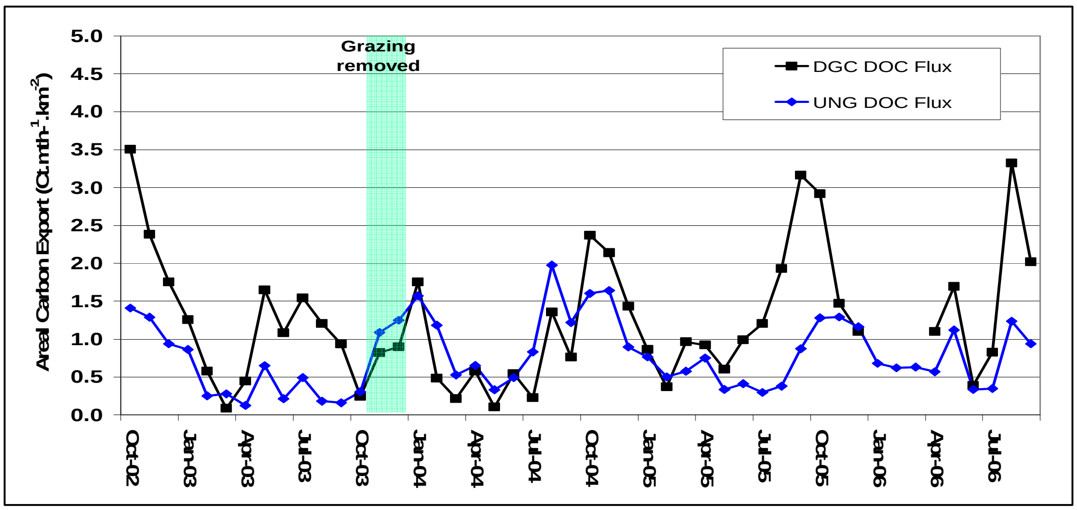


Figure 8.11b: Doctors Gate Clough and Upper North Grain Observed Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Sept 2006



The fit between observed and predicted monthly mean DOC flux for the period Oct 2002–Dec 2003 was relatively poor (r^2 = 0.455) and is shown in Figure 8.11c where the observed (black) and predicted (red) lines do not follow the same pattern and the residuals (shown in Figure 8.11d) were relatively large. In previous analysis of monthly mean colour (paired with Red Clough) and monthly mean ASQ (paired with Upper North Grain) the residuals of observed and predicted monthly colour or ASQ increased and became much larger post-management manipulation in Jan 2004. However, when considering areal export of DOC, there was no obvious increase in the residuals at this point and a seasonal pattern continued with a general over-prediction of DOC flux during the winter-spring and an under-prediction, particularly in the late summer of each year when the water was highly discoloured by the iron oxidation (see Section 6.3).

Figure 8.11c: Doctors Gate Clough Observed and Predicted Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain

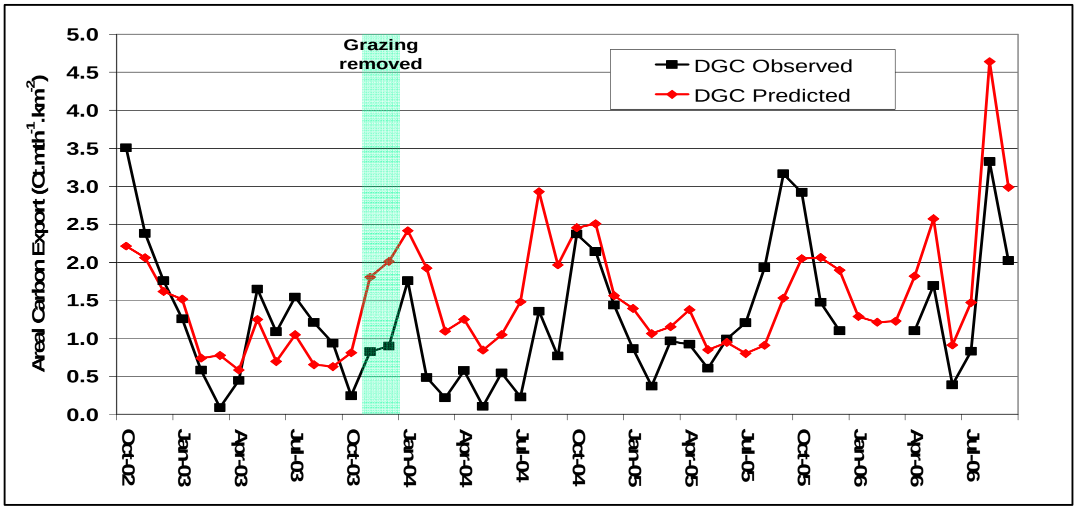
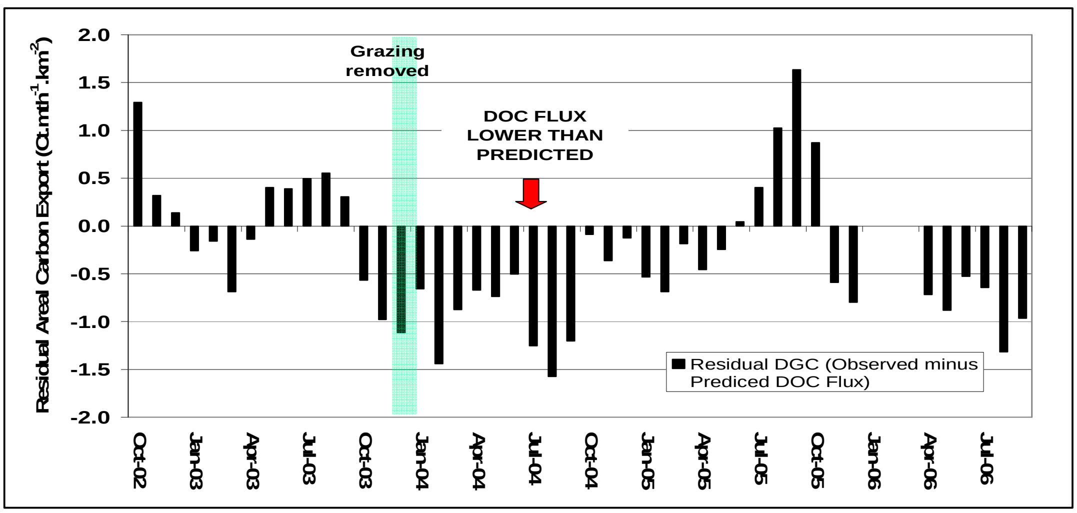


Figure 8.11d: Doctors Gate Clough Monthly Mean Areal Export of DOC (Ct.mth^{-1}km^{-2}) Residuals (Observed minus predicted) Oct 2002-Sept 2006 using Paired Catchment Upper North Grain



The model generally over-predicted the areal export of DOC at Doctors Gate Clough throughout the remainder of the study period post management manipulation, with the exception of Aug-Oct 2005 when warm, dry conditions prevailed and the colour levels at Doctors Gate Clough escalated and DOC flux was under-predicted. It should be noted that data are missing from Dec 2005-Mar 2006 at Doctors Gate Clough and therefore the predictive ability of the model during the final winter is uncertain. Nevertheless, the model did partially account for the elevation in DOC flux during the summer, particularly in the first and second year post manipulation, but was less able to predict the increase in colour during the winter months (associated with organic carbon). This illustrates the complex processes occurring on the catchment in the generation of colour from two different sources, that is, largely organic carbon in the autumn/winter and precipitation of iron during the summer. This was further complicated by the non-stationarity of the colour associated with the preceding drought conditions and time-lag effects in colour storage on the catchment which may only be released when the catchment rewets.

Table 8.18: Statistical Summary of Residuals in Monthly Mean Areal Export of DOC ($Ct.mth^{-1}km^{-2}$) Doctors Gate Clough Pre and Post Management Manipulation (Observed minus Predicted) using Paired Catchment Upper North Grain

Residuals of Areal Export of DOC	N	Median ($Ct.mth^{-1}.km^{-2}$)	Mean ($Ct.mth^{-1}.km^{-2}$)	Mann Whitney U Probability	ANOVA Probability	F
DGC pre mgt residuals (Oct 2002 – Dec 2003)	15	0.14	-0.0007			
DGC post mgt residuals (Jan 2004 – Sept 2006)	30	-0.62	-0.4693	0.03*	0.04*	4.55

** indicates significance p <0.01   * indicates significance p <0.05

Table 8.18 presents a summary of the statistical analysis of differences in the residuals (Doctors Gate Clough minus Upper North Grain monthly mean areal export of DOC) pre and post management manipulation. The main findings are summarised in Table 8.19.

8.3.4 Summary of Prediction of Areal Export of DOC using Paired Catchment Model

Table 8.19 presents a summary of the main findings for the prediction of areal export of DOC at the sites.

Table 8.19: Summary of Prediction of Areal Export of DOC Flux ($Ct.mth.km^{-2}$) using Paired Catchment Model

Site	Calibration Period Oct 2002-Dec 2003		Treatment Period Jan 2004-Sept 2006	
	Observed DOC flux	**Predicted DOC flux**	**Observed DOC flux**	**Predicted DOC flux**
Within Clough (gullies blocked) paired with Upper North Grain	Flush in winter 2002-03 and reduced summer 2003	Regression equation good fit ($r^2 = 0.884$) General under prediction in winter and over prediction in summer	Flush winter 2003-04 similar to 2002-03 Flush winter 2004-05 similar to 2002-03 Flush winter 2005-06 lower than 2002-03	From Oct 03 to Sept 05 prolonged period of under prediction, although residuals May 05-Oct 05 very small Winter 05 under prediction and summer 06 over prediction (similar to pattern observed during calibration period) Differences in residuals between calibration and treatment period decrease 0.24 $Ct.mth^{-1}km^{-2}$ from that predicted and statistically significant Practical significant reduction of 2.88 Ct $yr^{-1}km^{-2}$ from that predicted
Nether Gate Clough (cessation of burning) paired with Upper North Grain	Flush in winter 2002-03 and reduced summer 2003	Regression equation good fit ($r^2 = 0.886$) General under prediction in winter and over prediction in summer	Flush winter 2003-04 similar to 2002-03 Flush winter 2004-05 higher than 2002-03 Flush winter 2005-06 higher than 2002-03	Continued seasonal pattern but altered from calibration year with over prediction winter 2003-04 and summer 04, followed by under predicted winter 2004-05, summer 05, winter 2005-06 and larger over prediction summer 2006 Differences in residuals between calibration and treatment period decrease 0.08 $Ct.mth^{-1}km^{-2}$, not statistically significant. No practical reduction 0.24 $Ctyr^{-1}km^{-2}$ from that predicted
Doctors Gate Clough (removal of grazing) paired with Upper North Grain	Flush in winter 2002-03 and second flush summer 2004	Regression equation poor fit ($r^2 = 0.455$) General under prediction winter 2002-03, over prediction spring 03, under prediction summer 03	Flush winter 2003-04 lower than 2002-03 Flush winter 2004-05 lower than 2002-03, but higher than 2003-04 Flush winter 2005-06 lower than 2002-03 Flushes during summer 03,04,05 and 06 – associated with iron dissolution.	Large over prediction Oct 03-May 05 followed by large under prediction summer 05 and over prediction winter 05-summer 06 Residual differences between calibration and treatment period statistically significant.(decrease 0.47 $Ct.mth^{-1}km^{-2}$) Significant practical decrease of 5.64 $Ctyr^{-1}km^{-2}$ from that predicted

8.4 Summary

A paired catchment approach was used to overcome the problems associated with changing responses to climatic conditions and the non-stationarity of catchment response, and to enable identification of catchment response specifically resulting from land management manipulation. Predictions of water colour, ASQ and DOC flux were determined using a paired catchment model from appropriate pairings established during the calibration period.

Two control catchments (Upper Gate Clough and Upper North Grain) were compared to determine if differences in true colour pre and post management changes might be significant. Statistical analysis found that the differences in true colour were not significant (ANOVA $p = 0.484$, Mann Whitney U $p = 0.225$) and could suggest that changes observed on treated sites may have occurred from changes in land use.

Although the water colour increased at Within Clough (gullies blocked) and colour was higher than that predicted by the control catchment (Upper North Grain), the residual difference between observed and predicted colour remained small post gully-blocking and differences were only weakly statistically significant (ANOVA $p = 0.09$, Mann Whitney U $p = 0.06$).

The paired catchment model over-predicted colour at Nether Gate Clough (cessation of burning) during the spring/summer and under predicted colour during the autumn/winter both pre and post management implementation. The difference in colour response pre and post management was similar and not statistically significant (ANOVA $p = 0.89$, Mann Whitney U $p = 0.94$).

The paired catchment model over-predicted colour at Doctors Gate Clough (removal of grazing) post management manipulation, that is, despite the high colour levels at Doctors Gate Clough they were lower than expected when predicted by the paired catchment Red Clough. However, the relationship between the two catchments particularly changed during the summer 2004 when the differences in colour between the catchments became much greater (Red Clough increased in colour similar to levels observed at Doctors Gate Clough) and differences in colour response pre and post management implementation were found to be statistically significant.

At Within Clough (gullies blocked) the differences in the mean and median residuals of ASQ pre and post gully-blocking were highly significant ($p < 0.01$). The residuals were small pre-gully-blocking suggesting Within Clough and Upper North Grain had a similar runoff response. Post gully-blocking the residuals became much larger and the model generally over-predicted the observed volume of ASQ discharged from Within

Clough. This suggests a change in catchment response and runoff production that continued to winter 2006. At that point a change occurred and the observed volume of runoff was greater than predicted. The model reverted to a larger over-prediction of runoff from spring 2006 to the end of the monitoring period. This suggests the gully-blocks were still able to retain water on the catchment and were particularly effective during the drier spring/summer 2006.

At Nether Gate Clough (cessation of burning) the residuals followed a seasonal pattern whereby ASQ was higher than predicted during the winter to early summer and then lower than predicted in late summer/autumn. This suggests less water than expected was being discharged from the catchment during the drier summers. This seasonal trend continued during the treatment period, but in the final year the residual difference increased from Oct 2005. During the winter 2005/06, the volume of ASQ was higher than predicted, followed in spring 2006 by a prolonged period when ASQ was lower than predicted. This change in pattern of ASQ at Nether Gate Clough suggests the catchment may have been rewetting as there was less runoff occurring during the spring/summer. This suggests more water was retained on the catchment following the cessation of burning and may have been caused by the change in vegetation composition and a lower percentage of newly burnt areas associated with high runoff. It is also acknowledged that the changes in ASQ may have been temporary as the pioneer vegetation from the previously burnt areas would gradually mature and increase potential for areas of vegetation to degenerate and increase wildfire risk, but further long-term monitoring would be required to determine this trend. The difference in residuals pre and post management change were weakly statistically significant (ANOVA $p = 0.085$) which tentatively suggests the land management may have had an affect on ASQ.

The small catchment area at Doctors Gate Clough (removal of grazing) meant that a relatively large change in ASQ was required (of the order of 17 $ls^{-1}.km^{-2}$) before it was certain that a change was real. The residuals during pre-management manipulation at Doctors Gate Clough were small and suggested Upper North Grain provided a good model to predict changes at Doctors Gate Clough. However, from Jan 2004-Sept 2006 the residuals post-management became much larger and this suggests that the relationship between Doctors Gate Clough and Upper North Grain weakened during this period. Generally ASQ was over-predicted at Doctors Gate Clough during the treatment period, and it appears that there may have been a real decrease in flow, although it should be emphasised that the change in management would be unlikely to be a direct causative effect of sudden changes in discharge.

The differences in residuals pre and post management intervention were statistically significant (ANOVA $p < 0.001$, Mann Whitney U $p < 0.001$), but it should again be emphasised that although the change was significant, land management manipulation may not have been the causative factor in generating this change in ASQ. Changes in vegetation composition and soil compaction from the removal of grazing are extremely unlikely to have had an almost immediate effect on discharge rates as could be suggested from the data and timing of the land management changes.

At Within Clough (gullies blocked) the differences in the mean and median residuals of areal export of DOC pre and post gully-blocking were highly significant ($p < 0.01$). The residuals were small pre-gully-blocking suggesting Within Clough and Upper North Grain had a similar runoff response. Post gully-blocking the residuals became larger and the model generally over-predicted the observed volume of DOC flux discharged from Within Clough. This suggests that the export of DOC was heavily influenced by a change in catchment response and runoff production that continued to winter 2006 when the observed volume of DOC flux was greater than predicted. The model reverted to a larger over-prediction of DOC flux from spring 2006 to the end of the monitoring period. This suggests the gully-blocks were still able to retain water on the catchment and were therefore effective in controlling the volume of discoloured runoff from the site.

At Nether Gate Clough (cessation of burning) the residuals of areal export of DOC followed a seasonal pattern whereby ASQ was higher than predicted during the winter to early summer and then lower than predicted in late summer/autumn. This suggests less discoloured runoff than expected was being discharged from the catchment during the drier summers. This seasonal pattern continued during the treatment period, but in the final year the residual difference increased from Oct 2005, influenced by the change in runoff. Although the change in pattern of ASQ at Nether Gate Clough suggests the catchment may have been rewetting and suggests more water was retained on the catchment following the cessation of burning; when combined with the change in DOC there was no statistically significant differences in residuals between the calibration and treatment periods. The difference in observed and predicted change in export of DOC was also considered to be of little practical value (0.24 $Ct.yr^{-1}$) during the limited period of study.

The paired catchment (Upper North Grain to predict changes at Doctors Gate Clough) was a weak model (goodness of fit $r^2 = 0.455$) with a general under-prediction in winter, over-prediction in spring and a further under-prediction in summer when the volume of discoloured runoff was contaminated largely by iron deposits. However, changes in ASQ during the treatment period further weakened the paired catchment model and the change in ASQ at Doctors Gate Clough strongly influenced the change in areal export of DOC from the site

From Jan 2004-Sept 2006 the residuals post-management became much larger and this suggests that the relationship between Doctors Gate Clough and Upper North Grain weakened during this period. Generally areal export of DOC was over-predicted at Doctors Gate Clough during the treatment period, and it appears that there may have been a real decrease in flow, although it should be emphasised that the change in management would be unlikely to be a direct causative effect of sudden changes in discharge.

The differences in residuals pre and post management intervention were statistically significant (ANOVA $p < 0.001$, Mann Whitney U $p < 0.001$), and the decrease in areal export of DOC of 5.64 $Ct.yr^{-1}$ could be considered practically significant, but it should again be emphasised that although the change was significant, land management manipulation may not have been the causative factor in generating this change.

In summary, the differences in the residuals of the three independent variables (colour, ASQ and areal export of DOC) found that colour did not change significantly at any of the treated sites, and ASQ changed significantly at two of the treated sites (Within Clough and Doctors Gate Clough) and was weakly significant at Nether Gate Clough. The ASQ consequently had the largest influence on areal export of DOC which was again found to be significant at Within Clough and Doctors Gate Clough, but not significant at Nether Gate Clough. Catchment rewetting and its contribution to changes in colour production, ASQ and export of DOC has been discussed in this chapter.

9 DISCUSSION

9.1 Introduction

This chapter discusses the results of the study by relating them to previous work and placing them in context with current understanding and research relating to the effects of upland land management practices on water discolouration, runoff and DOC export. The principal aims of this study were to examine the role of blanket peat moorland management in (1) the generation and (2) the amelioration of discolouration of surface water supplies, using a paired catchment approach. The study considered the impact on yield, water colour and DOC export through the manipulation of traditional moorland practices and drainage processes using a number of strategies, namely, blocking of gullies, cessation of burning and removal of grazing.

Table 9.1 presents an overall summary of the main findings of the study. Note that the observed data compared the monthly mean of the daily variable in the first year (2002-03) with the final year during the treatment period (2005-06). Statistical analysis of individual water years (Oct-Sept) are in the following sections. Monthly mean of daily true colour (°H) Table 6.8 (Section 6.2.4), monthly mean of daily ASQ ($ls^{-1}.km^{-2}$) Table 7.8 (Section 7.2.5), and DOC flux ($Ct.mth^{-1}.km^{-2}$) Table 7.14 (Section 7.3.2). The "paired data" compared the residual (observed minus predicted) monthly mean of the daily variable during the calibration period (1 Oct 2002-31 Dec 2003) with the monthly mean of the daily variable during the treatment period (1 Jan 2004-30 Sept 2006). Statistical analyses are in the following sections. True colour (°H) Tables 8.4-8.7 (Section 8.3.1), ASQ ($ls^{-1}.km^{-2}$) Tables 8.10-8.13 (Section 8.3.3) and DOC flux ($Ct.mth^{-1}.km^{-2}$) Tables 8.16-8.19 (Section 8.3.5).

Table 9.1: Summary Table of Ashop Catchments Observed and Predicted Monthly Mean of Daily Variables Oct 2002-Sept 2006

PREDICTED							
Catchment Mgt	**Flow ls^{-1}.km^{-2}**	**True Colour °H**	**DOC Flux Ct.mth^{-1}.km-^{2}**	**Catchment Mgt**	**Flow ls^{-1}.km^{-2}**	**True Colour °H**	**DOC Flux Ct.mth^{-1}.km-^{2}**
Gullies Blocked	↑	↑	↑	**Gullies Blocked**	↓	↑	↓
Quantity	2.94	25	0.12	**Quantity**	8.8	11	0.24
Significance		p = 0.216	p = 0.62	**Significance**	p <0.01	p = 0.09	p <0.01
No Burning	↑	↑	↑	**No Burning**	↓	↑	↓
Quantity	2.04	14	0.05	**Quantity**	2.5	2	0.08
Significance	p = 0.525	p = 0.628	p = 0.86	**Significance**	p = 0.085	p = 0.891	p = 0.404
No Grazing	↓	↑	↑	**No Grazing**	↓	↓	↓
Quantity	3.65	14	0.04	**Quantity**	12.8	51	0.47
Significance	P = 0.647	P = 0.601	P = 0.98	**Significance**	p <0.01	p <0.01	P = 0.04
Controls (no treatment)	↑	↑	↑	**Controls (no treatment)**	↑	↑	—
Quantity (UNG)	10.8	18	0.3	**Quantity**	0.47	7	
Significance	p = 0.008	p = 0.281	p = 0.098	**Significance**	p = 0.793	p = 0.317	
Quantity (RC)	9.9	34	0.32				
Significance	p = 0.07	p = 0.258	p = 0.042				

9.2 Experimental Design in Context to Previous Work

In terms of data collection this study represents some of the most extensive and intensive work completed; examination of the appendices of raw data illustrates this. Whilst other workers had considered management techniques for water colour amelioration at a laboratory or plot-scale, (for example, Jolly and Chapman 1987, Mitchell and McDonald 1992, Tipping *et al* 1999, Holden and Burt 2002a), no previous study had evaluated the impact of these approaches at a catchment scale, making it operationally useful and where a high degree of experimental control was maintained.

The study reflected the need for a long-term catchment investigation into the feasibility of controlling water colour and export of DOC by means of sustainable land management. The four-year study may be considered long-term when compared to the more usual shorter-term PhD studies which cover at best, two years of data. It also contrasts with other short-term studies reflecting scientific evidence governed largely by financial constraints from the water industry (e.g. Holden 2005c, Armstrong *et al* 2005, Worrall *et al* 2007a). In terms of understanding the natural chemical, biological and physical processes generating water colour/DOC, further complicated by their interaction with past and present climatic conditions and the additional anthropogenic influences of land management and atmospheric pollution, it is difficult to disentangle the cause and effect processes in the short and longer-term. Given the long time scales involved in catchment carbon response, management decisions made on short data sets could be misleading and it is acknowledged that this study is still short when compared to other long-term studies such as the Coweeta and Hubbard Brook catchment experiments.

Paired catchments have been used traditionally as water balance experiments, for instance, to determine changes in water yield following afforestation and deforestation e.g. Coweeta, USA (Hewlett and Helvey 1978, Webster *et al* 1992, Burt and Swank 2002) and Plynlimon, Wales (Reynolds *et al* 1997, Neal 2004, Neal *et al* 2005). Very little research has been done using a paired catchment approach on sensitive upland peat environments to determine changes in management practices such as gully-blocking, cessation of burning and removal of grazing. Whilst the experiments at Coweeta and Plynlimon have concentrated on the catchment-scale, studies of the effects of burning or grazing have generally been at a plot scale and tended to focus on the effects of changes in vegetation, soil and its erosion (Evans 1997, 1998, 2005, Tucker 2003, Pakeman *et al* 2003, Stewart *et al* 2004).

Many previous studies have used annual data to assess changes between treatment and control catchments (e.g. Elliott *et al* 1999, Evans and Warburton 2001, Burt and Swank 2002). However increasingly, seasonal or monthly analysis of paired catchment data have been used to overcome the problem of insufficient data being available during the calibration period by which the similarities in catchment variables might be identified (Lane and Mackay 2001). This study collected 14 months of data prior to management changes. In comparison to some long-term studies such as the Coweeta this might be considered a very short period (Hibbert 1969, Swank *et al* 2001). However, some experiments don't include a calibration period at all e.g. Wallage *et al* (2006) study of drained and blocked sites, and therefore making a spatial comparison is difficult when the condition of a site is not known prior to land management alteration.

This study has focused on the effects of traditional moorland management practices (prescribed burning and sheep grazing) and drainage from naturally eroding gullies on water colour/DOC and runoff. The pioneering techniques of gully-blocking used by the National Trust have generated much media and scientific interest as a suitable method for not only improving water quality, but potentially restoring blanket bog, sequestering carbon and off-setting carbon emissions. This one technique could theoretically provide solutions for a number of agendas and the demand for science-based evidence in order to extend this technique to other upland areas has placed demands to validate the technique's success. This is a very short time in the context of the time required for carbon to sequester and blanket bog to develop These aspects are discussed further in Section 9.4.1 when the findings are compared to other recent gully-blocking studies in the UK.

Similarly, interest in the effects of prescribed burning on the uplands and the impact on water quality, hydrology and soils has been largely motivated by government policy. Many upland areas had been identified as being in unfavourable condition by Natural England (previously English Nature) and burning was identified as one of the main causes in the uplands deterioration (JNCC 2006). Much interest was generated in the study largely due to Natural England's requirement to achieve the Public Service Agreement (PSA) 3 target of 95% of SSSIs being in recovering or favourable condition by 2010 (Williams 2006), together with an opportunity sought by Defra to overhaul burning practices in England and potentially stop prescribed burning on areas of blanket bog through the review of the Heather and Grassland Burning Regulations (Defra 2007),. Prescribed burning had been temporarily stopped at a catchment-scale during the study following agreement with the National Trust, shooting tenants and gamekeepers and provided results at an operational scale compared to previous studies largely completed at the laboratory or plot scale (for example, Mallik *et al* 1984, Martin 1992, Mitchell and McDonald 1992, Garnett *et al* 2000). Implications of the study's findings are discussed in Section 9.4.2.

Finally, the opportunity to study the impacts of grazing at a catchment scale were timely following changes in agricultural schemes in 2001 when support for the Less Favoured Areas (LFA) changed from headage payments to an area-based mechanism. The scheme was aimed at encouraging de-stocking whilst indirectly supporting the recovery of ecosystems such as blanket bog by reducing pressure on the land. Logistically the removal of sheep from the Alport moor which included the study catchment of Doctors Gate Clough, involved sheep being rounded up , physically removed from the moor and transported to other areas, whilst the erection of 22 km of post and wire fencing acted as a deterrent to their regaining access (English Nature 2005). Compared to previous studies which had tended to be at a plot scale because of the difficulties of removing sheep from entire areas of moorland (for example, Rawes 1983, Welch 1998, Evans 1997, 2005, Worrall *et al* 2007a) the catchment-scale study again provided the opportunity to study the effects on a practical and operational level. Implications of the study's findings are discussed in Section 9.4.3.

9.3 Relationship between Water Colour and Environmental Variables (Objectives (i) and (iii))

Objective i) To establish baseline relationships between meteorological inputs and hydrological responses during a calibration period prior to intervention in blanket peat moorland management;

Objective iii) To determine the relationships between meteorological inputs and changes in water quality, runoff and DOC export on control (management unaltered) and treated (management manipulated) sites during the pre and post management periods;

An evaluation of factors influencing the surface runoff of discoloured water/DOC from soils to surface waters was found to be dependent on a number of natural and anthropogenic factors and their interactions. Climate has been found to be one of the strongest influences on the concentration and volume of discoloured water/DOC being exported from upland catchments (Goldsmith *et al* 1997, Freeman *et al* 2001a, Belyea and Malmer 2004, Worrall *et al* 2004). Growing concerns of the impact of climate change on upland peat catchments already sensitive to increased temperatures, changes in the amount and intensity of rainfall and alternatively, prolonged periods of drought, have been linked by many researchers to carbon loss in the form of dissolved, particulate and gaseous carbon (Tipping *et al* 1999, Dawson *et al* 2002, Evans *et al* 2002, Freeman *et al* 2004, Worrall and Burt 2005).

The discharge of water colour during the study was found to be linked to changes in meteorological conditions (see Sections 5.2 and 5.3) and showed a clear pattern of seasonality with water colour peaks associated with the release of organic carbon in autumn/winter and reduction in spring/summer. This strongly suggests that water colour was being flushed out following the onset of increased rainfall and more frequent storm events in the autumn/winter. This supports previous findings by, for example, Dobbs and Watts 1987, Goldsmith *et al* 1997, Evans *et al* 1999, Watts *et al* 2001 and Worrall *et al* 2002, 2004. However, the response of colour was made more complex with a step-rise in colour during the late summer 2004 following a period of low rainfall and drought conditions which occurred during the first year of study (summer 2003) (see Section 6.4). Because the drought continued through the winter of 2003-04 the colour response appeared to have been delayed until the onset of a series of storms in late summer (August 2004), some 12-14 months following the drought conditions in the previous summer 2003. The colour peaks in this year were higher than the previous and subsequent autumn flushes, although it is unclear from the data set (four years) whether the drought conditions had triggered a longer-term response in which peaks in water colour would continue to rise. Certainly the mean annual water colour and peaks during the autumn months, although showing some recovery in the final year (Oct 2005-Sept 2006), still did not fall below those recorded during the first year prior to land management manipulation. These results support similar studies where increased colour and DOC were observed in response to droughts in the mid 1970s, 1980s and early 1990s (e.g. Mitchell and McDonald 1992, Butcher *et al* 1995, Pattinson *et al* 1995, Hughes *et al* 1997, Scott *et al* 1998, Grieve 2001, Watts *et al* 2001) and Naden and McDonald (1989) observed similar responses with time lags of 3 and 14 months between drought conditions and an increase in water colour.

Holden and Burt (2002a) argue that droughts could augment DOC production by causing a decrease in water table below the long-term average position (the boundary between the acrotelm and catotelm), thereby triggering additional aerobic production. Researchers have found that such significant lowering of the water table could change the relationship between flow and DOC (Worrall and Burt 2004) and the de-coupling of soil respiration and DOC production which may persist for several years post-drought (Worrall *et al* 2005) and this may account for the increasing trend in water colour/DOC observed on the catchments associated with drought conditions.

More recently Freeman *et al* (2004) have rejected the hypothesis of reduced summer precipitation (and ensuing drought conditions) generating a rise in DOC trends on catchments being rewet, after finding peat DOC concentrations were substantially lower on a manipulated (drought) catchment compared to a control (un-manipulated) catchment. These findings differ from the Ashop study (see Section 6.2) and many other studies that have associated a rise in water colour/DOC with drought conditions. Freeman *et al* (2004) suggested that the similarity in catchment response at their sites was caused by gaseous CO_2 rather than dissolved aqueous CO_2 prevailing at the drought-manipulated site which had been caused by the increased decomposition rate of plant material. Measurements of gaseous CO_2 at the sites would have to be monitored during drought conditions to confirm this at the Ashop sites.

Tranvik and Jannson (2002) however, argued that the changes in DOC were also related to hydrology, explained by an increase in precipitation and runoff. This considers the increase in concentration of DOC by river transport, that is, the product of concentration and discharge which is of particular interest to water companies treating water draining from these upland catchments where the general trend in water colour/DOC flux is increasing (Watts *et al* 2001, Freeman *et al* 2001a, Worrall *et al* 2004). The daily data sets of water colour/DOC and discharge on the study sites demonstrated a positive correlation between the release of water colour/DOC and stream discharge (see Section 7.2.4) with maximum colour concentrations occurring during storm events. Examination of individual storm events also showed that hysteresis effects occurred during the runoff events when water colour concentrations were found to be higher at a given discharge on the falling limb of the hydrograph (see Section 6.4) and supports previous studies (e.g. Grieve 1984, Hope *et al* 1997). The temporal change in water colour/DOC concentrations could therefore have been caused by the leaching of carbon from the upper layers of the soil and dilution of DOC during high precipitation.

The four year daily and monthly data sets also demonstrated a noticeable rise in water colour/DOC concentrations during the autumn/winter. This is likely to have been generated by the amount of contact time between soil and soil solution on the catchments (Boyer *et al* 1996), that is, low DOC concentrations were generally observed on the catchments during the spring when more water passed rapidly through the upper soil horizons as surface and shallow sub-surface flow, observed from water table measurements and general field observations during rainfall events. In the summer, incidents of increased water colour/DOC concentrations were observed during episodic events when soil water content was low and the contact time between soil and soil solution was greater. Finally in autumn/winter the autumn "flush" of water colour/DOC was observed at all the sites as the soils recharged (depth to water table decreased at all sites during the winter – see Section 9.5) and the soil solution having been in contact for the longest time during the summer was flushed out.

Recently Worrall *et al* (2008) have continued to support the argument that the level of DOC concentration and flux is limited by the degree of solubility and that its production is influenced by the time-scale of runoff events. Although previous studies have examined long-term data sets of water colour and DOC concentrations, there has been very little detailed analysis of flux time series. This is probably because of the lack of appropriately sited gauging stations on upland catchments and the resource-demanding methods of estimating discharge from small, un-gauged catchments.

However, Worrall *et al* (2008) concluded from the analysis of a 34-year data set for three sites in the North Pennines that there was no significant correlation between drought variables and DOC flux and that the most important variable for explaining the changes in DOC flux was the runoff from catchments overlying a seasonal cycle and an underlying upward trend. Cooper *et al* (2007) similarly concluded from their study of the Birnie Burn, northeast Scotland, that the release of DOC was most heavily influenced by event magnitude and soil water flow. Certainly there is evidence of low discharge in 2003 (see Section 7.2) which may have stored carbon, followed by increased discharge at the Ashop sites after the drought period which coincided with an increase in water colour/DOC concentrations in August 2005. This corroborates similar patterns described in the North Pennines, albeit on a much longer time-scale (Worrall *et al* 2008).

Previous research however, has advocated a relationship between the biogeochemical production of DOC stimulated by drought. The increased microbial activity of the extracellular enzyme phenol oxidase during periods of increased aerobic conditions within the soils, usually occurring as the depth to water table increases, has been associated with the storage capacity of carbon in peat soils (Freeman *et al* 2001). The increased activity has particularly been associated with oxygen-saturated conditions which raises the humification rate and potential dissolvable carbon store. However, van Hees *et al* (2005) found that when modelling DOC production it could be based purely on a description of DOC solubility and runoff from the soils with no additional biogeochemical production of DOC stimulated by drought.

The relationship between daily water colour and rainfall on the day or within the last two months was strongly correlated at the study sites (see Section 5.2.4) which suggests a shorter residence time of carbon in solution and reflects the flushing mechanism of flow through the upper layers of the peat and seasonal pattern such that colour levels were elevated during the autumn/winter. This appears to support the findings of Cooper *et al* (2007) and Worrall *et al* (2008). However, the relationship between monthly rainfall and water colour was only statistically significant during the first two years of the study when a pattern of low colour:low rainfall and high colour:high rainfall was observed (see Section 5.2.4). In the final two years of the study the colour response differed and peaks in rainfall were associated with lower colour. For example, in August 2006 lower monthly colour and higher monthly rainfall may suggest an exhaustion of colour following high rainfall or a failure of rainfall to rewet soils and raise water tables and so store carbon for a longer period in solution.

The paradigm shift of colour/DOC production being based on drought to one which is influenced by changes in runoff and carbon solubility only is a major one and at present is based on few records of carbon flux. Therefore, although the pattern of water colour during the study appears to fit both theories there is insufficient evidence to support the recently advocated theory and the effects of the 2002-03 drought on the production of water colour/DOC cannot be dismissed.

Other climatic variables such as temperature and soil moisture, closely associated to drought conditions, have also been linked to water colour/DOC concentrations. Freeman *et al* (2001a) suggested that the primary long-term factor influencing peatland DOC production was soil moisture because the decomposition rate would increase under drier conditions. This study also found a noticeable pattern between water colour and soil moisture deficit (SMD) in that water colour was low when SMD was high and only increased when the soils rewetted during the autumn/winter (see Section 5.3.4). An inverse relationship between SMD and colour was found at four of the study sites, but was only statistically significant at two of the sites, Nether Gate Clough where prescribed burning had been stopped and Upper Gate Clough where management had not been manipulated. At these sites there was a noticeable seasonal pattern of colour production with high colour discharged in the autumn/winter and low colour in the spring/summer. The two larger catchments of Within Clough where the gullies were blocked and Upper North Grain (control) also had an inverse relationship between SMD and colour, but this was not statistically significant and suggests that the generation of colour at the two sites was more complex.

The link between water colour and temperature, usually also associated with prolonged periods of little or no precipitation, has also been found to promote the generation of DOC by lowering water table levels and increasing aerobic conditions in the upper acrotelm layer of soil and so accelerate microbial activity and humification (Mulholland *et al* 1999, Freeman *et al* 2001a, Glatzel *et al* 2003, Glatzel *et al* 2006). However, studies have also found that temperature was not highly correlated to DOC release, (e.g. Christ and David 1996, Yeakley *et al* 1998, Tipping *et al* 1999,Kalbitz *et al* 2000, Worrall *et al* 2003). Tipping *et al* (1999) showed that increases in temperature *per se* would not lead to the increased release of DOC, but had to be combined with the effects of seasonal warming and drying cycles.

During the study monthly temperature and colour were found to be poorly correlated, having an inverse relationship such that higher water colour was associated with lower temperatures (see Section 5.3.4). This supports previous findings and suggests that the flush of organic colour was discharged largely during the autumn/winter following the build-up of mobile carbon during the summer. The temperature at the study sites in the Ashop catchment indicated some variation between each water year, but the temperature was consistently highest in the summer months when maximum air temperature was recorded at above 30 °C in all three years (2003-2006), whilst minimum temperatures were generally lower in February-March. The extremes of temperature could exacerbate physical processes on the catchment by surface desiccation of bare soils during the summer, which in turn could reduce the infiltration capacity during rainfall events and so lower the ability for soils to rewet and water tables to recharge. The warming and drying cycles could stimulate microbial degradation and also allow increased oxygen into the soil and a greater reserve of mobile organic carbon to accumulate during the summer resulting in a greater flux of carbon release during the autumn/winter as discharge rates increased (Worrall *et al* 2003). During the winter the extreme temperatures could potentially freeze surface layers and also prevent infiltration during rainfall events whilst needle-ice could increase erosion and so expose deeper layers of previously unexposed peat soils with larger carbon storage and potentially leach greater levels of water colour and DOC as they desiccate and are rewet during the onset of storms.

9.4 Changes in Water Colour, DOC and Runoff in Response to Management Manipulation (Objective (iv))

> Objective iv) To quantify changes in hydrological behaviour, water colour and DOC export following controlled intervention in blanket peat moorland management and to observe catchment responses where natural drainage processes are altered, prescribed burning stopped temporarily and grazing removed.

Catchment runoff (and DOC flux) is a result of spatial integration and provides a signal of the soil system functioning and an opportunity to estimate the effects of landuse change at a catchment scale (Seibert *et al* 1997). During the study all the catchments, irrespective of management changes, responded rapidly to rainfall events with a rapid rise in water colour, area specific discharge and DOC flux. Temporal changes in these variables were also observed with a general rise during the autumn/winter months when catchments rewet and rainfall events were greater and caused the colour to be flushed from the catchments. There was a general reduction in water colour, area specific discharge (ASQ) and DOC flux during spring/summer as rainfall was less and hydrological processes such as surface and shallow sub-surface flow which contributed to ASQ and DOC were less frequent or intense.

Changes in water colour/DOC, runoff and DOC flux are discussed in terms of response to management manipulation, but it should be noted that research both on the techniques of grip blocking in the UK and the resultant hydrological and hydrochemical effects has been limited due to the lack of funding. Land managers and agencies have tended to prioritise practical management over monitoring and therefore a lack of science-based evidence exists. In fact most of the research has been completed in the last five years and started after the commencement of this research, which emphasises the importance of this comparatively long-term study.

9.4.1 Change Where No Management Manipulated (Contol Catchment)

Median and mean ASQ increased significantly between year 1 (2002-03) and year 2 (2003-04) on the two control catchments (Upper North Grain and Red Clough). The differences between the years were not within the accepted error in discharge per unit area for each change in cm of stage (see Table 7.1) and therefore it is believed climatic changes between the two years were likely to be responsible for a real difference. Similarly, the change in areal export of DOC was statistically significant in year 1 - 2 and year 1 – 3 at Red Clough and weakly significant at Upper North Grain respectively.

9.4.2 Changes in Response to Gully-blocking

This study found that the mean, median and variance of monthly water colour at Within Clough increased significantly two years after the gully-blocks were installed compared to water colour in the year prior to the blocking (see Section 6.5.1 and 8.3.1.2). The daily mean ASQ was similar between year 1 and year 2 (24.75 and 24.68 $ls^{-1}.km^{-2}$) and the difference was statistically insignificant ($p = 0.964$) despite the catchment being subject to the same climatic conditions as the control sites (higher annual rainfall in year 2 compared to year 1 and more frequent rainfall events). The results suggest that gully blocking may have retained sufficient water on the catchment in the second year (that is, the year during and after blockages were installed) to affect the discharge from the catchment.

In year 3 (2004-05) and year 4 (2005-06) there were significant differences compared with year 1 daily mean ASQ at Within Clough ($p < 0.001$). This may have been because the hydrological conditions and runoff regime on the catchment had succeeded in raising water table levels which then increased the surface and sub-surface flow from the catchment and raised ASQ levels once again by the final year (that is, approximately 14 months post gully-blocking). However, the differences in monthly mean ASQ at Within Clough were statistically insignificant in the final two years, despite there being an observed decrease of monthly mean ASQ of 6 $ls^{-1}.km^{-2}$ between year 1 and year 3 and an increase in year 4 of 3 $ls^{-1}km^{-2}$ compared to year 1 which again suggests some recovery of runoff levels.

This rise may have been caused by increased disturbance in the top aerobic layers of peat during the blocking, together with the subsequent rise in water table and flushing out of colour when the catchment rewet following the completion of blocking. There was no such statistically significant difference in water colour between the calibration and treatment periods on any of the control catchments where land management remained unaltered (see Section 8.3.1.1). However, these results differ from those of Wallage *et al* (2006) who examined individual blocked/unblocked drains on the Oughtershaw Brook, northern England. They found that blocked drains produced significantly lower rates of water colour/DOC compared to drained sites, which could suggest a store exhaustion process and alteration of hydrochemcal processes. Their findings showed that the colour:carbon ratio was highest at 0.2 m depth where greater levels of humification and oxidation of deeper peat were likely. Although their findings suggest that raising and maintaining water table levels through ditch blocking could be a suitable means of ameliorating the enhanced water colour and DOC associated with peatland drainage, they did not monitor the same drains before and after the blocking. This current study differed and indicated that water discolouration could increase in the short-term as the water tables rise. These findings are similar to those of Hughes *et al* (1995) who studied the effects of rewetting a naturally drained gully mire and found that the concentration of DOC substantially increased once the site had been rewet compared to samples from sites that continued to be naturally drained.

These conflicting results emphasise the continuing need to determine both the short and long-term consequences of gully-blocking on water colour across a number of sites at a range of scales and the need to investigate further the changes in soil properties from drainage caused by long-term erosion of deep peat and the much shorter exposure of grips and their subsequent blockage.

It should be noted that the observed change in monthly mean runoff between the first year prior to gully blocking and third year (when gully-blocking was complete) was a reduction of 5.72 $ls^{-1}.km^{-2}$. This equates to 180.4 $mm.yr^{-1}$ (see Section 7.2.5.2). Similar observations were made by Holden (2005c) during the study of blocked and drained sites at the Geltdale and Glendue SSSI, when less discharge was observed in the second year compared to the first year and low flows were maintained in the blocked grip during the second summer. Armstong *et al* (2005) and Worrall *et al* (2007) also found a reduction of up to 90% runoff in a blocked grip, with an average 70% decrease in flow, whilst Holden *et al* (2006b) found blocked ditches had a mean flow of two orders of magnitude lower than that in clear drains.

Whilst achieving the main objectives for rewetting a site and potentially restoring hydrological function, the retention of water on a catchment could affect water supplies and have serious consequences for water companies. Such implications are discussed further in Section 9.7.

The monthly areal DOC flux at Within Clough was generally lower after the gully blocking was completed in winter 2003. However, the differences between DOC flux pre-gully blocking and post-gully blocking were not statistically significant and ranged from only 0.05 $Ct.km^{-2}$ to 0.12 $Ct.km^{-2}$ which suggests greater stability and less extremes of colour export from the catchment. Nevertheless, when compared to the control catchments which had a significant increased flow and DOC flux in the year 3 and year 4, the insignificant changes observed at Within Clough during these two years could be considered as a decrease over what might have been expected.

The results of this research at a catchment scale, together with the plot-scale research conducted in the last five years suggests that the effects of gully or grip-blocking are beneficial for rewetting the area, at least in the short-term. However, there is a need to collate spatial and temporal data to determine if initial changes may have resulted from variability in catchment conditions or are a result of changes in land use and the blocking of gullies or grips.

9.4.3 Changes in Response to the Cessation of Burning

This study also investigated the effect of the temporary cessation of burning on water colour/DOC, ASQ and DOC flux. Despite the agreement negotiated with gamekeepers there was a small amount of burning in the catchment during 2003-04, but it was distant from the water course and much less than would have been undertaken (typically). Water colour increased (insignificantly) at Nether Gate Clough during the study (see Sections 6.2.2, 6.2.4, 6.7.2 and 8.3.1.3). Certainly previous research suggests that moorland burning may lower infiltration capacities and enhance drying of the sub-surface soil, so producing extreme colour when the soils rewet (Mitchell and McDonald 1992). Martin (1992) found the magnitude and timescale of colour production were related to fire characteristics of which temperature was the most significant. She found that hotter burns (~ 600 °C) produced more colour than cooler burns (~ 300 °C). Garnett *et al* (2000) also found that hydrophobic compounds could be deposited within the soil through distillation during prolonged smouldering burns, which could then create layers of soil that could interfere with water and root penetration and create structural weaknesses that could be more prone to erosion. This supports the findings of earlier work by Imeson (1971) who found a relationship between moor burning and gully development which could exacerbate peat desiccation and humification processes, although the extensive review by Stewart *et al* (2004) was inconclusive as to whether prescribed burning degraded blanket bog.

Differences in daily ASQ at Nether Gate Clough (cessation of burning) between year 1 and the subsequent years were all statistically significant ($p < 0.01$), but the monthly mean and median ASQ were only weakly significant (ANOVA and Mann Whitney $p = 0.07$) between year 1 and year 2. This amounted to a small reduction of 1.47% and the observed difference between the ASQ between the first two years was 5.97 $ls^{-1}.km^{-2}$ which falls within the accepted level of error of 6.6 $ls^{-1}.km^{-2}$ (see Table 7.1) and may therefore have resulted from a mechanical error rather than as a result of changes in the burning regime. The differences in monthly mean and median discharge and ASQ for the remaining years (years 3 and 4) were not statistically significant and therefore the linkage between cessation of burning and ASQ remains unclear.

Although the observed differences in monthly ASQ following the cessation of burning were weakly significant only from the first to the second year, and for the remaining years were not statistically significant where the management had not been manipulated, there was a statistically significant difference in mean ASQ between the first and the second year and also the first and the final year at Upper North Grain. The change in ASQ between water years on the control catchments was much larger than observed at Nether Gate Clough where management had been altered and this suggests that these changes were caused by climatic conditions on the control sites (see Section 7.2.5.1). This supports the research of Imeson (1971) who found that burning reduced interception and transpiration of precipitation and moisture, causing an increase in the volume and intensity of throughflow. The temporary cessation of burning is likely to increase interception and transpiration of precipitation and moisture as *Calluna* was allowed to develop across the site, thereby affecting volume and intensity of throughflow at a catchment-scale. Holden (2005a, 2005b) also found that mature heather stands were associated with an increase in soil piping in moorlands which created changes in hydrological flowpaths, water quality and carbon fluxes. Thus, by supporting management that encourages heather growth, burning could indirectly cause the deterioration of water quality, and increase water yield and DOC flux.

Although Nether Gate Clough monthly areal DOC flux demonstrated a seasonal pattern, the DOC flux remained higher during the first, third and fourth winter than on other catchments. However, the differences in the variance of monthly DOC flux between year 1 and subsequent years was not significant with increases of only 0.05 - 0.4 $Ctkm^{-2}$ from the catchment. This may suggest that the catchment was becoming more stable and that there were fewer extremes of colour export on a catchment-scale. Alternatively, it could also emphasise the need for a longer period of study with the four-year period being of insufficient length to determine the effects of prescribed burning on runoff and DOC flux.

9.4.4 Changes in Response to the Removal of Grazing

Upland agricultural landuse in the UK is still generally restricted to rough and improved pasture for grazing and although the uplands are being increasingly recognised for their importance as providers of several ecosystem services including potable water supplies, the relationship between grazing and water quality is still poorly understood. Past research has focused on the effects of grazing on bog vegetation (Anderson and Radford 1994, Welch 1998, Pakeman *et al* 2003), and more recently on erosion (Johns 1997, McHugh *et al* 2002, Evans 1997, 1998, 2005).

Clearly the two processes of vegetation removal and erosion are inter-linked and chemical, physical and biological processes which may generate the production of humic substances and their subsequent flushing can be inferred (Quinton *et al* 2006). However, there have been relatively few studies that have focused on the relationship between grazing manipulation and water quality or yield (e.g. Martin 1992, Garnett 1998, Emmerich and Heitschmidt 2002, Worrall *et al* 2007a).

During the current study the water colour/DOC increased during the summer (associated with iron oxidation) at the site where grazing was removed (Doctors Gate Clough) (see Sections 6.2 and 6.5.3). During the winter months the catchment also discharged high colour/DOC associated with organic matter, but the difference in monthly mean of daily colour between the calibration and treatment years was not significant in any of the years after the sheep were removed. These findings are similar to those reported by Worrall *et al* (2006) who found that the concentration of DOC showed no significant difference on sites of different grazing treatments.

Doctors Gate Clough had the highest area specific discharge (ASQ) rates for each year and the response to rainfall events was higher than the other sites which could suggest that relatively little water was being stored on the catchment from these events (see Sections 7.2.3.4 and 7.2.5.4). This may be a result from a legacy of intensive grazing, which previous researchers have found to result in soil compaction, shorter vegetation or its entire removal, increased exposure of bare earth and erosion (Mackay and Tallis 1996, Hulme and Birnie 1997, Evans 1997, 1998, 2005). All of these could contribute to an increase or maintenance of high runoff. The differences in the monthly mean of daily ASQ between the calibration period and third and fourth year during the treatment period were not statistically significant but amounted to a small reduction of 0.9-1.9% of runoff. Although the differences were small the findings support those reported by Holden *et al* (2007a) of unpublished work by Holden and Zhao (University of Leeds). They compared a grazed and ungrazed site in the north Pennines and found where grazing occurred the hydraulic conductivity and infiltration rate was much lower across the hillslopes than where grazing had been restricted. They suggested that within five years an ungrazed site could recover hydrologically towards that of a system that had had no grazing for over 40 years. Sansom (1999) also found that the annual water yield had increased in the north Derwent catchment where sheep numbers had doubled from 1944-1975 and Clement (2005) found runoff was greater outside an exclosure than where sheep had been excluded at Burnt Hill, Cumbria. These findings suggest that sheep grazing may have a spatial and temporal effect on stream flow, particularly from areas more vulnerable to erosion and where sheep tracks may readily form which could act as hydrological flowpaths for water draining off the site (Holden *et al* 2007). Carroll *et al* (2004) also found that infiltration rates doubled on pastures grazed by sheep over a 15-year period.

Short-term changes within three years of the removal of grazing on the catchment do not appear to have had a noticeable affect on the runoff regime at Doctors Gate Clough. This may not perhaps be surprising where soil compaction and revegetation of bare soils would be slow to recover in such a harsh environment such as that found in the Peak District. Again, this emphasises the need for a longer-term study to determine changes following management manipulation.

The mean areal DOC flux decreased significantly by 0.76 $Ctkm^{-2}$ (ANOVA $p = 0.029$) at Doctors Gate Clough in year 2 which differed from the remaining sites which all had an increase in DOC flux. However, this decrease may have been caused by the prolonged periods of low flow when water stage levels were particularly low in the second year (see Section 7.2.3.3). Although the land management was manipulated in year 2 it is unlikely that the response in areal DOC flux would have been so immediate, for example, the impacts of intensive sheep grazing such as soil compaction, short vegetation and increased erosion would be unlikely to recover within 12 months of the sheep being removed so as to affect runoff significantly. However, similarly to the other manipulated catchments, the changes at Doctors Gate Clough, whilst being insignificant in years 3 and 4, may also be considered as a decrease over what might have been expected when compared to the increases in flow and flux on the control catchments during the same period.

9.5 Prediction of Water Colour, Runoff and DOC Flux From the Manipulation of Land Management (Objectives(ii),(v))

Objective ii) To identify paired sub-catchments of similar morphological, pedological and land management characteristics and establish similarities;

Objective v) To develop a paired catchment model as a means of predicting the outcome of management manipulation on hydrological behaviour, water colour and DOC export as a means of discussing the future generation or amelioration of discoloured surface water supplies;

A paired catchment approach was adopted to determine the magnitude of changes in water colour/DOC, water yield and DOC flux, and identify changes that may have occurred as a result of management being manipulated at the sites. This approach is recognised as the traditional way that hydrologists may quantify and understand the effects of landuse change on stream water quality and quantity (Seibert *et al* 1997). Perhaps more importantly, without paired catchments, the effects of climate on the temporal and spatial change in colour/DOC, ASQ and DOC flux and the non-stationarity of land management may be difficult to distinguish from other factors such as changes in climatic variability (Evans *et al* 2005a, Dawson and Smith 2007). In order to overcome this problem of climate variability paired catchments were used to analyse changes resulting from management manipulation at a catchment scale.

Using the paired catchment approach to determine changes across the sites, this study found that there was no statistical difference in the observed and predicted water colour at the two control sites where management had remained unaltered (see Section 8.3.1.1). The predicted increase in colour at Within Clough (gullies blocked) was weakly significant ($p = 0.09$), but there was no statistical significant change between the observed and predicted water colour at Nether Gate Clough where prescribed burning had been temporarily stopped (see Section 8.3.1.3). At Doctors Gate Clough there was a statistically significant difference between the observed and predicted water colour (expected increase of 51°H over that observed) (see Section 8.3.1.4), although this is likely to have been caused by a non-organic source (iron oxidation) (see Section 6.3.1) and the increase in colour at the paired control site (Red Clough) during the study (see Table 9.1). This suggests that changing land management is not a solution to concerns over water quality related to DOC.

This study found that the observed water colour was higher than that predicted following gully-blocking, the rise was only weakly significant ($p = 0.09$). The result differs from the three-year study by Wallage *et al* (2006) who found a significant decrease in water colour/DOC concentrations of individual blocked drains (blocked prior to the study), but this is difficult to compare because of the differences in experimental scale from plot to catchment and methodologies used to sample water. In contrast, the results of Worrall *et al* (2006) study of grip-blocking at the Whitendale catchment found that water colour/DOC was higher in blocked drains than unblocked drains and although a paired study was used, this was limited to one year during which 6 sample sets were collected pre-blocking and 13 sample sets post-blocking.

The differences in the results from short and medium-term studies at a range of scales emphasise that the processes that generate water colour/DOC are indeed complex and that gully or grip-blocking may not necessarily be the “quick-fix” to ameliorate water quality in the short and medium-term. Resources clearly have to be invested in long-term research if this technique is to be used as a widespread sustainable means of ameliorating water quality in the future.

This study found that gully-blocking retained water on the site (see Section 8.3.3.2) and that the differences between the observed and expected runoff between the calibration and treatment period were statistically significance with an estimated reduction in total runoff of 278 $mm.yr^{-1}$ (equivalent to 1% capacity of Ladybower reservoir). This predicted reduction in runoff is higher than the observed reduction in runoff between the first and third year (see Section 9.4.1). Whilst water remaining on site could assist in restoring hydrological function, improve ecological condition and encourage vegetation associated with bog habitat, such “losses” of water yield may affect water companies ability to provide potable water to its consumers from areas traditionally seen as sources of plentiful supply. Recently, the Peak District has been identified as an area of “moderate” water stress to water companies in the governments’ water strategy for England *Future Water* (Defra 2008a). Such areas have been identified so that areas of serious water stress may be designated for the purpose of accelerated water metering and so combat the effects of increased risks of drought, deterioration in water quality and higher risk of flooding. Programmes such as gully-blocking and the reduction of water yield may therefore place added pressure on the expected changes arising from climate change.

Largely as a result of reduced runoff, the difference in observed and predicted DOC flux from this catchment was an estimated reduction of 2.88 $Ct.km^{-2}yr^{-1}$ from that expected. It could be argued that the retention of carbon on the site and potential for the blanket bog to become a sink for carbon storage with the associated benefits of controlling effects of climate change, could outweigh the values of water supply placed upon these upland catchments.

Whilst the observed water colour increased significantly at Nether Gate Clough (where prescribed burning had been temporarily halted), the difference between the observed and predicted water colour using the paired catchment approach was determined as a small increase in colour (2°H) which was not statistically significant. This suggests that the observed change in colour at the site may have been influenced more by climate and certainly a seasonal pattern of colour was clearly observed during the study, with high colour being discharged in the winter and lower colour in the summer. The time-scale for biological, physical and chemical processes associated with burning described by previous researchers (see Section 2.4.1 and 9.4.2) may have been insufficient for it to have been reversed and for some improvement in water quality following the cessation of burning to be observed. Clearly, on a catchment-scale the cessation of burning does not appear to have had a beneficial effect on ameliorating water colour from the site over the 3-year treatment period, particularly when a small amount of burning occurred on the catchment in year 2.

Changes in the observed and predicted ASQ using the paired catchment approach were, however, weakly significant at Nether Gate Clough amounting to a predicted decrease in runoff of 84 $mm.yr^{-1}$. This supports the findings of previous research which found that continued burning increased the volume and intensity of throughflow (Imeson 1971). The temporary cessation of burning reduced the number of areas of new burns over a three-year period which could typically have amounted to as much as 9-12% of surface area if a conservative estimate of 3-4% of the catchment was not burnt each year during the temporary agreement. Newly burnt areas are sites for increased surface runoff from the exposed peat or pioneer bryophyte vegetation following the burn (Imeson 1971, Cosgrove 2004, Glaves *et al* 2005, Worrall *et al* 2007a). Not burning new areas and allowing other areas to revegetate and develop stands of building and mature heather could increase interception and allow precipitation to infiltrate and be stored in the soil, thus accounting for the decrease in runoff from the site.

The difference in the observed and predicted DOC flux for the catchment estimated a reduction of 0.24 $Ct.km^{-2}yr^{-1}$ (not statistically significant) largely because of the predicted small rise in colour and larger decrease in runoff.

The predicted change in ASQ over that expected at Doctors Gate Clough (where grazing had been removed) was also statistically significant (see Section 8.3.3.4). Differences between the observed and predicted ASQ at the site predicted a reduction of 430 $mm.yr^{-1}$ runoff post-management manipulation from that expected. Although this is particularly high it does support research which suggests the hydraulic conductivity and infiltration rate could be higher at sites where grazing has been removed (Holden *et al* 2007) and the hydrological flowpaths created by the continued use of sheep tracks may have begun to disappear allowing areas to naturally revegetate and not rapidly drain water from the site (Evans 1998, 2005, Clement 2005, McHugh 2007). Similarly to Nether Gate Clough, the reduction in ASQ was also supported by a decrease in observed depth to water table as the water table recharged following the removal of grazing from the site (see Section 9.4). The rise in water table was significant and again supports previous research by Worrall *et al* (2006) discussed in Section 9.4.3. It should also be noted that the large difference in observed and predicted runoff may have been caused by mechanical error regarding the accuracy of the stage logger (see Section 7.2) and may have under-recorded stage during the study. In addition, the control site (Upper North Grain) paired with Doctors Gate Clough to predict runoff had an observed increase in runoff of ~ 11 $ls^{-1}.km^{-2}$ between the first and final year of the study and would therefore predict a high runoff at the treated site.

The predicted change in DOC flux over that expected was a decrease of 0.47 $Ct.yr^{-1}.km^{-2}$ and was statistically insignificant. This estimation may not be reliable because of the difficulties in measuring runoff from stage logger error (see Section 7.2) and also the large prediction of reduced true colour at the site when using Red Clough control to predict colour during the treatment period. During this period the control site had a rise in colour during the summer months caused by iron oxidation (see Section 6.5.3). This accounts for the predicted increase in colour at

Doctors Gate Clough following the removal of grazing. It is therefore unclear what effect the removal of grazing may have had on DOC flux during the study.

9.6 Implications for the Future – Policy and Practice

Water quality is considered key to a full understanding and management of water resources, but there is an increasing recognition that scientists, politicians and land managers have to work collaboratively towards developing best practice management (JNCC 2006). However, the different aims and objectives of the three groups poses a challenge because the questions most relevant to policy decisions may not have scientifically well-founded answers (Dessler and Parson 2006). This research has exemplified this very point as shown by the debate on prescribed burning in the uplands during the review of the Heather and Grassland Burning Regulations and Code (Defra 2007) and more recently on the effects of gully-blocking in developing techniques for carbon retention to off-set emissions exacerbating climate change whilst at the same time enhancing habitat quality to assist with the integration of the Water Framework Directive (2000/60/EC).

Whilst political debate demands fast answers and is unsympathetic to scientific caution (Dessler and Parson 2006 p 38) there is an increasing demand to understand the processes involved, in this case, in the generation of water colour/DOC and water yield/DOC flux from upland catchments. In theory the top-down approach of understanding the system can then lead to problem solving; then managing the process through a cost–benefit analysis and finally political input if required. By understanding the processes it should lead to action. However, in reality the bottom-up approach may be taken when political pressures are placed on management with the need to implement policy and regulations and therefore very rarely do the decision-making processes involve an understanding of the system (Harris 2008). There is a clear need for this to be reversed to enable political decisions to be based on science-based evidence and allow land to be managed more effectively in the future.

Trudgill (2001) also recognised the complexities of science in the context of economic, social and political circumstances. Figure 9.1 illustrates the internal use of science and the external meaning with regard to, for example, water resource management. The three groups of meaning are identifiable within this study. The first is the self-defined meaning derived from the data (relative to experimental observation) and the conclusions drawn e.g. the decrease in water yield from gully-blocked catchments. The second is the generalised meaning and implications for the whole subject matter in which the research topic is nested e.g. the implications of decreased runoff to stream hydrology and ecology, and water quality. The third is the external cultural/social or management meaning and their interpretation within these contexts e.g. implications of reduced water yield on potable water supply to customers and introduction of water metering to restrict water use in areas where water is in limited supply. This section discusses the implications of current policy and practice on the management of water quality in the future.

Figure 9.1: The Three Domains of Science (adapted from Trudgill 2001) p 50

Implications	Internal		Internal		External		
	For research topic		For subject as a whole		Implications		
					Constructs		
					Orthodoxies		
	Design						
	Data						
	Interpretations						
	Conclusions				**ACTIONS**		
	Debates						Economic
	Evidence					Context	Social
	Complexity						Political
	E.g. water colour		Hydrology		Water resource management		

9.6.1 Integrated Catchment Management

Peatlands have been recognised as valuable and this value usually relate to human use (Hughes and Heathwaite 1995). Immirizi (1997) recognised that the biochemical, ecological and hydrological functions of these wetlands yielded a number of products and attributes, and although not necessarily of economic value, they would have value placed on them by society. More recently, the approach exemplified by Immirzi (1997) has been extended to recognising that ecosystems and the biological diversity contained within them provide many goods, services and other benefits which have been referred to collectively as "Ecosystem Services" (Defra 2006). Table 9.2 shows the grouped ecosystem services into six broad categories reviewed by eftec (2005).

Table 9.2: Ecosystem Service Categories (eftec 2005)

Category	Function
Regeneration and Production	production of biomass providing raw materials , food, pollination, seed
Regulation and Stabilisation	pest and disease control, climate regulation, mitigation of storms and floods, erosion control, regulation of rainfall and water supply
Habitat Provision	refuge for animals and plants, storehouse for genetic material
Cycling Processes	nutrient cycling, nitrogen fixation, carbon sequestration, soil formation
Information/Life-fulfilling	aesthetic, recreational, cultural and spiritual role, education and research
Purification and Detoxification	filtration, purification and detoxification of air, water and soils

Table 9.2 shows that "purification and detoxification", and "regulation and stabilisation" are two services in which water quality and water quantity are highly valued, are but two values amongst the many services provided by upland catchments. Increasingly, there has been a need to prioritise the pressures placed upon these categories and so safeguard and maximise the functions that are

valued. One suggested method of achieving this is through Integrated Catchment Management (ICM) and has been described as:

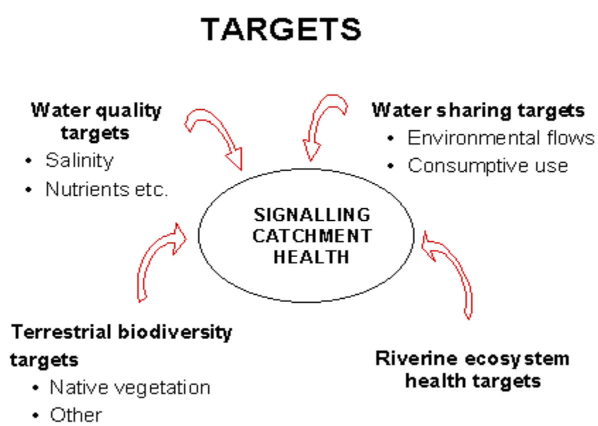
> *"a process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment".*

(Murray-Darling Basin Commission 2006)

This holistic approach to land management incorporates research knowledge, policy and legislation and community action and is recognised as a convenient unit for increasing understanding, providing a focus for objectives, facilitating cooperation amongst land managers and finally to coordinate action and implement activities, that is, "understanding into action" (Cummings 1999).

Such an approach could facilitate the scientific knowledge and evidence gained from this and other related research, implement policy and legislation such as integration of the Water Framework Directive (2000/60/EC), Habitats Directive (92/43/EEC) and proposed Soil Strategy and management by land owners. Figure 9.2 shows ICM may be a means of achieving the targets set by a number of agendas: for example, "good" water quality, water quantity and ecological status of surface waters (required by the Water Framework Directive) and favourable habitat condition (PSA3 target, Habitats Directive).

Figure 9.2: Model of Indicators of Catchment Condition (adapted from Murray-Darling Basin Commission 2006)



The bottom-up approach of political pressure is perhaps most evident with the current debate on climate change. Changes in rainfall patterns, frequency of drought and intensity of storm events, together with extremes of temperature are likely to affect upland areas with soils high in organic matter (Chapman and Thurlow 1996, Goldsmith *et al* 1997, Jones and Petts 2006, Worrall *et al* 2006). Such areas are valued for "cycling processes" through carbon sequestration and have been recognised as an important carbon sink by which carbon emissions could potentially be off-set and so reduce the effects of climate change (Milne and Brown 1997, Lal 2003, Bellamy *et* *al* 2005). However, such areas may also be vulnerable to carbon loss through natural processes such as weathering through wind and rain-splash erosion (Tallis 1973, 1998, Evans and Warburton 2001, Warburton 2003). These processes may be exacerbated by land use and management and this has focussed an interest on land management activities and the need for science-based evidence to provide the answers. As discussed in Section 9.2-9.5 the effects of some of the land management changes remain unclear following this research which took place over a relatively short time period. Certainly it remains doubtful as to how long some processes will require to recover (if ever) and for water quality to improve or DOC flux to decrease. Whilst scientists insist on funding for long-term monitoring and continue to advocate caution, some politicians argue that they "can't wait to understand everything before we act". Whilst it could be argued that valuable monitoring by, for example, the UK Acid Water Monitoring Network in the last 15 years has identified temperature and acid deposition as good predictors of observed trends in DOC flux across their sites, it is still less clear what influence the effects of landuse may have on individual catchments (Evans *et al* 2005). The conflicting results of short and medium studies emphasise the requirement for further research and improvement of understanding before major policies and legislation should be implemented.

9.6.2 Water Management

The perception of how important water resources might be and how limited a resource it may become in the future has focused interest on finding ways of using water much more efficiently and sustainably if we are to continue to enjoy high standards and constant supply (Defra 2008a). Since 1989 Water Service Companies such as Severn Trent Water (STW), United Utilities (UU) and Yorkshire Water (YW) have been responsible for providing drinking water in England and Wales and despite the increased trend in water colour from DOC, the companies have still been required to comply with standards set by the EU Drinking Water Directive (98/83/EEC) enforced by the Water Supply (Water Quality Regulations) (2000) and Drinking Water Inspectorate (DWI).

Water companies whose main gathering grounds are in the uplands are particularly concerned with the increasing costs and difficulties of achieving the water quality standards. Several companies e.g. STW, YW and UU have had to upgrade their treatment works and introduce new filter processes. For example, YW is planning to install a Magnetic Ion Exchange (MIEX) at the Albert Water Treatment Works (WTW), Halifax by 2009 in order to meet the demands of the DWI and uncertainty about the colour problem is hampering its long-term management (Holden *et al* 2006a). YW estimated in 2006 that the cost of treating the rise in colour at Albert WTW (increase from 65 to 100 °H) was a total of £25 per megalitre (ML) of water and bearing in mind that YW processes 1.24 billion litres of drinking water every day these increases in costs are highly significant to the business (Holden *et al* 2006a).

Not surprisingly, alternative and supportive mechanisms have been considered which include changing methods in which the uplands have been traditionally managed. However, this research has confirmed that despite changes in land management the absolute values of water colour at the study sites increased over a four-year period irrespective of changes initiated. This again is of obvious concern to water companies when considering degradation of these upland catchments that have traditionally been seen as cheap sources of water for potable water supply (Naden and McDonald 1989). However, sustainable catchment management is still seen by some water companies as a viable option and supportive role to traditional water treatment processes. This is evident by the number of studies that have been funded by water companies in recent years to determine whether traditional land management such as grazing and prescribed burning, together with proactive gully and grip-blocking measures could ameliorate water colour/DOC. Although this study was the first to investigate these practices on a catchment scale, UU, YW and North West Water have more recently financed short or medium term research carried out by the Universities of Durham, Manchester and Leeds to determine the cost-effectiveness of such measures on their own catchments.

Perhaps this approach has been best exemplified by UU in their Sustainable Catchment Management Project (SCaMP) for the period 2005-10 which incorporates some of the methods suggested by Integrated Catchment Management (ICM) discussed in Section 9.6.1. The company owns much of its gathering grounds and the land is managed by tenanted farmers. UU has taken an holistic approach through negotiation and agreed a number of management plans with the tenants aimed at controlling soil processes and improving raw water quality to reduce the treatment costs. UU was able to adopt this programme of intervention by agreement with the Water Services Regulatory Authority (OFWAT) in the last Asset Management Planning process (AMP4) in 2004 which reviewed the performance of the water company and agreed the activities of the company for the next five years (2005-10). This was achieved by demonstrating the problem to OFWAT to gain permission to spend resources on addressing the problem and charging customers for its implementation. A programme of extensive grip-blocking, grazing exclosures and restrictions on prescribed burning has since been adopted and monitored by Penny Anderson Associates on behalf of UU as part of the £2.9 billion programme of investment and maintenance works. Of this, £1.19 billion has been allocated on improving drinking water quality and incorporates the SCaMP Project (Tickle 2006).

Whilst UU can take advantage of the opportunities provided by OFWAT, water companies have already begun preparations for the next AMP period (2010-2015) and to prepare their Periodic Review (PR) to OFWAT. The general consensus is that OFWAT is unlikely to support similar sustainable catchment programmes to improve water quality as they are uncertain that customers should be charged indirectly through catchment management for the quality of their drinking water (*pers comm*. Mr A Warren 2007, STW). Therefore despite the undoubted interest in catchment management from water companies, assessments of the relative costs of catchment management to water treatment are difficult to determine. The measures to reduce colour levels in raw water would need to be quantified before accurate costs could be calculated and without the support of OFWAT to enable funding to be available for such projects by passing costs onto consumers it is unclear how this sustainable approach to catchment management might progress. In addition, the flexibility practiced by companies such as UU and YW is not available to all water companies, for example, STW gather much of their water from the south Pennines to fill the reservoirs that supply water to most of the Midlands, but they own very little of it. It would therefore be difficult to negotiate such agreements with the landowners who would be likely to want some financial compensation if it were to affect their income from other sources e.g. grouse shooting. Although carbon credits have been considered as potential reward for managing the land to sequester carbon, it is still unclear whether this would be a viable option and the politicians of the UK and Europe are still a long way from implementing such policies (Flitcroft 2006).

One land management change that has been widely introduced into the upland catchments in recent years is that of grip and gully-blocking. Whilst those water companies that own their land have the flexibility to introduce such techniques to determine if water colour/DOC levels will be ameliorated, other companies do not have such control over the sites from which most of the water flowing into the reservoirs derives. Landowners such as the National Trust, supported by Natural England, are enthusiastic about extending their gully-blocking programme to degraded areas of moorland in an effort to rewet the soils, restrict sediment loss and encourage *sphagnum* and other bog species to recolonise (Black 2007). Whilst this is supportive of Natural England's PSA target for SSSIs to return to favourable condition, most water companies wish to maximum water yield from such areas, particularly during droughts and periods of low rainfall. This study has shown that whilst the gully blocking was successful in rewetting the site, there was a period of ~14 months post gully blocking when runoff was significantly reduced as the water was retained in the gullies by the dams and the water tables recharged. Up to the end of the study, the research also indicated that during periods of low rainfall in the summer, water yield was also low as again, the dams prevented discharge. The water companies' main purpose is to provide water to its customers and whilst being supportive of gully-blocking programmes on a small-scale, the extended rolling-programme envisaged by some landowners may have serious effects on runoff in the short-term immediately following gully-blocking, but also in the longer term during periods of drought – a time when demand for water is at its highest. Whilst conservationists want to maximise water retention on these sensitive catchments, water companies want to maximise water yield and it is difficult to predict who might have the last say, particularly where land ownership is an issue.

The water companies are also faced with the dilemma of supplying water from areas seen traditionally as being in plentiful supply, such as the Peak District, to the new reservoirs and desalination plants in the south of England (Jowit 2008). However, the Peak District has recently been designated as an area under "moderate water stress" because of the forecast change in climate (Defra 2008a). The combination of effects from climate change, transferring water to the south and conserving the blanket bog through gully-blocking may deplete water supplies from the uplands and have serious consequences in how water is supplied and recycled by water companies in the future

In addition, the requirements of the Water Framework Directive (WFD) are to achieve "good ecological status" by 2015, that is, good chemical, morphological and biological status. It is anticipated that significant changes in land management will be required to ameliorate diffuse pollution and the Environment Agency (EA) are advocating a policy of Integrated Catchment Management and agreements with land managers to achieve this. The problems of diffuse pollution from fine organic sediment released as soils erode, together with the discolouration of waters with higher concentrations of DOC means that this is not only a WFD problem, but also one for raw water treatment as the use of chlorination of highly coloured waters and release of trihalomethanes (THMs) are still considered to be potentially toxic and carcinogenic (Chow *et al* 2003, Toledano *et al* 2005). Sustainable catchment management through the manipulation of burning and grazing, together with proactive restoration might therefore very well be the way forward in achieving the objectives of the WFD whilst meeting the requirements of the water companies in the future.

10 CONCLUSIONS

10.1 Introduction

The investigation focused on blanket peat moorlands in the Ladybower catchment from which water is treated at Bamford Treatment Works. Whilst other workers have considered management techniques for water colour amelioration at laboratory and plot scale, no previous study had evaluated the impact of these approaches at a catchment scale with a sufficient degree of experimental control. This was achieved by establishing the baseline relationships between meteorological inputs and hydrological responses during a calibration period of fourteen months prior to intervention in blanket peat moorland management. Six catchments of the River Ashop were instrumented and during this period the relationships between water discolouration and hydrological and land management characteristics were identified. From this, suitable pairings of catchments were determined with similar hydrological, morphological, pedological and land management characteristics. One catchment was then treated to a management practice, such as the removal of grazing, whilst the management on another was not affected. Using this paired approach, it was then possible to assess the impact of management on the treated catchment in comparison with the untreated or control catchment. Following controlled intervention in blanket peat moorland management on three of the catchments (gullies blocked, cessation of burning and removal of grazing), all study sites were monitored for a further three years to identify and quantify changes in hydrological response, water discolouration and DOC flux and predict responses post management intervention.

10.2 Major Findings in Respect of Research Aims and Objectives

The principal aim of this study was to evaluate the role of catchment management in the production of discoloured surface runoff and DOC flux from catchments used as gathering grounds for public water supply. This has been achieved through the objectives set:

i) A baseline relationship between meteorological inputs and hydrological responses was established during the calibration period prior to intervention in blanket peat moorland management;

ii) Paired catchments of similar morphological, pedological and land management characteristics were identified and similarities between catchments established;

iii) The relationships between meteorological inputs and changes in water quality, runoff and DOC export on control (management unaltered) and treated (management manipulated) sites during the pre- and post-management periods were analysed;

iv) Changes in hydrological behaviour, water colour and DOC export following controlled intervention in blanket peat moorland management were quanitified and catchment responses observed where management was manipulated;

v) A paired catchment model was developed to predict the outcome of management manipulation on hydrological behaviour, water colour and DOC export and identify the future generation or amelioration of discoloured surface water supplies.

The major findings of this research can be divided into the three types of land management manipulation and their impacts on water colour/DOC, water yield, DOC flux and vegetation.

(1) Gully-blocking

The effect of gully-blocking appears dependent on the aims and objectives of the blocking programme and the judgement of that success depends on the aims and objectives of stakeholders and their differing views. The effects of gully-blocking in the current study were:

- Water colour amelioration – water colour increased during the study post gully-blocking (in line with the remaining catchments) and showed recovery in the last year, although not to levels pre-gully blocking. Potentially, catchment rewetting should allow more surface runoff and less residence time of water in peat soils when colour would normally be generated, but the process of rewetting produces a short-term colour flush. This can be seen as a negative impact at one time scale for a positive one at a longer-time scale when water colour would normally be expected to decrease, but it is still uncertain the time needed to achieve this .

- Water storage – gully-blocking has retained water on the catchment, initially as surface water within the blocked gullies and over a longer period decreased the depth to water level below the surface over a wider area. Rewetting the blanket bog has had important ecological and hydrological implications and can be seen as a sign of recovery of this protected habitat.

- Gully-blocking reduced the volume of water being discharged (and so potentially the amount available for water supplies). However, this affect appeared short-term and runoff levels did increase again ~ 14 months after gully-blocking which suggests an increase in overland flow following the saturation of peat soils.

- DOC flux - The observed differences between DOC flux pre- and post-gully blocking ranged from 0.05-0.12 $Ct.yr^{-1}.km^{-2}$ and were not statistically significant. This suggests greater stability and less extremes of colour export from the catchment. The difference in observed and predicted DOC flux between pre and post gully-blocking was significant (reduction of 2.88 $Ct.yr^{-1}.km^{-2}$ compared to that expected).

(2) Cessation of Burning

- Water colour amelioration – water colour also increased during the study after the cessation of burning (in line with the remaining catchments), but showed signs of recovery in the last year. It is still unclear if burning has a direct causative effect on water quality.

- Water Storage – the cessation of burning on relatively newly burnt areas demonstrated that depth to water table decreases and catchments can rewet, at least in the short-term on areas of pioneer and young heather where water can infiltrate into the soils. Runoff was reduced whilst water tables recharged and again this may affect the catchment potential to supply water. However, similarly to gully-blocking this affect appeared short-term and increased volumes of surface runoff should potentially increase both the volume and quality of water from such catchments. For example, the runoff increased in the final year compared to the first year prior to management manipulation.

- DOC flux – There was no statistically significant difference in monthly areal DOC flux between the calibration period and the period when burning was stopped which may suggest that the catchment was becoming more stable compared to other catchments with fewer episodes of colour export on a catchment-scale. The difference in observed and predicted DOC flux between the calibration and treatment period was also not statistically significant and a longer period of study is required to determine changes at this scale.

(3) Removal of Grazing

- Water colour amelioration - The direct effects upon water quality from the removal of grazing are still unclear. The observed data indicate that water colour increased following the removal of grazing (in line with the remaining catchments), but the increase was not statistically significant. Using the paired catchment approach, the data suggest that water quality may improve (despite the high discolouration, this was still less than predicted), but the water was highly discoloured during the summer through iron oxidation at both the treatment site and control site in addition to the high colour flush from organic matter during the autumn/winter. It is still uncertain what the recovery time and rate of a catchments soil, hydrology and vegetation may be and what impact this would have in the short and long-term on water quality. A series of long-term replicate plots are recommended to study and determine the affects of a non-grazing regime on the catchments.

- Water storage - Doctors Gate Clough had the highest area specific discharge (ASQ) rates for each year and the response to rainfall events was higher than the other sites which could suggest that relatively little water was being stored on the catchment from these events. This may be a result from a legacy of intensive grazing, which previous researchers have found to result in soil compaction, shorter vegetation or its entire removal, increased exposure of bare earth and erosion which could affect surface and sub-surface flow through the upper layers of soil.

- The observed and predicted runoff decreased following the removal of grazing and this could indicate that there was some recovery. Hydraulic conductivity and infiltration rate of soils may have increased and vegetation across areas such as sheep tracks and bare areas of peat which would have acted as hydrological flowpaths for water draining off the site when sheep were still actively grazing the site may have recovered.

- DOC flux - The mean areal DOC flux decreased in year 2 following the removal of grazing, but increased again in the third year. This pattern differed from the remaining sites which all had an increase in DOC flux during the treatment period (years 2-4 following management change). Although the removal of grazing may have affected the flow and generation of DOC, the decrease may also have been caused by mechanical problems with the stage logger and calculation of runoff in that year However, the difference in observed and predicted DOC flux between the calibration and treatment period was statistically significant (5.64 $Ct.yr^{-1}.km^{-2}$) which suggests the removal of grazing could assist with carbon retention.

10.3 Limitations of Research

Although the experimental design was good in terms of a paired catchment approach being used with some degree of control, there are inevitably some methodological improvements which could be made for future studies. Firstly, the period of monitoring was over a four-year period, but in terms of conducting a paired catchment experiment this still limited the calibration period to just over a year to enable a sufficient period of post-monitoring during the treatment period to be completed. Ideally, the research should be conducted long-term to enable identification of short, medium and long-term responses to changes in management. In addition, a longer calibration period would have allowed differences in meteorological conditions to be further considered. For example, in the first year (calibration period) there were periods of drought and low monthly rainfall compared to the years during the treatment period. It is acknowledged however, that there may not be a “typical” year to represent climate in the area, particularly with the predictions of climate change with more frequent storm events, periods of drought and increased temperatures likely to be the norm in the future.

Despite the extensive datasets obtained from monitoring six sites for four years there were other opportunities for data collection if resources had permitted. The collection of a daily water sample made up of a small hourly sample taken from the stream located at the base of the catchment over a twenty-four period was accepted as a method of capturing the changes in water discolouration that might rapidly occur following the onset of a storm event and flushing of colour into the streams. This method did not however, capture the extremes of colour during the storms, although it is acknowledged that interpretation of such data would be difficult to disentangle from the affects of antecedent meteorological conditions and changing hydrological processes.

Samples of soil water from dipwells during their manual monthly measurement could have been analysed for water colour/DOC, pH and conductivity and related to changes in water table depths and land management changes across the catchments. In addition, further nests of dipwells could have been installed across the catchments, for example in newly burnt to mature heather stands and adjacent to a number of blocked gullies to determine changes across each catchment. However, it is appreciated that this method of monitoring is extremely time-consuming when walking across even a relatively small catchment.

However, whilst it is recognised that if resources had permitted, replicate sites monitoring water and discharge could have been set up across the catchments either as a series of short or longer-term experiments, the main aim of the research was to determine the changes in water colour/DOC and runoff at a catchment-scale. Although it is likely there would have been differences in these variables across the sites, the output of water quality and quantity at an operational scale at the base of the catchment was of more interest to the land owners and business managers and fulfilled the objectives of the study.

The study site was chosen as being representative of generally degraded upland catchments in the south Pennines and had been identified by streams discharging high colour following rainfall events. However, much of the area lies within the Dark Peak SSSI and is visited by several thousand visitors each year, mainly for recreation and its aesthetic value. Limitations were therefore placed on the siting of equipment. In particular restrictions were placed on the construction of any flumes or weirs within the channel because of the conservation status of the area. The in-channel construction would have assisted with maintaining accuracy of stage and flow measurements from which discharge was calculated and identifying with greater certainty the changes that may have resulted from land management manipulation, for example, at Doctors Gate Clough where large changes in discharge were observed following the removal of sheep from the site.

The collection of data from a natural environment, of which the study site is recognised as a fairly extreme environment in UK terms, is fraught with difficulties. These include extremes of temperature, rapid changes in stage and discharge in response to rainfall events, localised erosion of stream banks and landslides, to equipment damage from human interference and animals. In a short-term study some of these problems may not occur, but in a longer-term study over four years all these difficulties were encountered at one time or another and resulted in some data loss. However, the advantage of the long-term study was that such data loss could be minimised during analysis when considering monthly or annual data sets over the four years.

Furthermore, the range of equipment used to monitor the sites required regular visits for data collection and maintenance and were therefore heavily resource-dependent and costly to resources. Several water samplers, stage loggers and a rain gauge failed during the four years and had to be repaired during which some data were lost. As this automated equipment was either logging continuously or collecting samples hourly, it is unlikely that such failure could have been avoided in the harsh climatic conditions over the four years.

10.4 Recommendations for Future Sustainable Management

The research has successfully identified a number of areas where sustainable land management might ameliorate or reduce the degree of discolouration and DOC flux being discharged from upland catchments located primarily on blanket bog peat. It may therefore be possible to manage small/medium scale anthropogenic effects through appropriate moorland management to achieve improved water quality. However, it is recognised that the aims and objectives of a water company in maintaining yield and high quality water may differ greatly from the aims of conservation and statutory organisations such as the National Trust and Natural England.

It is clear from some of the main findings that recommendations can be made for the practical management of the sites to mitigate or reduce the degradation of peat soils and vegetation and also to positively assist in their recovery by taking a proactive approach to management, for example, with gully-blocking. In addition there are still several areas where practices continue with little or no science-based evidence to support whether their effect is positive or negative. There is thus a need to take the opportunity to study both the short and long-term effects of management change on such a sensitive environment as blanket bog. This section will consider firstly recommendations to practical management practices and secondly the future research opportunities that may assist in returning areas of blanket bog to a more favourable condition along with the associated benefits of doing so.

10.4.1 Gully-blocking

- A programme of more intense gully-blocking over a series of catchments would support the restoration of blanket bog and improvements in its ecology. However, it is still unclear if hydrological function could be restored using this method. In addition the function of upland catchments as important gathering grounds for water supply needs to be sustained, particularly in the light of climate change. Therefore serious consideration should be given to gully-blocking programmes and adequate monitoring to determine if both the quality and quantity of water supplies would be affected in the short or long-term.

- Whilst such findings are supportive of further gully-blocking particular care is required to ensure that blocks are not installed at inappropriate sites where the water table may already be high with little fluctuation between summer and winter water levels. Water may be retained in gullies at the expense of sensitive habitats further down the catchment e.g. acid flushes, or may cause localised flooding and/or increased runoff from the site once the catchments have rewet. These factors emphasise the importance of monitoring both short and long-term effects of such major restoration programmes and the collection of baseline data prior to making changes.

10.4.2 Cessation of Burning

- Whilst serious reservations regarding the cessation of burning have been voiced by practitioners and conservationists this study has found that water discolouration did not decrease on a catchment-scale following the temporary cessation of burning. However, findings such as reduced runoff, decreased depth to water table and change in species composition all indicate that the catchment had begun to rewet during the period when burning was stopped. Such conditions may support the long-term amelioration of water quality and DOC flux by reducing the aerobic conditions and microbial activity in soil responsible for humification and production of acids and suggests that prescribed burning should be halted or restricted on blanket bog.

- Observations of areas that continued to be burnt on rotation were found to have areas of bare peat on steep slopes that were prone to desiccation and cracking; and peat haggs at gully edges where hydrophobic soils were prone to erosion. It is recommended that such areas, particularly where the gully network is dense, should not be burnt to minimise the impacts of weathering, desiccation and carbon loss.

10.4.3 Removal of Grazing

- The effects of the removal of grazing at a catchment-scale are not clear-cut. The findings of the study showed that runoff decreased and water tables rose suggesting that the catchment was rewetting and although observed water colour did increase, it was still not as high as expected using the paired catchment approach. This suggests that the removal of grazing has had a favourable impact on the catchment, but it is still not clear how long livestock should be removed from a site in order for hydrological function to be restored.

10.4.4 Recommended Management Strategies

The following management strategies are therefore recommended:

- The continued maintenance of strict catchment management codes on agricultural practices, particularly with regard to drainage, prescribed burning and grazing.
- Highly sensitive areas most likely to generate high quantities of humic substances should be identified and appropriate action taken to reduce their discharge, e.g. by fencing off areas to prevent livestock or human intrusion and encourage natural regeneration and stabilisation of soils.
- Consideration of appropriate revegetation and restoration schemes with appropriate monitoring prior to any works being carried out in order to establish a baseline of data of prevailing conditions pre-restoration and so to further the understanding of changes in processes and vegetation that may occur post-restoration.
- A periodic review and updating by water authorities of the results of on-going research on humic substances and implementation of appropriate amendments to catchment management policy.

10.5 Recommendations for Future Research

The scope for future work on sustainable upland management to ameliorate or reduce water discolouration from upland gathering grounds is still considerable.

10.5.1 Gully blocking and Amelioration of Water Quality

- There is a need to understand more fully the soil, hydrological, hydrochemical and vegetation processes and changes that may occur at a plot scale and a larger catchment scale, together with the effects of gully/grip blocking further downstream e.g. on sediment flux, DOC, POC and water colour release. A particular concern is the potential increase in soil pipes on drained sites and the effects of grip-blocking on the soil pipe network in terms of runoff, erosion, oxidation and site degradation.
- Particular emphasis on changes in the soil moisture regime and an evaluation of its relationship with the extent of water table draw-down; the relationship of water colour to the magnitude and duration of the wet/dry cycles

and the conditions which might exacerbate decomposition.

- Further research needs to be completed into the most cost-effective and efficient techniques to be used for grip/gully blocking and whether it is feasible to encourage the natural revegetation of some sites, for example, by re-profiling gully sides. Natural revegetation of gullies and grips needs further study to understand the processes involved in the natural colonisation of flora and sediment accumulation in order to encourage and expand such processes on a catchment scale.

10.5.2 Prescribed Burning and Amelioration of Water Quality

- The recent debate and review of the Heather and Grassland Burning Regulations and Code (Defra 2007) has generated much interest regarding the potential impacts of prescribed burning on blanket bog. However, there still remains a dearth of information on the impacts of burning on the vegetation composition of blanket mire species, or the soil and hydrological processes affected by the frequency and intensity of burn.

- An impartial scientific evaluation of the impacts of burning on the soil and hydro-chemistry (e.g. DOC, carbon flux and sediment yield, pH, Fe, oxidation, humification) of peat needs to be investigated, together with an evaluation of the hydrological responses of burning at a range of scales e.g. plot scale run-off regimes to sub-catchment and whole catchment scales over a range of time periods in order to assess the cumulative impact locally and regionally. An assessment of soil infiltration under a range of burns, throughflow dynamics and water table fluctuations also require investigation.

- Further use of digital infrared (IR) photography to assess vegetation and areas burnt under a cool/hot burn and the recovery rate for the areas concerned could be developed to assess the temporal and spatial changes in burning patters and rates of recovery.

10.5.3 Grazing and Amelioration of Water Quality

- Workers such as Evans (1997, 2005) have studied the effects of sheep grazing on vegetation and upland erosion and semi-quantified the initiation and rate of re-colonisation of vegetation at particular sites within the Peak District. However, there is a need for a national inventory to monitor the extent and rates of erosion induced by animals. Evans (1977, 2005) found that on upland peat soils, re-colonisation only occurred when mineral subsoil was exhumed and concluded grazing regimes had to be such that bare soil was not created. This may not be practical and therefore further long-term research is required to determine the time required for upland areas to recover following the removal or reduction in livestock. In addition, further work is required to determine the optimum stocking rates and breeds of sheep grazed under a range of conditions, taking account of differences in geology, topography, soil and vegetation type.

- Further scientific evaluation of the effects of intensive grazing and/or the removal of livestock has on the soil hydrological and hydrochemical processes of peat soils is required. Whilst some work has been completed on determining the effects of vegetation loss and decreased soil infiltration on surface runoff (e.g. Meyles *et al* 2006), further investigation of the rates of recovery at different spatial and temporal scales is required.

- Further scientific evaluation is needed of the impacts on soil, hydrology and hydrochemical processes that occur where both prescribed burning and grazing occur together and on a plot or catchment scale. Such a management regime dominates in many upland areas where the main sources of income are from grazing and/or grouse shooting. The combination of this management which regularly creates bare areas with little vegetation cover, even where sheep densities have been reduced to the recommended levels may delay the re-colonisation of vegetation, create sheep tracks and channels for runoff and so facilitate rapid runoff from rainfall. These processes together with an investigation of the hydrochemical processes affecting water quality and carbon loss require further study, and should incorporate recent and older burns through the whole burning cycle.

Previous workers have recognised that research can often make things more complicated and ask more questions than are answered (Trudgill and Richards 1997) and indeed this study has raised some important and complex issues. Since the commencement of the study in 2002 the issues of water quality and carbon loss have gone up the agenda of water companies and government departments alike, and have continued to be a source of concern. This study has contributed to the knowledge and understanding of sustainable catchment management in terms of water quality, yield and DOC flux. However, it has also raised further questions and there is still much to be done, particularly as this is not a problem which will just go away.

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APPENDIX I: Ashop Catchments Daily Actual and True Colour Water Samples (°H)

AC = ACTUAL COLOUR

TC = TRUE COLOUR

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
01/10/2002												
02/10/2002												
03/10/2002												
04/10/2002												
05/10/2002					24.7	24.7	38.4	37.9	151.7	137.7	88.6	80.4
06/10/2002							5.5		177.7	165.9	136.0	100.1
07/10/2002					34.9	30.7	44.7	42.5	149.8	119.9	104.0	92.7
08/10/2002					35.4	29.4			156.3	112.7	84.5	71.3
09/10/2002					25.3	19.5			148.1	99.3	79.0	68.3
10/10/2002					22.8	20.0			149.8	117.1	73.2	62.6
11/10/2002	456.34	391.1	56.0	49.4	24.2	19.8	51.3	45.8	142.4	96.8	72.4	70.8
12/10/2002	276.72	219.1	239.2	218.3	227.6	193.4	64.5	42.0	152.8	107.0	374.1	354.3
13/10/2002	280.29	230.9			169.2	157.7	155.2	130.3	130.8	96.6	255.9	240.0
14/10/2002	277.27	246.0			264.4	245.7	134.4	118.2	138.8	99.8	201.9	195.6
15/10/2002	267.95	233.1			183.2	177.7	166.2	138.5	126.7	101.2	169.2	145.9
16/10/2002	267.95	243.8			271.0	254.5	133.6	123.2	85.6	74.3	234.2	233.1
17/10/2002	246.01	214.7			194.2	187.6	123.2	120.4	99.3	87.5	160.7	166.5
18/10/2002	225.44	199.9	119.0	112.2	159.1	147.3	147.8	137.4	113.3	96.3	293.4	205.1
19/10/2002			86.7	73.2	123.7	118.5	126.7	125.1	97.7	82.3	54.9	240.8
20/10/2002			69.1	60.4	108.9	107.5	93.5	83.4	101.5	95.7	285.2	212.3
21/10/2002	193.63	181.6	89.2	74.1	274.0	252.0	80.7	74.9	96.0	84.8	271.5	213.7
22/10/2002	236.68	223.0	184.9	168.7	270.7	264.4	179.1	167.0	99.3	83.9	233.1	211.7
23/10/2002	268.50	240.8	207.9	193.9	350.5	338.4			94.1	82.8	224.3	213.1
24/10/2002	241.90	233.4	220.0	205.1	243.8	241.3	275.6	249.6	123.4	103.4	256.2	238.3
25/10/2002	252.86	240.8	210.4	202.1	237.0	232.6	221.1	196.6	131.1	117.7	222.7	209.8
26/10/2002	201.58	193.4	209.0	199.1	251.2	244.1	202.4	195.6	182.9	153.3	203.8	189.8
27/10/2002	205.70	196.9			231.5	220.8			150.6	130.0		
28/10/2002	183.49	178.0	168.1	157.2	207.3	203.0	216.9	192.3	153.6	138.0		
29/10/2002	179.10	176.4			162.9	161.3	206.8	174.4	141.5	117.7	157.7	130.3
30/10/2002	201.04	186.5			182.4	178.0					133.9	111.6
31/10/2002	168.13	161.5	89.7	84.5	134.1	131.7	147.3	137.1	69.7	68.0	138.0	134.1
01/11/2002	173.34	156.3			134.9	132.8	103.1	97.1	60.6	59.8	147.6	140.4
02/11/2002	226.81	207.3			222.7	206.8	190.6	172.8	138.5	127.3	219.4	209.8
03/11/2002	249.85	236.7	178.8	175.3	226.8	217.8	205.7	202.1	170.9	159.4	238.9	233.4
04/11/2002	252.04	230.1	199.9	179.6	246.0	235.0	232.6	220.2	185.1	177.5	263.8	257.0
05/11/2002	231.75	220.0	167.0	157.4	188.1	184.3	164.6	163.2	151.4	117.9	224.6	224.3
06/11/2002	243.81	212.8	226.0	199.9	329.1	294.0	231.7	220.5	185.7	167.9	244.9	235.3
07/11/2002	242.17	227.6	168.1	161.3	202.4	195.6	174.7	171.7	127.8	122.9	238.6	227.9
08/11/2002	269.32	255.6	241.3	225.2	332.4	284.7	260.8	251.8	204.9	190.6	270.4	260.8
09/11/2002	246.28	232.3	173.9	169.0	196.6	187.9	189.5	188.1	151.1	139.3	235.6	231.5
10/11/2002	273.16	253.1	255.9	225.7	196.4	186.5	271.8	270.4	225.2	209.8	279.2	266.6
11/11/2002			188.7	177.7	119.0	117.9	189.2	187.6	142.1	139.3	258.3	255.6
12/11/2002			225.2	213.9	267.4	260.5	249.6	234.5	218.0	207.3	285.8	280.0

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
13/11/2002					312.1	268.8	302.2	279.5	212.3	198.3		
14/11/2002					328.0	276.7	255.3	250.4				
15/11/2002					379.6	314.8	182.7	177.7				
16/11/2002	221.88	113.0	133.0	131.9	194.5	184.9	122.1	119.9	216.1	203.0	183.8	183.2
17/11/2002	253.69	133.9	121.2	88.3	146.7	143.4	101.2	99.3	88.9	71.9	140.4	137.4
18/11/2002	191.16	93.5	88.3	68.9	128.4	122.3			85.6	68.9	105.6	102.0
19/11/2002	187.32	132.5	68.3	59.3	145.6	136.0	74.1	72.7	83.4	72.1	93.0	89.4
20/11/2002	180.47	204.1	60.4	48.3	106.7	102.0	67.5	64.7	81.7	72.7	202.1	200.2
21/11/2002	227.36	223.5	197.2	148.1	225.2	214.5	193.9	191.4	157.2	141.3	268.2	263.6
22/11/2002	287.42	196.9	251.2	220.5	318.1	307.2	268.2	260.0	191.4	178.8	274.0	268.2
23/11/2002	283.58	189.8	243.3	208.2	301.7	298.9	253.7	248.8	181.6	172.8	226.8	220.2
24/11/2002	223.80	127.8	171.1	139.9	213.7	207.1	181.0	177.7	122.6	113.8	176.9	176.6
25/11/2002	222.15	118.8	116.6	103.7	165.9	159.4	129.2	129.2	90.5	85.9	141.8	133.3
26/11/2002	195.83	111.6	98.2	79.0	137.7	137.4	92.7	92.7	81.5	80.4	123.4	118.5
27/11/2002	180.47	111.6	211.2	64.7	129.5	128.9	79.0	74.1	80.7	72.7	203.5	197.5
28/11/2002			188.7	154.7	220.5	212.0	187.1	176.9	164.0	151.4		
29/11/2002			117.7	101.2	165.9	164.8	122.3	118.8				
30/11/2002					154.4	153.0						
01/12/2002					284.7	280.0						
02/12/2002					287.4	309.9						
03/12/2002					206.5	204.6	182.4	179.1	121.0	111.9	210.6	203.2
04/12/2002					268.5	254.2	223.8	162.6	168.4		226.0	175.5
05/12/2002	212.28	174.7			194.2	187.9	201.0	149.8			224.3	192.0
06/12/2002	250.40	154.7	120.1	108.1	167.6	157.2	136.6	119.0			197.2	164.3
07/12/2002	311.55	197.5	224.1	196.1	255.6	246.6	220.8	173.9			240.2	198.3
08/12/2002	231.47	179.9	178.5	165.1	224.1	232.6	175.0	144.8			229.0	201.9
09/12/2002	184.86	145.1	100.4	85.3	167.6	165.4	119.3	144.5			179.6	146.7
10/12/2002	153.59	107.8	58.2	50.8	132.5	133.6	74.6	60.9			131.4	105.6
11/12/2002			51.6	49.1	113.8	101.8	49.9	41.7				
12/12/2002			51.0	45.8	98.7	92.4	48.0	35.1	46.6	40.6	74.6	64.5
13/12/2002			32.9	36.0	121.0	95.5	115.5	81.7	168.7	55.1		
14/12/2002	121.51	96.6	103.4	94.1	240.8	206.2	118.8	88.9	74.3	51.0		
15/12/2002	178.28	60.4	98.5	81.5	213.7	171.4	152.5	120.7	102.6	65.8		
16/12/2002	262.46	73.0	119.0	93.5	201.6	167.9	152.2	115.5	87.0	58.2		
17/12/2002	183.76	80.9	97.4	88.9	153.3	138.5	146.2	118.2	96.3	56.2		
18/12/2002	92.44	40.3	50.8	44.2	130.6	110.0	96.8	71.1	76.8	50.5		
19/12/2002	93.27	76.0	48.0	58.4	100.4	91.3	65.6	54.3	44.5	29.4	97.4	74.3
20/12/2002	99.02	84.5	50.8	36.0	184.3	147.0	87.8	71.6	56.2	34.3	86.7	65.0
21/12/2002	112.46	84.2			194.2	165.1	113.6	89.4			158.3	104.8
22/12/2002	123.43	102.0			222.4	194.2	155.0	120.4			155.0	121.0
23/12/2002	160.45	122.3			196.1	171.1	161.0	125.9			192.5	151.1
24/12/2002	162.92		132.8	108.6	214.7	195.8	181.8	152.5			183.2	156.9
25/12/2002	160.45	124.0	140.7	118.5	246.3	211.5	169.0	142.6			182.1	153.0

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
26/12/2002	199.39	114.4	145.1	122.3	200.5	178.0	215.8	179.1			227.6	185.4
27/12/2002	212.55	147.0			203.5	169.5	201.3	171.1			229.0	184.0
28/12/2002	183.49	151.7	175.0	137.1	179.4	169.5	145.4	124.8			246.8	170.9
29/12/2002	187.32	144.3	131.9	115.2	231.5	181.3						
30/12/2002	223.52	141.0	215.0	134.1	185.7	159.1	174.4	142.1	153.6	112.5	195.6	187.6
31/12/2002	102.31	63.6	155.8	134.4			71.1	66.9			158.8	125.3
01/01/2003	195.00	61.5	136.3	114.4			117.1	110.5	181.3	145.4	193.4	142.4
02/01/2003	208.44	65.6	180.5	152.8			107.0	91.9			194.7	172.5
03/01/2003	198.02	65.3	172.2	143.4			181.6	161.0			192.5	172.8
04/01/2003	194.18	66.7	133.9	119.9			190.1	164.0			137.7	169.2
05/01/2003							117.7	110.8				
06/01/2003	212.28	62.6					93.3	84.8				
07/01/2003							71.6	65.8				
08/01/2003							63.1	57.9				
09/01/2003			29.6	29.1								
10/01/2003	122.33	82.3									100.4	76.8
11/01/2003	116.57	82.3									73.2	61.5
12/01/2003											82.6	56.0
13/01/2003												
14/01/2003												
15/01/2003	191.16	144.3	149.8	129.5	220.8	182.9	212.6	173.6	185.1	128.4	210.9	172.8
16/01/2003	217.76	137.7	120.4	100.4	184.9	147.6	151.4	136.9			156.3	130.3
17/01/2003	139.88	87.8	82.6	88.1	177.2	148.4	178.3	103.7			150.0	133.3
18/01/2003	170.87	109.4	139.9	119.3	191.4	172.2	167.3	147.8			165.1	131.9
19/01/2003	179.37	104.0	155.5	133.0	225.7	188.1	173.1	166.5			223.5	173.9
20/01/2003	181.84	127.0	162.1	144.3	227.4	192.8	190.1	177.2			201.0	147.6
21/01/2003	176.90	128.6	150.9	137.4	195.0	181.6	176.4	170.6				
22/01/2003	188.97	139.9	163.5	148.9	207.3	171.7	186.0	173.3				
23/01/2003	170.05	124.0	161.8	126.2	143.4	146.2	135.2	118.8				
24/01/2003	147.84	115.5	97.4	96.0	135.2	116.0	98.5	89.7				
25/01/2003	180.19	122.1	89.2	84.2	165.7	139.1	127.3	117.9				
26/01/2003	196.92	133.9			228.7	191.7	188.1	162.9				
27/01/2003	215.30	149.2					220.8	186.0				
28/01/2003	214.75	150.9			249.6	211.5	211.5	211.2				
29/01/2003	173.34	127.8	110.3	118.2	181.0	156.9	188.1	156.9	100.7		189.8	152.8
30/01/2003	114.93	87.8	52.1	44.2	159.1	153.3	116.8	105.3	71.6	53.5	172.2	156.3
31/01/2003	111.36	93.3	34.6	29.4	151.9	142.6	73.5	69.4	34.9	28.3	102.3	99.0
01/02/2003	99.02	74.1	87.8	70.2			86.1	74.9	37.9	32.9	143.4	119.6
02/02/2003	85.04	68.9	83.7	76.8	190.1	164.0	108.9	110.8	74.6	57.1	138.8	110.0
03/02/2003	93.81	79.3	54.1	43.9	186.5	171.4	120.7	108.9	66.4	62.6	127.0	106.2
04/02/2003	94.64	78.2	48.0	38.4	153.6	139.1	96.0	86.1	45.6	32.1	155.0	95.2
05/02/2003	88.88	70.0	43.1	41.4	132.8	113.0	76.5	71.3			132.5	92.7
06/02/2003	112.74	72.7	90.8	82.3	138.8	140.4	64.2	62.3	56.8	55.1	132.5	107.0

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
07/02/2003	109.99	80.1	96.8	84.8	132.2	108.6	102.9	93.3	88.9	57.9	153.6	115.5
08/02/2003	129.46	93.3	105.9	80.1	151.9	126.2	115.2	99.0	79.0	68.9	141.0	120.1
09/02/2003	133.03	101.2	110.3	87.5	162.6	134.7	123.4	102.3	102.0	67.8	147.0	127.0
10/02/2003	137.42	117.4			162.6	136.3	125.3	109.7	88.3	75.4	160.2	140.2
11/02/2003					179.6	138.5	140.7	121.2	97.9	83.9	131.4	109.2
12/02/2003			70.0	57.3	160.5	134.7	129.5	114.4	88.6	79.0	132.5	124.8
13/02/2003	94.91	68.3	61.5	57.9	85.0	74.3	111.1	94.9	40.6	29.6	78.2	70.0
14/02/2003	96.56	74.9	60.6	55.1					42.0	29.6	56.0	50.5
15/02/2003	89.15	56.2	41.2	34.3			72.4	64.5	38.4	23.9	58.2	51.6
16/02/2003	97.38	68.3	34.3	31.0			49.1	42.8	32.9	20.0	59.5	46.4
17/02/2003	100.40	77.9	31.3	25.0			37.0	33.5	39.0	26.6	50.2	41.2
18/02/2003	113.01	80.7	32.7	25.8			38.4	29.1	49.7	44.2	32.7	27.5
19/02/2003	102.31	76.8	31.8	28.5			29.4	23.1	41.2	35.4	39.5	36.0
20/02/2003	83.94	65.3	29.6	22.5	53.5	49.7	26.9	24.4	44.2	38.7	42.5	39.5
21/02/2003	80.38	68.3	25.3	21.7	56.2	49.4	21.7	19.8	40.3	36.0	48.8	42.3
22/02/2003	101.22	64.7			49.7	43.9	29.9	25.8	48.3	37.9	53.8	42.0
23/02/2003	82.57	63.1			58.2	48.0	31.3	27.2	52.1	37.9	54.1	45.6
24/02/2003	88.88	65.3			54.6	43.1	50.2	37.0	46.4	41.4	54.9	43.1
25/02/2003	119.59	74.9	25.8	22.8	40.3	33.8	40.9	38.4	50.5	43.1	47.2	40.6
26/02/2003	128.91	81.5	31.8	28.0	45.6	41.4	42.5	32.4	48.0	38.7	40.1	39.2
27/02/2003	129.46	81.2	34.9	25.5	40.6	37.0	79.0	54.3	50.8	39.8	31.0	29.9
28/02/2003	127.82	68.6	87.2	54.1	122.3	106.7	111.9	86.4	104.8	51.3	145.6	75.4
01/03/2003	108.90	67.8	93.0	70.0	160.2	131.9	93.8	75.7	86.1	58.2	118.5	84.8
02/03/2003	84.76	66.9	71.1	57.3	143.2	126.4	63.1	56.0	53.8	34.3	120.4	66.4
03/03/2003	80.65	68.3	49.7	42.5	112.5	104.5	133.9	101.5	53.2	46.4	71.9	66.1
04/03/2003	98.48	69.7	102.0	77.9	187.1	160.5	105.1	89.7	74.6	56.5	114.7	97.9
05/03/2003	91.62	67.8	67.5	58.7	145.6	131.4	73.8	63.6	63.6	41.2	104.8	85.0
06/03/2003	77.91	58.7	61.7	43.4	147.3	131.9	151.7	92.7	59.8	39.2	87.0	70.0
07/03/2003	102.04	77.6	131.9	78.2	116.6	110.3	157.7	112.5	119.3	73.0	75.4	64.7
08/03/2003	181.84	78.2	120.7	75.4	209.5	164.8	107.0	93.5	94.6	71.3	170.6	105.3
09/03/2003	117.40	86.1	104.8	77.1	160.5	123.4	109.7	97.9	74.1	60.9	159.1	97.9
10/03/2003	145.64	103.4	140.4	109.2	95.5	84.8	126.7	112.5	83.9	71.6	113.6	94.6
11/03/2003	135.22	99.0			134.1	110.5	98.2	89.7	74.1	57.1	136.6	110.3
12/03/2003	111.36	87.8			157.4	138.2	42.5	36.8	58.4	45.3	142.4	113.3
13/03/2003	68.04	51.3			128.6	123.4	33.5	30.5	53.8	39.5	105.1	85.6
14/03/2003	79.55	45.6			78.2	73.0	34.3	26.1	48.8	43.4	52.1	53.8
15/03/2003	92.72	42.5			69.1	61.2	29.6	24.2	50.2	43.6	54.3	48.8
16/03/2003	97.93	63.6			38.4	29.9	24.7	21.4	42.3	40.6	47.5	42.0
17/03/2003	105.06	85.3			64.2	55.1	22.8	20.3	40.6	39.0	39.8	37.0
18/03/2003	156.89	81.5			40.3	34.9	22.0	22.0	51.6	41.7	45.0	41.7
19/03/2003	185.95	154.1			55.7	46.6	22.8	20.3	48.0	45.0	36.0	33.5
20/03/2003	211.18	93.3			49.7	40.6	23.3	22.5	36.8	35.1	35.4	34.6

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
21/03/2003	242.17	165.1			43.9	36.0	25.8	20.0	51.9	44.5	41.7	40.9
22/03/2003	303.32	193.1			55.7	46.1	19.5	17.9	54.9	45.0	32.1	32.1
23/03/2003	287.97	203.0			50.5	44.2	22.0	18.1	53.0	49.9	51.3	36.0
24/03/2003	318.13	210.4			40.3	32.4			54.9	56.0	28.3	27.7
25/03/2003	270.96	196.6			29.6	25.8			56.5	49.9	33.5	30.2
26/03/2003	285.22	192.3	21.1	19.5			26.1	23.1	51.0	46.1	41.2	39.8
27/03/2003			23.3	22.8	31.0	29.6	26.9	25.5	46.4	39.8	46.9	36.0
28/03/2003			21.1	20.0	29.4	28.8	24.2	22.2	61.2	51.3	39.8	37.9
29/03/2003			25.5	23.9	32.7	26.4	22.8	20.3	54.9	48.8	42.5	34.0
30/03/2003			25.0	24.2	26.9	24.4	24.2	21.7	58.7	52.1	45.3	33.2
31/03/2003			27.7	26.9	28.0	23.1	33.2	29.1	64.5	41.4	54.3	38.7
01/04/2003			46.1	39.0	62.0	53.8	72.7	59.8	51.6	34.0	70.5	66.1
02/04/2003			77.4	65.8	139.6	127.5	36.5	32.1	40.6	33.2	53.5	43.4
03/04/2003			42.8	35.4	68.3	61.2	23.9	22.5	60.6	35.4	40.6	32.4
04/04/2003			28.5	26.1	53.2	48.8	22.0	20.0	72.4	46.4	38.7	30.2
05/04/2003			31.6	29.4	44.7	40.1	28.8	26.9	58.2	41.4	41.7	31.3
06/04/2003			30.7	28.8	39.2	35.4	23.3	22.0	60.6	45.6	40.1	30.2
07/04/2003			33.8	29.9	33.8	30.7			58.4	44.7	38.4	31.3
08/04/2003			29.4	27.2	32.7	29.9	20.3	18.7	61.5	55.7	30.7	25.8
09/04/2003	181.84	139.6	31.0	29.4	25.0	24.2	21.4	19.0	52.7	49.1	38.7	34.3
10/04/2003	284.13	134.9	32.1	29.9	32.4	27.5	22.2	19.8	62.6	53.2	28.0	23.6
11/04/2003	262.46	142.9	32.9	26.6	31.3	23.3	23.3	20.3	56.5	52.4	42.0	30.2
12/04/2003	411.37	79.6	26.1	20.6	27.5	22.0	25.0	22.0	59.8	59.5	40.3	26.6
13/04/2003	283.58	153.3	32.7	28.0	29.6	21.7	24.4	21.7	57.1	53.0	33.2	28.5
14/04/2003	270.69	131.9	29.4	28.8	26.6	22.5	32.4	23.3	59.8	45.3	37.0	30.5
15/04/2003	245.46	121.0	31.0	28.8		5.5	24.2	20.0	66.4	57.6	40.9	30.2
16/04/2003	256.43	126.2	37.6	31.3	22.5	20.6	29.6	21.7	63.4	54.9	59.8	39.5
17/04/2003			35.1	31.3	26.6	20.9	23.6	21.1	64.7	54.6	39.0	35.4
18/04/2003	437.14	162.4	33.8	31.0	25.3	22.0	34.9	28.8	63.4	55.1	34.0	31.6
19/04/2003	459.08	90.8	35.7	22.8	23.3	19.2	40.6	32.4	74.6	41.2	41.2	34.0
20/04/2003			33.2	31.6	19.8	15.9	45.6	35.1	54.3	36.2	37.0	29.9
21/04/2003			41.2	43.6	25.0	20.9			65.8	59.3	40.9	34.6
22/04/2003			41.7	53.5	85.9	70.2			85.9	72.4	34.0	29.9
23/04/2003	221.05	159.1	32.7	32.1	34.9	30.2	28.5	26.6	81.2	68.6	57.3	31.8
24/04/2003	234.22	153.6	40.9	34.6	31.8	24.7	31.3	28.0	58.2	48.3	46.1	28.5
25/04/2003	209.54	132.5	25.5	23.1	33.8	26.9	38.4	32.9	61.2	38.1	43.4	32.9
26/04/2003	174.16	89.7	34.3	29.1	32.1	28.3	97.1	58.4	62.0	39.8	56.8	35.4
27/04/2003	123.70	65.8	59.0	40.6	48.0	38.1	123.2	87.0	93.3	61.5	89.7	43.1
28/04/2003	157.43	52.7	111.6	64.7	110.8	90.8	159.6	131.4	111.1	76.0	154.4	81.7
29/04/2003	113.01	76.3	99.3	79.6	163.2	141.3	138.0	115.8	86.1	67.5	179.1	112.7
30/04/2003	172.52	115.8	141.0	102.3	215.6	184.3	192.5	164.6	122.1	85.6	153.9	77.6
01/05/2003	156.06	103.1	127.5	95.7	169.0	151.7	209.5	204.1	150.3	107.0	178.0	137.1
02/05/2003	159.63	113.0	154.1	128.6	243.8	196.1	156.3	152.2	106.2	90.8	211.7	165.1

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
03/05/2003	176.08	137.4	158.0	135.5	250.7	202.7	89.4	91.1	63.1	48.6	176.9	134.9
04/05/2003	172.24	121.0	142.1	125.9	184.0	154.4	44.5	41.4	45.6	38.4	127.5	95.5
05/05/2003	120.14	93.8	69.7	61.5	122.1	116.3	37.3	31.8			76.3	63.6
06/05/2003	113.56	88.1	52.7	45.0	84.2	75.4	36.5	32.7	63.4	49.4		
07/05/2003	97.10	87.2	49.9	45.8	65.6	63.6	30.7	29.6	58.2	49.9	68.3	61.2
08/05/2003	137.69	81.5	40.1	35.1	59.3	54.6	35.4	28.5	53.8	45.8	55.7	50.8
09/05/2003	165.93	128.9	42.3	41.2	50.8	49.9	32.4	29.4	65.6	57.3	51.3	42.8
10/05/2003	166.21	99.0	32.1	32.9	45.8	41.7	39.8	35.1	66.7	59.3	46.9	42.5
11/05/2003			33.8	32.7	52.7	49.9	129.2	111.4	71.1	67.5	52.7	45.6
12/05/2003			51.6	45.0	57.3	52.7	58.7	57.1	78.5	65.6	60.4	45.6
13/05/2003			62.6	54.3	53.2	51.0	112.5	90.0	124.3	99.6	57.3	49.4
14/05/2003			152.5	126.7	183.2	167.3	211.2	179.1	93.3	68.9	159.4	136.6
15/05/2003			76.0	74.9	140.7	129.2	237.8	197.2	88.6	73.5	128.9	110.5
16/05/2003			86.7	63.4	147.6	134.1			160.5	123.4	88.3	77.1
17/05/2003			174.4	139.9	327.5	269.9	233.7	193.9	154.4	125.9	229.3	175.0
18/05/2003			167.0	137.4					138.5	117.7	231.5	195.6
19/05/2003			162.1	140.7					161.5	130.6	231.2	193.6
20/05/2003	195.83	159.1	200.2	154.7	326.9	243.8					233.1	196.1
21/05/2003	202.96	180.7	170.3	149.5	314.8	252.3	251.2	209.3	175.0	146.7	247.1	190.6
22/05/2003	216.94	191.4	169.2	152.5	288.5	234.8	247.7	207.9	173.6	145.9	239.7	201.6
23/05/2003	219.41	195.6	173.6	151.1	264.7	224.1	216.9	194.2	176.6	149.2	253.4	220.0
24/05/2003	200.76	185.4	124.0	110.8	162.6	158.8	163.7	145.4	165.9	139.6	203.2	178.8
25/05/2003	197.75	179.1	142.6	122.9	125.1	115.2	113.0	105.1	136.3	114.1	206.8	192.3
26/05/2003	167.58	144.8	78.7	78.5	107.3	105.3	70.0	68.0	99.6	92.7	205.4	195.0
27/05/2003	172.79	145.6	56.8	54.6	86.4	84.2	54.1	49.7	94.4	71.1	93.8	88.1
28/05/2003	190.07	162.6	51.9	51.6	87.2	86.4	50.2	44.7	87.8	71.6	95.5	89.2
29/05/2003	234.49	162.9	48.8	47.7	77.4	69.1	46.9	44.2	97.7	79.6	90.5	83.9
30/05/2003	292.35	195.3	45.3	43.1	68.9	65.0	42.8	40.9	110.5	94.1	87.2	77.9
31/05/2003	307.71	215.0	40.3	39.0	67.2	63.9	39.5	39.5	108.6	94.9	73.2	66.9
01/06/2003	383.94	229.6	45.3	40.6			41.4	39.2	115.8	77.9	68.0	62.0
02/06/2003	393.27	191.7	42.3	39.0			43.9	42.3	122.3	112.7	59.8	55.7
03/06/2003	415.75	233.4	42.8	40.3			48.3	41.4	149.2	91.1	54.6	51.6
04/06/2003	383.94	222.7	30.7	30.5	37.0	33.5	40.3	35.7	132.5	80.1	57.3	46.9
05/06/2003	532.03	130.0	44.5	33.8	40.3	36.2	52.1	39.5	143.4	86.7	49.1	44.5
06/06/2003	323.61	167.6	45.6	31.0	72.1	68.0	118.5	100.4			87.5	50.8
07/06/2003			94.1	60.9	107.3	96.8	71.6	61.7			138.0	113.0
08/06/2003			59.5	57.9	55.1	54.3	58.4	45.3			84.2	63.6
09/06/2003			168.4	102.9	169.2	145.4	134.1	117.4			207.1	159.9
10/06/2003	410.27	222.7	88.1	59.3	86.1	80.9	64.5	56.5			114.9	107.3
11/06/2003			49.4	36.8	57.6	49.4	51.3	46.1			105.1	81.5
12/06/2003			29.1	27.2	39.8	38.4	49.7	43.4			71.9	46.4
13/06/2003			25.5	24.7	37.3	33.2	43.4	38.1			84.5	43.9
14/06/2003			36.0	30.7	32.7	30.5	40.3	35.7			111.6	79.6

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
15/06/2003			36.8	36.8	32.4	31.3	44.5	38.7			74.9	49.1
16/06/2003			28.3	27.2	31.8	26.9					65.3	41.2
17/06/2003					29.9	27.2					144.0	86.1
18/06/2003	415.21	163.7	44.2	45.8	24.4	31.8	46.1	51.0	60.9	31.3	133.0	102.0
19/06/2003	522.15	167.9	102.0	69.4	37.0	33.2	72.1	53.5	49.7	26.1	39.8	22.8
20/06/2003	476.63	151.9	73.8	54.9	43.1	42.5	72.1	53.8	79.0	33.8	40.1	14.6
21/06/2003	328.00	165.1	52.1	39.5	33.2	31.3	42.0	43.4	57.6	36.8	33.2	29.6
22/06/2003	381.75	222.7	51.6	38.4	28.5	27.5	40.1	47.5	60.6	41.7	54.9	38.4
23/06/2003	369.68	196.9	105.1	68.3	71.3	58.7	115.8	84.2	73.8	29.4	53.8	40.1
24/06/2003	537.51	157.2	64.2	52.4	66.1	63.1	79.0	68.0	63.4	30.7	36.0	29.4
25/06/2003	666.40	190.6	53.5	47.7	41.4	39.8	47.5	43.9	154.1	109.7	116.0	76.5
26/06/2003	472.24	266.6	45.8	42.3	34.6	28.8	53.2	41.2	161.5	103.4		
27/06/2003	560.82	221.1	59.8	41.4	35.4	29.9	40.1	41.7	178.5	109.7		
28/06/2003	499.94	227.9	153.0	111.9	178.5	152.2	133.6	110.3	189.8	116.0		
29/06/2003	259.99	198.0	163.2	112.5	100.4	92.4	81.5	73.2	140.7	97.9		
30/06/2003	317.03	215.3			93.8	82.8			144.8	95.7		
01/07/2003	289.06	203.8	234.5	170.9	413.0	311.5			203.5	146.5	298.9	223.0
02/07/2003	249.85	184.0	138.0	107.9	347.2	291.3	259.7	240.7	243.5	218.3	256.7	214.2
03/07/2003	329.10	256.0	218.3	188.8	257.3	210.9	293.4	256.3	182.1	149.5	241.3	211.5
04/07/2003	319.78	238.0	240.2	204.9	271.8	232.6	153.6	136.1	195.0	148.9	188.7	165.1
05/07/2003			178.3	140.0	155.2	141.8	92.2	79.8	154.4	112.2	123.7	101.8
06/07/2003			113.0	87.6	106.7	88.1	69.4	57.3	137.1	91.9	98.5	83.9
07/07/2003			70.8	56.7	85.0	77.4	56.0	45.5	120.1	92.4	81.5	69.7
08/07/2003			61.5	47.5	74.6	65.6	54.1	43.9	137.1	106.4	82.8	82.3
09/07/2003			50.8	39.1	65.3	62.8	56.8	41.7	181.3	125.6	80.4	66.9
10/07/2003			55.4	42.2	52.7	49.9	45.0	39.0	138.5	101.2	73.8	61.2
11/07/2003			51.0	38.0	43.1	42.5	47.2	42.5	137.4	104.2	75.4	58.2
12/07/2003			47.7	41.4	48.0	36.5	44.7	39.8	161.3	120.7	76.5	64.5
13/07/2003			51.0	37.2	39.8	34.0	44.2	40.6	145.6	106.7	69.1	54.9
14/07/2003			38.7	36.7	34.9	31.0			156.1	116.3	67.8	59.8
15/07/2003					37.3	35.1			146.5	119.9	76.3	61.5
16/07/2003					37.9	27.2			167.0	122.1	79.3	52.6
17/07/2003					30.7	26.6			181.6	133.3	73.5	57.3
18/07/2003											81.7	56.8
19/07/2003											75.2	55.8
20/07/2003											80.1	59.9
21/07/2003											90.5	60.5
22/07/2003	588.24	416.3	55.4	44.3	37.3	43.2	47.7	43.3			192.8	94.2
23/07/2003	562.19	382.5	46.4	44.6	37.3	31.1	52.1	44.1	311.5	162.3	93.8	57.9
24/07/2003	577.27	326.4	62.6	52.8	168.1	131.1	234.2	162.9	223.8	118.4	204.1	109.6
25/07/2003	490.89	277.0	147.0	88.6	251.8	206.6	162.4	142.8	152.5	122.5	243.0	175.0
26/07/2003	278.92	207.5	248.2	180.9	107.8	103.7	76.3	67.7	243.5	150.4	138.8	105.7
27/07/2003	275.90	203.3	102.3	79.9	66.1	60.9	61.7	46.0	127.8	88.9	99.6	71.5

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
28/07/2003	286.87	200.9	61.5	48.3	52.1	46.4	53.0	42.2	121.2	80.2	95.2	56.0
29/07/2003	273.16	139.6	66.9	57.8	252.3	214.5	257.0	210.4			201.9	163.2
30/07/2003	366.39	271.7	271.0	213.0	368.0	313.7	264.1	234.8	235.9	180.7	457.4	273.8
31/07/2003	384.49	281.7	295.1	254.7	204.6	167.0	125.9	116.0	261.6	188.9	231.7	198.8
01/08/2003	382.85	298.4	210.6	175.9			70.5	68.3	314.8	121.1	148.4	115.6
02/08/2003	440.43	191.9			102.3	92.3					90.5	76.9
03/08/2003					70.5	62.0					93.5	72.0
04/08/2003					54.1	49.0					79.6	56.5
05/08/2003	528.19	306.0			44.7	42.2	49.7	46.8	170.9	116.0	44.2	40.1
06/08/2003	596.47	259.4			44.2	41.4	50.8	45.2	158.3	112.7	82.0	65.4
07/08/2003					37.6	33.2	64.5	50.8	209.5	172.1	73.5	58.6
08/08/2003					37.9	33.7	52.1	43.9	173.1	128.2	75.2	57.9
09/08/2003					34.3	29.2	51.0	44.7	172.2	124.7	73.0	61.0
10/08/2003					32.1	29.0	53.0	44.4	171.7	119.5	77.9	62.0
11/08/2003					35.1	29.8	50.8	44.9	188.7	132.0	76.3	59.2
12/08/2003	822.70	460.0			22.0	21.1	52.4	47.3	176.9	134.1	87.5	62.8
13/08/2003		298.8					50.8	44.4	184.3	138.5	71.9	60.7
14/08/2003	800.77	309.8					47.7	41.7	176.6	136.3	79.0	58.9
15/08/2003	563.56	199.2					46.4	40.6	163.5	122.0	85.0	53.9
16/08/2003							47.2	39.0	156.1	113.0	94.6	73.5
17/08/2003									167.0	118.4	69.1	51.1
18/08/2003											83.1	49.2
19/08/2003											103.7	51.1
20/08/2003			51.6	40.4							88.9	63.3
21/08/2003		297.9	77.1	54.1			44.5	38.5	271.5	146.9	305.0	76.9
22/08/2003			140.7	78.1	43.4	33.7	54.9	42.5	265.2	176.1	154.4	81.9
23/08/2003			96.3	70.7	54.9	40.8	60.1	49.0	218.9	161.8	115.2	62.8
24/08/2003			68.3	55.4	45.3	39.3	56.8	47.3	191.2	134.7	133.0	59.2
25/08/2003			56.8	47.5	34.6	27.9	49.9	38.8	232.8	165.6	88.1	52.9
26/08/2003			59.5	49.6	28.5	25.5	55.4	42.8	217.8	162.3	108.6	52.6
27/08/2003			57.6	48.3	28.0	24.0	57.9	43.3	189.8	128.2	170.6	89.8
28/08/2003			63.9	53.6	31.3	26.6	47.7	37.4	160.2	116.8	97.4	63.3
29/08/2003			53.5	45.9	29.6	26.1	48.3	36.1	173.3	123.3	131.9	61.8
30/08/2003			55.7	44.9	27.7	24.2	52.4	35.8	165.7	121.4	99.3	59.7
31/08/2003			54.9	45.1	29.1	24.5	46.1	35.3	192.0	146.1	84.5	54.7
01/09/2003			52.7	45.9	26.9	24.0	49.7	34.5	143.2	112.5	90.5	52.9
02/09/2003			52.4	48.0			45.0	33.7	144.5	105.4	131.1	83.2
03/09/2003			56.2	46.2	25.0	21.8			149.2	103.8	89.2	57.9
04/09/2003			60.6	47.5	23.9	21.1	46.6	35.8	154.4	101.9	110.0	77.7
05/09/2003	522.15	353.0	58.7	47.5	28.0	22.9	71.1	38.5	275.6	162.0	194.5	76.4
06/09/2003	458.53	290.3	64.2	51.5	27.2	25.0	65.6	43.6	258.9	193.2	170.3	76.9
07/09/2003	388.88	215.1	72.4	54.6	28.0	20.5	46.9	38.5	190.6	131.7	162.4	83.2
08/09/2003	454.15	312.6	61.2	52.8	25.3	22.6	64.7	36.9	227.4	154.5	107.0	73.3

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
09/09/2003	445.37	290.3	64.2	54.6	25.8	22.6	75.4	39.3	165.7	127.6	200.2	78.2
10/09/2003	528.19	324.0	206.5	84.1	25.0	20.8	295.6	145.0	290.2	158.0	217.2	138.9
11/09/2003	589.61	372.5	135.8	97.8	82.3	70.4	147.0	88.1	216.1	152.0	119.3	82.4
12/09/2003	543.54	317.4	127.3	94.2	70.0	58.3	120.7	84.1	167.6	116.5	131.1	86.1
13/09/2003			92.2	72.0	48.8	44.5	84.8	55.9	162.1	120.6	100.7	77.7
14/09/2003			70.5	58.3	46.6	33.7	86.1	54.0	172.8	129.5	129.7	79.3
15/09/2003			66.9	55.1	30.2	25.3	58.7	46.8	195.0	155.3	130.6	81.4
16/09/2003			65.0	53.8	29.1	23.7			147.6	120.6	117.9	84.3
17/09/2003			66.9	53.8	30.5	21.3	108.9	50.6	200.8	153.4	104.2	67.5
18/09/2003	637.60	368.2	76.5	68.6	27.5	21.6	93.0	47.1	209.5	169.1	126.4	86.9
19/09/2003	590.98	334.5	71.9	60.9	28.8	24.7	81.5	46.8	239.2	180.7	128.6	88.7
20/09/2003	713.01	340.2	80.7	64.1	31.6	24.0	56.5	45.2	197.7	151.2	114.1	84.3
21/09/2003	759.08	362.5	100.7	75.7	32.7	25.0	87.0	49.0	237.2	175.3	152.5	100.5
22/09/2003	606.07	383.9	87.2	79.7	29.1	25.0	144.8	84.1	218.9	173.7	114.4	88.7
23/09/2003	476.08	241.8	171.1	114.5	31.6	24.5	74.9	56.5	290.2	133.3	181.8	127.7
24/09/2003	386.14	264.1	85.3	86.3			58.2	44.7	202.7	151.2	111.9	92.9
25/09/2003	482.12	328.3	82.6	69.4			55.4	43.1	192.5	156.6	107.5	84.0
26/09/2003	510.64	338.8	81.7	65.2					179.1	150.9	91.9	71.7
27/09/2003	493.09	331.6	77.1	66.5					179.6	147.1	93.0	72.8
28/09/2003			71.9	65.4					177.7	143.6	89.7	71.5
29/09/2003			75.4	64.6					180.2	143.1	88.1	68.1
30/09/2003			79.3	69.9					180.5	141.7	87.2	69.4
01/10/2003			78.2	69.1	24.2	23.6	56.8	42.5	168.4	141.5	91.9	77.1
02/10/2003	663.65	259.8	73.2	58.3	25.0	19.5	54.1	39.6	186.5	149.3	99.0	75.6
03/10/2003	494.18	265.5	66.1	58.0	30.7	22.6	51.3	38.2	179.6	149.6	88.3	71.5
04/10/2003	433.30	240.6	67.2	57.3	24.7	19.5	40.1	34.7	147.6	126.3	85.3	72.0
05/10/2003	515.57	262.2	67.8	56.6	20.3	19.2	40.6	31.8	158.3	135.2	83.1	69.4
06/10/2003	732.21	251.5	79.8	62.7	26.9	24.5	105.1	74.7	194.7	146.3	77.1	59.2
07/10/2003	246.28	177.1	134.4	87.0	102.0	81.8	96.6	80.6	219.4	104.1	117.9	85.8
08/10/2003	213.10	146.7	141.5	95.5	96.8	83.9	157.7	127.8	108.1	103.5	114.1	84.5
09/10/2003	215.57	151.2	221.3	151.4	178.3	144.8	152.2	135.3	119.3	87.0	142.6	126.4
10/10/2003	202.96	139.8	183.8	146.0	184.6	159.6	134.4	116.5	113.3	90.5	134.7	113.3
11/10/2003	182.39	132.7	120.7	93.6	154.4	137.7			101.5	77.0	133.3	111.2
12/10/2003			75.4	64.3	91.6	80.2			95.7	83.5	92.2	74.6
13/10/2003			66.7	55.7	58.2	52.5			106.2	91.9	83.7	64.9
14/10/2003			54.9	49.6	43.1	39.8			115.8	104.1	65.3	70.4
15/10/2003			52.1	47.3	36.2	33.5			127.5	108.9	63.6	55.2
16/10/2003	636.23	328.3	51.6	46.6	34.9	29.8	38.7	36.9	133.9	119.8	55.4	49.8
17/10/2003	448.11	261.7	54.3	45.2	26.4	25.0	36.2	31.3	139.6	119.8	55.1	47.9
18/10/2003	404.78	261.7	53.2	46.1	26.4	20.3	35.7	29.4	137.7	118.7	59.8	44.0
19/10/2003	401.49	259.4	51.9	44.7	23.1	18.9	35.7	29.6	134.1	117.9	57.9	48.2
20/10/2003	377.36	243.2	52.4	44.5	22.0	18.1	33.2	28.8	134.4	114.9	56.5	45.3
21/10/2003	386.69	238.0	52.1	46.3	22.8	18.9	33.2	27.0	122.3	104.6	54.1	46.4

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
22/10/2003	349.39	217.8	55.1	48.7	27.7	20.8	37.9	29.6	130.3	112.5	54.6	43.0
23/10/2003	331.29	177.6	53.2	45.6	131.7	110.0	33.2	27.2	132.2	113.0	57.3	44.5
24/10/2003	352.13	199.9	52.1	46.8					129.7	107.9	52.4	42.2
25/10/2003	342.81	194.9	57.3	47.5					135.2	115.7	54.9	47.9
26/10/2003			54.6	46.8					132.5	107.3	63.4	48.7
27/10/2003									125.6	104.1	59.8	47.1
28/10/2003									135.8	114.9	61.7	49.2
29/10/2003									252.3	116.8	141.5	109.6
30/10/2003	188.97	129.3	186.0	139.4			146.7	121.6	136.0	93.0	153.6	122.4
31/10/2003	250.40	152.4	170.6	139.2	231.2	174.1	192.0	155.7	132.5	101.4	182.4	133.2
01/11/2003	199.12	139.8	194.2	151.1	234.5	193.4	159.6	134.0	106.2	82.7	185.4	146.0
02/11/2003	227.91	173.3	206.0	165.4	251.5	206.8	204.9	172.3	150.9	129.8	172.0	142.3
03/11/2003	242.99	189.2	153.3	129.6	237.5	202.4	170.0	150.6	113.3	91.1	215.6	174.7
04/11/2003	204.87	158.1	95.2	83.1	191.7	167.3	94.6	87.3	71.9	59.6	183.2	155.4
05/11/2003	165.93	129.3	71.9	64.3	139.6	121.9	64.5	60.5	66.9	54.0	130.0	110.1
06/11/2003	153.32	118.2	60.9	55.5	105.6	92.8	52.7	47.3	69.7	58.0	97.7	85.0
07/11/2003	168.95	128.6	54.1	50.1	86.4	75.4	43.9	42.5	73.2	60.7	83.1	73.0
08/11/2003	198.84	147.9	53.5	48.9	74.3	64.6	42.5	40.6	78.7	65.9	73.5	63.9
09/11/2003	205.97	142.6	99.3	80.3	68.3	59.8	42.5	35.5	85.6	68.0	69.7	60.2
10/11/2003	195.00	144.3	94.6	78.6	71.1	62.2					73.8	63.6
11/11/2003											76.0	65.4
12/11/2003											143.4	107.5
13/11/2003			179.1	130.8	201.3	179.4	148.7	129.4			215.8	176.3
14/11/2003			209.5	138.0	258.6	197.9	202.7	160.5			156.9	114.6
15/11/2003	242.17	159.3	119.0	95.9	167.0	144.6	148.1	127.3			207.3	166.9
16/11/2003	228.73	147.2	164.6	129.8	173.9	157.5	116.6	101.0			171.4	138.1
17/11/2003	179.65	131.9	191.2	147.8	230.7	200.8	208.7	178.2			138.5	112.5
18/11/2003	194.18	141.7	144.8	124.2	201.9	167.5	159.6	137.7			227.6	186.0
19/11/2003	247.38	180.4	224.3	188.1	220.0	199.5	211.2	177.2			199.7	164.3
20/11/2003	207.89	155.7	205.7	163.5	204.1	180.5	204.3	175.3			233.4	188.8
21/11/2003	297.29	231.8	140.4	110.2	144.8	135.3	121.0	103.9			247.1	209.5
22/11/2003	264.11	220.1			126.2	115.3	86.1	77.7			202.7	178.1
23/11/2003	212.55	163.3										
24/11/2003	182.11	137.6										
25/11/2003	162.37	119.3										
26/11/2003												
27/11/2003							133.9	112.3				
28/11/2003	200.76	152.4	139.3	105.5	153.3	141.9	97.1	89.2			176.6	137.6
29/11/2003	193.63	153.8	202.4	148.3	138.2	122.4	232.0	211.0			143.2	116.7
30/11/2003	264.38	194.9	222.2	168.2	233.7	207.4	204.3	183.9			246.8	210.0
01/12/2003	272.61	204.7	219.4	170.5	254.0	221.6	238.1	202.9			240.0	205.3
02/12/2003	236.68	182.3	198.8	152.5	261.6	243.5	197.2	180.6			253.1	205.0
03/12/2003	269.59	200.2	198.3	154.2	230.4	211.3	181.0	162.4			234.2	199.3

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
04/12/2003	211.73	169.5	159.1	128.4	185.1	169.9	107.8	100.5	166.2	137.4	221.9	190.4
05/12/2003	169.23	131.5	92.4	69.3	144.3	132.4	77.4	73.4	95.2	71.0	170.9	146.2
06/12/2003	167.31	132.7	106.7	84.5	114.4	108.9			74.6	60.2	132.2	110.1
07/12/2003	153.87	116.5			100.1	89.1			69.1	61.3	107.3	81.4
08/12/2003	150.30	108.4			89.4	83.9			62.0	57.2		
09/12/2003	157.98	116.3			74.6	70.1			59.0	50.2		
10/12/2003					66.1	61.7			57.6	54.5		
11/12/2003	272.61	196.6	243.8	169.4	320.3	264.1	229.8	197.0	83.1	68.9		
12/12/2003	239.98	190.7	247.7	190.9	288.0	268.6	225.7	184.1	162.6	133.3	260.3	208.2
13/12/2003	244.64	185.4	238.1	172.6	261.1	229.5	223.0	191.4	176.1	152.8	257.5	212.6
14/12/2003	203.78	165.2	168.7	133.6	177.2	157.8	161.5	140.1	183.5	150.1	252.3	212.1
15/12/2003	160.45	130.5	102.6	83.5	121.8	111.0	89.2	81.4	141.3	118.4	216.9	183.1
16/12/2003	142.35	113.2	92.7	71.1	99.6	89.9	77.9	64.8	62.8	56.4	143.7	120.3
17/12/2003	124.53	103.9			91.3	81.8	63.1	54.6	56.8	49.4	122.9	101.5
18/12/2003	108.62	89.9	50.2	45.2			57.6	47.3	56.5	47.7	95.2	78.2
19/12/2003	112.19	85.1	64.2	55.9			52.7	46.5	53.2	43.7	85.0	73.0
20/12/2003									117.9	98.9	75.4	63.6
21/12/2003									113.0	96.2	192.5	154.9
22/12/2003	117.67	88.9	70.2	60.8	118.8	107.6	85.3	78.2	59.8	52.6		
23/12/2003	140.16	116.0			192.8	173.3	181.8	146.9	119.3	95.7	105.3	89.8
24/12/2003	142.63	118.2			142.6	133.5	144.5	124.6	92.7	80.5	156.6	138.4
25/12/2003	204.60	162.8			132.5	123.7	119.6	106.1	88.3	78.1	137.7	123.7
26/12/2003	228.46	180.7			224.6	200.5			148.1	130.6	157.2	133.4
27/12/2003	192.81	155.5			190.3	174.4			138.8	122.0	196.1	173.7
28/12/2003	156.06	124.6			141.8	128.7					192.8	170.3
29/12/2003					122.9	114.2					157.2	146.7
30/12/2003					103.7	94.2					113.3	103.3
31/12/2003					94.6	86.8					79.8	69.1
01/01/2004					189.2	168.6					77.1	65.2
02/01/2004					158.0	146.1					158.5	137.6
03/01/2004					175.5	157.2					152.8	133.4
04/01/2004					196.1	183.6					161.3	138.1
05/01/2004					186.2	171.7					177.7	157.2
06/01/2004												
07/01/2004	162.37	140.3	117.7	97.6								
08/01/2004	179.65	141.7	180.7	142.2	225.4	212.4			151.7	130.1	150.6	131.1
09/01/2004	185.95	147.4	148.1	123.5	158.8	152.5			121.2	102.7	192.3	165.3
10/01/2004	186.50	150.2	146.7	117.4	185.1	168.3			120.4	106.2	158.3	142.6
11/01/2004	190.62	151.0	150.3	127.0	180.5	163.0			141.8	122.5	178.3	157.7
12/01/2004	156.89	130.3	112.2	95.2	164.3	146.4			107.3	93.2	179.1	156.9
13/01/2004	163.74	125.3	151.9	126.1	188.7	172.8			128.1	112.7	169.2	159.3
14/01/2004	149.21	122.0	124.8	109.7	161.5	152.7			120.4	84.8	167.9	151.7
15/01/2004	130.01	106.5	120.7	100.1	198.3	183.1					156.6	143.6

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
16/01/2004	145.37	117.7	116.3	102.5								
17/01/2004	134.12	106.0	80.1	70.4								
18/01/2004			94.1	80.0								
19/01/2004			160.5	129.8								
20/01/2004	174.71	144.3	181.6	135.0	191.7	170.2	158.0	145.2	97.9	81.9		
21/01/2004	195.28	152.9	130.3	113.9	154.7	147.5			124.5	111.1	203.2	170.3
22/01/2004	182.39	147.4	127.8	111.4	168.4	161.5			151.9	134.4	164.0	148.8
23/01/2004	195.00	164.0	180.5	142.2	206.0	193.4			154.1	138.2	213.7	188.8
24/01/2004	218.59	178.5	171.1	142.9	200.2	185.2			152.2	132.5	214.2	195.1
25/01/2004	193.36	166.7	109.7	96.4	147.8	140.9			114.9	104.9	212.6	189.4
26/01/2004	164.29	140.3	76.3	70.0	122.3	116.3			87.5	72.4	172.8	154.9
27/01/2004	120.96	107.5			107.5	102.1			74.9	66.4	129.7	116.7
28/01/2004					97.9	91.5						
29/01/2004					96.6	91.3						
30/01/2004					201.3	173.6						
31/01/2004					194.5	172.8						
01/02/2004	177.18	146.2	127.0	106.0	173.9	162.2			126.2	109.2	175.5	154.1
02/02/2004	246.83	176.2	191.2	139.4	182.1	168.6	335.7	185.5	154.7	127.9	202.1	182.3
03/02/2004	258.35	205.6	193.4	155.6	208.4	199.5	326.4	180.6	185.4	153.4	230.7	196.7
04/02/2004	225.72	184.7	212.3	150.7	220.0	205.5	432.2	169.1	182.9	147.4	244.9	194.1
05/02/2004	183.49	156.0	126.4	113.7	149.2	143.8	257.8	178.5	136.0	111.7	189.8	157.5
06/02/2004	246.56	201.6	179.4	140.6	219.4	210.5	527.1	224.9	178.8	147.4	231.2	194.3
07/02/2004	136.87	115.1	191.4	158.6	213.7	204.5	490.9	210.4	163.5	140.1	241.9	200.6
08/02/2004	87.23	75.4	187.1	147.6	193.6	184.7	70.8	65.6	116.8	94.3		
09/02/2004	97.10	81.5			120.1	115.8	128.9	91.3	53.5	50.7	115.8	101.3
10/02/2004	129.46	64.9	116.6	84.5	125.9	116.6	68.0	60.5	68.3	60.7	114.9	97.9
11/02/2004	116.85	100.1			151.9	146.4	68.9	63.7	61.5	45.0	122.6	103.3
12/02/2004	96.28	75.4			141.0	90.5	83.4	75.8	56.8	47.2	107.5	84.5
13/02/2004	75.44	67.0			111.1	103.7	68.3	65.9	69.4	56.9	123.2	99.7
14/02/2004	95.46	81.3			134.1	127.1	98.5	89.7	65.3	54.0	123.4	96.8
15/02/2004	108.35	95.6			137.7	132.7	102.6	93.2	68.0	57.5	111.9	91.8
16/02/2004	102.86	91.5			160.2	130.8	96.0	86.0	74.6	60.2	96.6	75.1
17/02/2004	92.72	84.4			127.5	110.8	76.0	68.3			133.9	92.4
18/02/2004	108.07	91.5			146.5	135.3	120.1	106.4			112.5	88.4
19/02/2004					125.3	126.4	89.2	82.2			95.7	79.6
20/02/2004					110.3	107.6	72.7	68.5			79.6	67.3
21/02/2004					87.8	98.9						
22/02/2004					84.5	78.1						
23/02/2004	131.11	110.3			74.3	71.5	32.9	30.4	82.3	56.9	63.4	53.7
24/02/2004	88.60	69.7			113.0	98.4	69.4	64.5	27.7	24.7	26.4	24.1
25/02/2004	89.15	74.4			112.2	100.8	50.5	45.5	32.4	25.8		
26/02/2004	91.89	74.9			109.7	99.4			42.5	35.0		
27/02/2004	97.65	82.0							46.6	43.1		

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
28/02/2004	108.07	86.8							51.0	44.2		
29/02/2004									54.9	45.8		
01/03/2004									63.6	50.7		
02/03/2004									70.5	56.7		
03/03/2004									76.5	60.5		
04/03/2004												
05/03/2004												
06/03/2004												
07/03/2004												
08/03/2004	109.72	87.0	70.8	53.8	125.1	114.2			88.6	70.2	78.5	66.5
09/03/2004	118.77	97.2	46.4	44.2	103.4	90.7	61.2	55.9	81.2	70.8	75.7	62.6
10/03/2004	116.03	97.0	46.1	44.0	87.5	80.2	54.3	49.2	93.0	80.5	67.2	55.2
11/03/2004	130.56	106.7	48.6	42.1	83.7	77.0	41.7	39.3	83.7	70.5		
12/03/2004	131.93	101.8	77.9	58.0	80.7	75.9	40.3	38.0	81.2	73.2		
13/03/2004	99.85	84.6	98.7	77.4	141.5	129.3	88.6	84.1	99.0	76.4		
14/03/2004	104.23	85.1	110.5	82.6	160.2	145.6	106.7	92.7	85.6	68.9		
15/03/2004	97.93	82.7	102.3	78.4	155.5	139.8	96.6	88.1	83.1	66.4		
16/03/2004	97.10	80.4	65.0	58.7	133.9	126.1	87.5	78.5	81.5	64.8		
17/03/2004	115.48	87.5	57.9	49.8	112.7	100.5	58.4	55.1	79.8	67.0		
18/03/2004	113.56	89.6	206.5	80.7			55.7	47.9	85.6	69.1		
19/03/2004			385.6	102.7			119.6	108.2	113.8	83.5		
20/03/2004			272.1	101.8			167.0	143.4	136.6	101.4		
21/03/2004												
22/03/2004												
23/03/2004	93.54	84.6	96.0	83.8	164.6	157.0					130.8	115.4
24/03/2004	83.12	73.5	358.2	64.3	113.8	106.8	71.1	68.3	63.6	59.1	87.5	76.9
25/03/2004	83.94	74.2	212.8	80.5	147.0	138.8	104.2	99.6	77.4	67.8	107.5	97.9
26/03/2004	76.26	65.1	70.5	62.7	130.6	125.6	76.0	72.6	58.2	53.1	89.4	80.3
27/03/2004	82.84	74.2	76.3	67.9	119.3	114.5	122.1	81.9	66.1	57.2	90.8	84.8
28/03/2004	78.46	72.8	65.8	59.4	94.6	90.7	77.1	66.1			83.7	75.6
29/03/2004	78.46	68.7	69.7	54.5	110.0	99.7	52.1	50.0			77.4	62.0
30/03/2004	87.51	71.3	44.5	43.5	84.5	81.8	41.4	38.8			61.7	57.3
31/03/2004	98.20	81.3	42.5	42.1	79.8	74.1	38.1	36.3			59.0	53.1
01/04/2004	110.82	74.4	45.6	44.9	77.9	71.5	39.2	36.1			59.5	55.0
02/04/2004	148.11	117.4	52.1	51.0			55.4	53.2			62.0	55.8
03/04/2004			160.2	106.4			149.8	127.8			96.0	76.7
04/04/2004			169.8	116.5			167.3	151.4				
05/04/2004												
06/04/2004												
07/04/2004												
08/04/2004	142.90	108.2	68.3	58.0	116.6	111.6	106.2	102.9	91.9	77.5	126.4	114.6
09/04/2004			55.7	51.3	104.5	90.5			68.9	53.7	98.2	88.2
10/04/2004			77.4	67.6	88.1	82.0			62.6	57.5		

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
11/04/2004			55.4	53.8	94.1	86.8			75.4	59.1		
12/04/2004			51.3	47.5	88.1	79.1			62.0	52.9		
13/04/2004			45.0	40.3	80.7	72.2			62.8	55.3		
14/04/2004			43.4	49.1	73.2	68.6			64.2	51.8		
15/04/2004	154.69	114.4	121.5	43.8	67.5	62.7			67.2	72.7		
16/04/2004	191.16	130.3	111.4	90.1	78.2	79.4			72.1	56.7		
17/04/2004					221.1	191.3			169.8	135.0		
18/04/2004					212.8	184.9			140.2	116.3		
19/04/2004					191.7	166.2			153.9	135.2		
20/04/2004	142.08	107.0	92.4	80.5	177.7	158.5	114.7	105.0	154.1	117.6	140.2	116.4
21/04/2004	174.71	142.4	136.0	104.8	185.4	171.0	143.4	133.2	115.5	98.7	153.0	132.4
22/04/2004	156.61	129.8	120.1	99.0	158.3	145.6	144.0	136.1	117.9	103.3	141.8	125.8
23/04/2004	135.50	112.2	62.3	56.9	124.8	117.6	77.4	73.9	77.1	68.6	89.7	80.1
24/04/2004	145.09	115.3	50.8	47.7	101.2	94.2	53.0	51.1	71.6	62.4	88.9	81.4
25/04/2004			48.6	44.9	88.6	82.0	49.9	46.8	84.8	75.9	75.2	65.7
26/04/2004	177.73	138.4	44.2	40.7	80.9	78.3	51.9	43.1	83.1	74.5	70.2	63.9
27/04/2004	198.84	146.2	52.1	47.7	77.6	73.8	59.8	58.3	91.3	79.7	78.5	71.7
28/04/2004	225.99	171.9	96.8	74.9	89.2	83.9	196.6	177.2	102.3	86.7	78.2	67.8
29/04/2004	230.93	190.2	194.5	156.0	182.1	164.9	196.1	181.5	195.3	155.8	199.1	168.4
30/04/2004	181.29	148.8	117.7	91.7	131.9	123.4	87.2	80.6	135.5	109.5	136.9	112.5
01/05/2004			303.9	82.1	97.7	93.9	54.1	54.0				
02/05/2004					83.4	78.8	49.1	47.1				
03/05/2004							53.8	49.0				
04/05/2004							48.6	47.3				
05/05/2004												
06/05/2004												
07/05/2004	181.29	147.2	87.8	74.9	135.8	125.0	108.6	99.4	124.3	108.4	139.3	116.9
08/05/2004	239.70	189.0	218.9	164.2	143.7	89.9	205.1	186.8	198.0	162.9	256.7	209.0
09/05/2004	272.06	169.0	123.7	96.2	59.8	53.0	161.5	150.1	146.5	110.3	77.6	61.5
10/05/2004	176.36	133.4	76.0	66.0	47.5	55.1	173.6	159.7	124.8	98.4	50.5	43.7
11/05/2004	185.95	137.9	63.1	51.7	43.9	40.1			107.5	82.4	42.5	36.2
12/05/2004	200.21	150.5	53.0	48.0	36.8	35.6			117.7	97.8	37.3	31.2
13/05/2004	223.52	164.3	51.6	45.6	39.2	32.1			121.8	104.1	34.0	28.8
14/05/2004	217.22	152.6	46.6	45.9	76.3	73.0			130.8	112.5	33.8	30.1
15/05/2004	238.06	147.6	45.8	45.6	66.9	63.8			131.1	114.6	31.0	27.0
16/05/2004	283.58	172.6	45.6	44.0					132.8	110.3	29.4	25.2
17/05/2004	302.22	171.2	41.2	41.2					137.4	110.3	28.8	23.6
18/05/2004			46.4	43.8							29.1	22.6
19/05/2004											27.7	22.3
20/05/2004												
21/05/2004	308.81	183.1	47.2	41.0	42.0	40.3	43.6	45.7	147.8	123.8	33.8	24.1
22/05/2004	811.73	146.9	45.6	42.4	19.0	17.9	42.0	40.6	147.3	118.4	26.6	25.2
23/05/2004	817.22	142.4	40.3	43.3	17.3	14.2	34.9	33.7	143.2	119.5	40.1	27.0

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
24/05/2004	555.33	149.1	40.6	38.9	19.8	15.5	36.0	33.9	127.3	103.8	25.0	23.1
25/05/2004	341.71	183.1	39.0	38.9	15.1	14.2	35.7	33.7	124.8	104.9	28.0	25.7
26/05/2004	368.59	165.0	41.4	40.0	12.9	12.9	38.1	33.9	125.6	97.3	24.4	23.1
27/05/2004	330.74	148.3	50.8	42.4	14.3	11.3	38.1	33.9	134.7	86.2	27.2	23.3
28/05/2004			50.8	45.2	14.8	14.2			122.6	94.1	26.4	25.4
29/05/2004			47.5	44.5	17.0	16.0			45.6	33.4	28.5	23.1
30/05/2004			47.2	44.2	12.1	11.0			51.6	38.0	30.2	22.6
31/05/2004			45.8	41.0	18.1	15.5			81.2	32.3	30.5	22.8
01/06/2004			66.7	63.2	25.8	25.5					50.5	27.3
02/06/2004	301.68	198.7	59.5	51.3	18.7	17.4	78.5	72.8	52.7	39.1	54.9	31.2
03/06/2004	445.37	183.1	70.0	63.6	40.1	30.3	47.5	41.7	157.4	139.0	85.9	71.7
04/06/2004			57.9	52.4	31.3	27.1	45.8	39.8	147.6	129.5	83.9	75.4
05/06/2004	402.04	225.4	53.5	50.3			44.7	38.8	148.9	128.5	85.0	75.9
06/06/2004	355.42	191.4	65.3	54.3			46.6	40.1	146.7	129.5	90.5	79.6
07/06/2004	471.15	238.9	52.4	51.0			48.3	42.8	147.6	126.3	101.2	84.0
08/06/2004	473.34	261.7	56.0	48.9			50.2	44.4	153.0	129.3	99.3	82.7
09/06/2004	484.86	249.1	54.6	48.7			50.5	46.8	161.3	136.8	97.7	81.1
10/06/2004	449.76	205.2	60.1	51.5			49.7	47.1	168.4	148.2	103.4	87.7
11/06/2004	376.81	253.2	54.9	48.0	32.7	27.9	50.2	46.8	182.1	149.6	100.9	69.4
12/06/2004	399.85	187.3	97.7	52.0	27.5	25.8	44.7	36.3	162.1	143.9	83.4	67.0
13/06/2004	789.80	172.4	50.5	43.3	26.9	24.0	42.0	38.5	156.9	133.1	102.6	75.9
14/06/2004	309.35	175.2	48.8	41.0	27.5	27.1	45.6	39.6	153.9	136.8	98.5	81.6
15/06/2004	345.55	199.2	54.9	44.9	25.5	24.5	41.7	39.3	147.0	131.7	89.4	79.0
16/06/2004	385.04	177.8	46.9	46.1	26.9	24.0	42.3	39.8	151.9	123.6	102.6	82.4
17/06/2004	504.60	162.4	70.2	57.3	34.3	30.0	46.4	39.6	133.0	117.6	87.2	73.8
18/06/2004	220.23	155.0	258.6	123.8	106.4	95.2	104.5	90.3	153.6	107.6	210.1	138.4
19/06/2004	343.91	167.6	114.1	85.2	73.8	69.3	86.7	80.1	144.0	106.8	146.7	113.3
20/06/2004			230.4	169.4	263.3	230.9	213.1	177.2	154.4	124.9	202.1	167.4
21/06/2004					235.6	204.7	137.7	120.6	107.3	86.7	146.2	117.7
22/06/2004							133.9	114.1	146.7	111.1	182.1	135.0
23/06/2004	315.94	196.6	106.4	51.3	339.0	280.5	243.5	197.5	146.2	115.2	189.2	150.4
24/06/2004			147.0	108.3			205.1	176.1	169.2	135.8	209.3	173.9
25/06/2004			89.7	73.7			104.5	98.0	107.5	98.9	141.3	118.0
26/06/2004	159.63	115.8	179.9	129.6			64.7	57.5	88.1	74.3	89.7	74.8
27/06/2004	153.87	113.4	218.9	169.1			46.1	39.0	88.9	76.2	68.0	62.6
28/06/2004	187.87	137.9	233.1	186.0			39.8	38.0	77.6	67.2	52.4	46.6
29/06/2004	206.79	151.9	117.1	100.1			30.5	29.4	85.3	72.4	92.4	63.9
30/06/2004			79.8	70.2			172.2	146.6	169.5	131.2		
01/07/2004			64.2	56.9			85.0	82.5	125.9	99.5		
02/07/2004	274.80	205.4	255.1	185.5			139.9	134.2	165.7	143.6		
03/07/2004							238.1	216.3	201.3	176.1		
04/07/2004							229.8	205.1	201.6	165.6		
05/07/2004							121.2	109.6	165.9	134.4		

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
06/07/2004							59.5	55.9	136.0	105.7		
07/07/2004												
08/07/2004												
09/07/2004	219.68	172.6	189.8	111.4	256.2	205.8	180.7	147.9	157.7	136.3	196.6	155.9
10/07/2004	230.93	167.6	119.0	88.4			148.1	114.1	155.2	122.8	173.6	160.6
11/07/2004	277.00	130.8	141.8	107.1			175.8	151.1	165.1	136.8	193.1	162.7
12/07/2004	213.38	154.1	93.3	77.7			115.5	96.7	133.0	105.2	165.9	124.3
13/07/2004	216.12	165.0	70.2	64.3			69.4	58.1	132.8	103.5	97.9	77.5
14/07/2004	285.22	200.9	193.6	158.6			255.3	227.1	225.2	192.4	249.0	216.8
15/07/2004	336.78	243.4	311.0	239.3			337.9	304.8	252.0	225.2	334.0	286.9
16/07/2004	274.25	198.7	209.0	160.0			248.5	221.4	209.8	157.2	257.8	237.5
17/07/2004	298.39	215.9	230.4	184.6			309.9	267.3	144.3	114.6	320.3	274.3
18/07/2004			142.4	111.6			178.3	153.3			226.0	193.8
19/07/2004	67.21	67.5	104.2	84.5			83.9	81.4				
20/07/2004			88.1	58.0			87.2	72.3				
21/07/2004	297.56	162.8	73.8	61.1	107.3	99.7	81.2	78.5	132.8	126.3	156.1	137.3
22/07/2004	371.88	258.4	83.4	61.5	84.8	72.0	71.1	63.7	173.6	135.8	96.0	82.4
23/07/2004	374.62	259.4	71.1	47.7	64.7	62.7	68.6	51.6				
24/07/2004	374.07	243.4	235.0	161.2	56.2	50.1	49.9	47.9				
25/07/2004	343.91	213.0	222.7	186.0	203.0	171.7	217.2	182.5				
26/07/2004	372.97	265.5	135.8	120.9	248.5	233.2	260.8	230.8				
27/07/2004	181.02	139.1	104.8	91.0	147.8	140.1	132.8	121.9				
28/07/2004	181.02	139.1	79.0	73.7	133.9	87.6	88.1	83.6				
29/07/2004	185.13	122.7			67.8	64.9	70.0	63.2				
30/07/2004					54.3	52.2	63.6	61.6				
31/07/2004					70.8	44.8	61.5	55.1				
01/08/2004					75.2	39.0	56.0	51.4				
02/08/2004					45.6	41.9	59.3	56.5				
03/08/2004	428.92	221.6	88.9	80.7	50.5	45.1	62.3	56.5	197.7	165.6	110.0	91.3
04/08/2004	323.61	263.2	354.9	249.1	167.0	142.5	184.0	171.0	188.4	170.4	332.4	245.1
05/08/2004	443.72	343.5			405.3	346.5	235.3	206.7	207.1	171.5		
06/08/2004	375.72	255.1			273.4	215.0	216.4	196.7	197.7	151.5		
07/08/2004	366.12	268.9			153.9	134.8	114.1	100.5	160.5	130.6		
08/08/2004	391.62	290.3			221.1	194.4	110.3	87.8	180.2	139.6		
09/08/2004	398.75	270.8			466.2	380.8	259.2	211.5	235.9	207.3		
10/08/2004	359.81	284.6			389.4	371.8	375.2	275.9	319.2	282.3		
11/08/2004	382.85	287.4			302.2	285.8			271.5	255.0		
12/08/2004			265.5	222.9	311.0	280.5	341.7	327.9	331.3	294.8	429.5	361.1
13/08/2004			422.3	346.9	460.7	412.4	475.0	436.3	371.3	337.6	471.7	391.5
14/08/2004			264.4	211.2	287.4	275.2	219.4	135.3	244.4	237.3	376.3	342.8
15/08/2004			136.9	121.7	201.9	195.0	239.2	171.3	178.5	174.5	441.0	384.1
16/08/2004			255.1	204.0	230.4	202.9	247.1	181.5	302.8	262.0		
17/08/2004			320.3	260.8	335.7	295.8	391.6	305.4	389.4	347.9		

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18/08/2004			408.1	338.9	465.7	416.1	445.4	400.9	445.9	412.3		
19/08/2004					349.4	185.7	317.6	287.1	337.3	308.9		
20/08/2004					516.7	471.0	443.2	390.7	421.2	365.2		
21/08/2004							266.3	257.4	285.8	285.0		
22/08/2004							150.3	181.7	204.3	192.4		
23/08/2004							436.0	355.8	375.7	327.8		
24/08/2004	450.85	340.7	270.7	240.5	374.1	320.6	352.7	323.1	336.2	305.1	405.3	380.5
25/08/2004	349.39	255.6	364.7	254.7	398.2	338.5			295.1	253.1	336.8	306.2
26/08/2004	332.39	260.3	296.7	231.8	341.7	301.1			292.9	254.4	350.5	308.3
27/08/2004	418.50	320.2	296.2	235.6	295.6	274.7			300.6	259.6	383.4	344.4
28/08/2004	337.87	266.0	156.1	136.6	184.6	178.3			184.3	176.4	241.9	225.2
29/08/2004	320.87	246.1	138.2	116.0	134.7	128.5			162.4	135.0	187.3	168.7
30/08/2004			140.2	121.2	116.3	109.2					198.0	179.4
31/08/2004			95.2	87.0					181.3	152.8	147.8	133.7
01/09/2004			73.8	69.7	96.0	90.5			181.8	155.0	113.0	103.1
02/09/2004			67.5	63.9	66.4	64.3			194.2	166.1	106.2	99.9
03/09/2004			61.5	58.5	58.7	56.4			186.0	162.3		
04/09/2004					47.7	45.3						
05/09/2004					44.7	43.5						
06/09/2004					48.3	44.0						
07/09/2004												
08/09/2004												
09/09/2004												
10/09/2004	597.84	216.6	65.8	61.3	32.7	31.3	47.7	40.9	183.5	160.4	100.7	89.0
11/09/2004	381.20	209.2	148.7	111.4	117.9	104.2	176.4	165.9	290.7	205.4	373.5	297.3
12/09/2004	309.90	214.4	215.3	161.6	218.3	194.2	230.4	196.7	315.9	182.1	147.0	125.6
13/09/2004	291.26	210.9	220.2	172.4	263.6	236.1	174.7	158.1	186.5	152.6		
14/09/2004	222.70	164.5	265.8	207.5	343.9	306.3	264.9	216.3	196.1	150.1		
15/09/2004	272.61	204.7	174.4	148.5	277.8	247.2	166.2	154.4				
16/09/2004	280.84	215.1	133.9	108.3	186.8	175.2	150.0	140.1				
17/09/2004	276.17	212.3	230.7	182.0	161.8	146.9	206.0	183.6				
18/09/2004			226.3	183.6			216.9	200.0				
19/09/2004			183.2	144.8			196.6	181.5				
20/09/2004			297.3	233.2			299.5	266.7				
21/09/2004			264.1	213.8			261.9	238.0				
22/09/2004							258.9	225.4				
23/09/2004							258.6	220.6				
24/09/2004	213.65	170.7	132.8	115.8	153.3	145.1	147.8	140.1	122.9	110.0	217.2	192.8
25/09/2004	277.27	208.3	213.7	175.2	200.2	186.3	194.7	166.7	164.8	151.7	289.1	260.0
26/09/2004	349.39	273.6	267.1	219.2	283.6	261.2	266.6	252.3	221.6	197.8	215.6	198.8
27/09/2004	357.62	281.2	324.7	260.8	382.3	347.0	340.1	300.0	255.1	221.6	383.4	328.2
28/09/2004	364.20	288.8	312.1	252.4	373.5	331.1	326.9	288.7	249.3	226.8	380.7	329.2
29/09/2004	324.71	259.8	233.1	191.3	291.3	272.0	246.3	224.9	204.6	186.1	314.8	275.4

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30/09/2004	371.88	298.4	304.4	242.8	329.1	304.8	319.2	286.1	265.5	239.2	367.5	321.9
01/10/2004	362.55	289.3	290.7	229.9	331.8	306.3	295.1	269.2	265.2	235.2	351.0	305.2
02/10/2004	311.55	257.9	218.9	168.2	262.7	244.8	216.7	202.4	196.9	173.4	289.1	260.7
03/10/2004			268.2	209.6	341.7	304.2	284.7	248.0	255.9	224.6	348.8	288.5
04/10/2004			306.6	228.3	298.4	272.0	369.7	263.8	226.0	202.1	381.2	306.2
05/10/2004					193.6	195.5			173.6	155.0		
06/10/2004									167.9	150.4		
07/10/2004									199.1	165.3		
08/10/2004	298.93	235.1	148.1	128.9	161.3	136.4	172.5	140.7	193.1	163.7	225.4	207.4
09/10/2004	265.20	208.0	103.1	87.3	125.1	120.8	98.2	86.5	161.0	154.2	150.0	131.8
10/10/2004	299.48	199.5	94.6	75.8	110.8	102.9	76.0	72.3	185.4	154.2	127.5	113.3
11/10/2004	285.77	213.7	77.9	68.1	96.0	90.7	65.0	62.4			113.0	102.3
12/10/2004	292.35	217.8	122.9	96.2	119.6	109.2	98.2	90.5			127.5	109.9
13/10/2004	261.09	207.3	233.1	184.8	273.2	248.8	228.5	205.1			266.0	223.1
14/10/2004	248.20	203.7	232.8	189.7	259.2	244.1					233.7	204.3
15/10/2004	230.65	188.0	223.5	175.9	317.0	297.4					257.8	220.0
16/10/2004	244.36	196.6	228.2	187.6	387.8	348.0					294.0	250.8
17/10/2004	280.29	208.7	211.7	175.0							283.0	253.9
18/10/2004			163.5	128.0							245.5	218.9
19/10/2004											203.2	182.0
20/10/2004											193.4	147.3
21/10/2004	289.61	226.1	231.2	188.5	324.2	300.0	277.0	245.8	194.2	163.9	316.5	271.2
22/10/2004	297.29	240.3	276.4	215.4	340.1	316.9			207.3	176.4	329.6	280.1
23/10/2004	275.90	217.3	248.2	203.3	295.6	278.4			202.4	183.2	312.1	282.7
24/10/2004	281.93	222.8	251.5	202.3	309.9	285.2			210.9	184.0	309.4	270.1
25/10/2004	263.56	208.7	242.4	194.4	311.0	277.8			185.7	163.4		
26/10/2004	239.98	195.4	192.8	154.6	235.0	219.2			143.4	134.4		
27/10/2004	279.19	222.5	187.9	157.9	204.3	194.7			154.1	136.3		
28/10/2004	276.72	221.3	226.3	185.0	265.2	242.5			162.9	146.1		
29/10/2004	272.61	215.9	249.6	205.1	321.4	294.2			178.0	156.6		
30/10/2004					235.9	222.7			148.7	130.9		
31/10/2004					180.5	172.0			145.6	129.8		
01/11/2004					160.7	150.6						
02/11/2004	255.06	201.4	105.1	95.5	149.8	138.5	183.8	166.7	188.1	157.7	190.6	179.7
03/11/2004	250.67	203.0	190.3	160.0					191.2	165.6	243.0	206.9
04/11/2004	237.23	186.4	228.2	188.5					170.6	152.0	273.4	245.1
05/11/2004	225.99	187.1	174.2	150.9					150.6	135.5	243.0	212.6
06/11/2004	231.75	192.1	245.5	194.6					181.6	159.3	303.9	259.4
07/11/2004			252.0	207.0					188.4	161.8	315.9	280.1
08/11/2004									167.6	148.5	295.1	269.6
09/11/2004			244.6	208.7					191.7	166.9	303.3	270.1
10/11/2004			175.0	156.3					156.9	136.6	253.1	233.3
11/11/2004			179.9	156.0					144.5	121.7	244.4	223.4

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
12/11/2004			272.6	214.5							307.7	275.4
13/11/2004											237.5	209.2
14/11/2004												
15/11/2004												
16/11/2004												
17/11/2004												
18/11/2004	253.69	204.2	221.3	175.0	324.7	289.5	277.5	250.9	147.0	129.0	243.5	205.0
19/11/2004					183.5	156.4	189.2	163.8	142.6	123.8		
20/11/2004	190.62	143.6			167.6	152.7	134.4	120.8	134.4	116.8	225.2	176.0
21/11/2004	213.38	149.3	182.1	127.0	259.2	221.6	199.9	170.2	166.2	141.2	255.1	200.6
22/11/2004	222.70	180.0	193.1	156.5	257.0	228.2	224.3	194.9	161.8	139.8	250.1	222.8
23/11/2004	228.46	185.4	194.7	161.6	238.1	224.5	210.1	189.2	153.6	132.5	263.3	233.0
24/11/2004	220.23	169.5	151.1	126.1	196.1	185.7	166.5	155.4	138.5	120.1	247.7	216.6
25/11/2004	227.09	179.0			185.1	176.5	165.9	149.3	149.5	132.5	238.3	211.1
26/11/2004	237.23	189.9			274.3	247.0	225.4	197.8	183.2	157.4	296.2	258.1
27/11/2004	213.38	170.2			263.3	245.1	208.7	190.6	171.7	145.8	243.0	216.3
28/11/2004					293.4	268.9	244.6	221.4	176.9	156.1		
29/11/2004					218.9	207.9	167.0	160.8	138.2	122.0		
30/11/2004					166.5	158.3	138.8	125.1	127.8	114.6		
01/12/2004					145.6	136.6			125.1	114.9		
02/12/2004					128.4	117.4			131.7	118.4		
03/12/2004	202.41	155.5	76.5	66.9	122.1	109.2	80.1	73.6	135.2	113.6	132.5	122.7
04/12/2004	194.45	157.4	165.7	131.9	212.8	197.3	170.6	160.0	165.9	140.1	210.1	181.5
05/12/2004	198.02	160.7	147.8	120.0	185.1	176.2	145.1	138.0	174.2	147.1	172.8	154.3
06/12/2004	202.13	158.1	125.9	106.2	156.3	150.9	121.5	113.9	174.7	148.2	155.8	139.9
07/12/2004	212.28	161.7	106.4	91.9	141.5	130.3	107.0	101.8	194.5	155.5	145.1	126.9
08/12/2004	212.83	161.4	87.8	74.4	128.9	121.3	92.2	87.0	211.5	168.5	130.6	121.4
09/12/2004	218.04	165.0	79.3	70.9	117.4	106.6	76.5	74.2	187.1	157.4	123.7	109.1
10/12/2004	222.15	162.8	68.9	64.1	105.1	99.7	71.1	66.9			124.3	104.9
11/12/2004	231.47	167.4	88.9	69.3	125.6	111.6	153.0	138.0			201.0	173.2
12/12/2004	245.73	177.6			125.3	116.3	139.6	130.2			169.5	149.9
13/12/2004					118.5	109.7					146.7	131.1
14/12/2004	296.74	197.3	82.6	71.4	110.0	101.3	96.0	92.4	198.3	166.9	144.5	127.7
15/12/2004	249.03	176.4			201.0	181.8	207.9	188.7	225.2	151.5	231.5	196.2
16/12/2004	182.11	139.1			347.2	304.2	243.3	214.4	183.5	144.4	268.5	229.4
17/12/2004	131.93	105.3			301.7	273.1	175.3	162.4	107.8	90.8	213.4	183.3
18/12/2004	119.87	93.0			229.8	205.8	152.5	137.7	90.8	76.2		
19/12/2004	189.52	93.2			171.4	160.4	111.4	106.4	114.9	82.1	168.1	147.0
20/12/2004	120.14	86.5			147.6	133.2	83.9	81.1	81.5	73.7	135.2	118.2
21/12/2004					188.4	169.9	116.3	105.0	120.1	88.9	153.0	133.2
22/12/2004					260.5	216.1	179.4	151.9	149.8	118.4	202.4	164.3
23/12/2004	174.71	139.6	152.5	119.8	263.6	226.1	169.2	143.6	148.7	112.7	250.4	188.3
24/12/2004	149.48	120.1	145.4	121.7	253.4	213.2			121.0	103.3	210.9	172.4

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
25/12/2004	159.35	103.9	130.3	112.5	209.0				106.2		204.9	169.2
26/12/2004	187.60	84.4	152.5	110.4	166.2				97.4			
27/12/2004	129.19	90.1	127.3	90.3	202.4	176.5			110.0	84.6	183.2	132.9
28/12/2004	113.56	88.7	111.9	92.9	213.1				91.3		170.3	142.8
29/12/2004	113.83	91.1	111.9	93.6	257.3				82.8		173.9	148.3
30/12/2004	126.99	101.5	116.8	102.5	263.3	221.9			94.6	77.8	181.3	150.1
31/12/2004	139.34	110.8	130.0	108.8	296.2				90.8		173.1	151.5
01/01/2005			136.6	115.1					106.7	93.0	185.4	166.6
02/01/2005									106.2	85.1	198.0	166.9
03/01/2005					119.3	112.4			97.1	84.8	171.1	150.7
04/01/2005	157.71	120.1	206.2	130.8	164.6	157.8	111.4	105.3	85.3	68.6	161.0	147.5
05/01/2005	107.53	89.9	115.8	91.9	193.4	186.3	131.9	124.6	80.1	64.8	185.7	154.6
06/01/2005	92.72	81.5	91.3	81.2	177.5	170.7	131.1	120.0	83.9	72.7	158.5	143.9
07/01/2005	118.49	96.5	127.8	109.0	181.0	170.4	159.6	150.9	97.9	77.8	175.3	158.0
08/01/2005	109.17	103.4	111.6	97.6	216.9	200.8	142.9	134.0	93.3	80.2	158.5	144.9
09/01/2005	106.70	88.0	87.5	80.7	199.7	188.9	131.1	122.7	113.8	96.2	141.0	132.4
10/01/2005	113.56	86.5	72.1	67.2	168.1	162.0	104.5	100.2	76.0	65.6	116.6	111.2
11/01/2005	118.77	95.8	66.1	62.0	148.1	141.1	92.2	85.7	83.9	74.5	105.6	92.6
12/01/2005	120.41	91.1	78.5	68.6	133.3	128.5	145.1	105.8	93.8	86.2	100.4	91.1
13/01/2005	110.54	91.1	104.0	90.1	125.6	121.3	114.9	110.4	107.0	91.1	143.4	129.8
14/01/2005	96.56	82.5	79.8	69.7			91.9	85.7	111.1	92.2	103.4	98.4
15/01/2005	92.44	77.3	76.3	66.0			90.8	88.1	104.8	87.8	94.4	85.6
16/01/2005	183.49	135.5					83.7	79.0	95.2	84.3	116.3	98.6
17/01/2005							146.5	133.7	89.7	76.4	170.3	149.6
18/01/2005							142.4	136.4	77.1	66.7		
19/01/2005									99.0	85.1		
20/01/2005												
21/01/2005												
22/01/2005												
23/01/2005												
24/01/2005												
25/01/2005												
26/01/2005	94.36	78.7	66.9	58.5	160.7	146.9	101.5	96.7	70.2	62.1	129.7	119.3
27/01/2005	102.86	88.4	107.3	89.6	215.6	198.7	137.7	124.1	83.4	69.1	151.9	131.6
28/01/2005	126.72	93.0	104.8	93.4	206.5	195.2	143.2	135.6	75.2	64.8	141.5	132.4
29/01/2005	113.01	91.5	102.6	88.7	191.4	183.6	132.2	128.9	77.4	66.4	146.5	135.8
30/01/2005	100.40	88.0	79.8	73.2	183.5	161.5	112.5	107.7	67.2	64.0	128.6	120.3
31/01/2005	118.49	102.0	88.3	77.9	165.9	156.7	120.7	116.3	83.1	72.9	131.7	125.3
01/02/2005	124.25	104.8	96.3	86.8	190.1	176.2	132.5	125.9	80.1	77.5	144.5	133.2
02/02/2005	127.27	104.6	76.0	71.6	182.7	172.3	125.6	121.6	87.2	78.3	132.5	123.7
03/02/2005	126.72	107.5	90.2	81.9	193.4	182.6	144.5	137.5	89.4	82.1	148.7	137.3
04/02/2005	129.46	105.8	71.9	67.6	174.2	167.8	115.8	111.4	91.3	82.7	129.7	119.6
05/02/2005	148.11	116.3	60.6	57.3	151.9	146.1	99.3	95.6	90.0	82.7	123.7	112.0

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
06/02/2005	178.28	119.8	96.3	83.5	192.3	181.2	155.0	147.7	105.1	94.9	169.2	150.7
07/02/2005					163.2	157.2	113.8	108.5	96.3	88.6	131.1	124.3
08/02/2005	152.77	126.0	60.6	58.0	150.9	139.8	110.8	97.0	87.0	77.3	123.2	114.1
09/02/2005	118.49	95.6	119.9	89.6	200.5	173.1	100.1	93.5	105.1	87.3	120.1	96.8
10/02/2005	155.79	121.5	131.4	106.4	212.6	195.5	225.4	194.1	107.5	93.0	249.0	180.2
11/02/2005	162.37	124.3	163.2	113.0	220.0	193.1	162.6	144.7	125.9	94.1		
12/02/2005	161.55	113.6	181.8	115.3	211.5	183.6	214.7	179.0	123.7	106.0		
13/02/2005	181.02	124.3	129.7	98.0	181.8	164.1	286.9	258.7	110.5	98.1		
14/02/2005	169.23	123.9	84.5	68.6	141.3	133.2	145.6	134.8	85.3	74.3		
15/02/2005	136.87	103.9	123.4	92.2	133.3	126.4	149.5	140.1				
16/02/2005	132.48	108.2	129.2	95.5	129.5	120.8	102.3	99.4				
17/02/2005	126.99	98.2	141.8	110.0	151.4	136.6	129.5	121.1				
18/02/2005	128.37	109.1	134.1	104.3	189.0	170.7	63.4	60.5				
19/02/2005	120.14	99.9			149.2	140.9						
20/02/2005												
21/02/2005												
22/02/2005												
23/02/2005												
24/02/2005												
25/02/2005												
26/02/2005												
27/02/2005												
28/02/2005												
01/03/2005												
02/03/2005												
03/03/2005												
04/03/2005												
05/03/2005												
06/03/2005												
07/03/2005												
08/03/2005	108.07	90.1	86.7	70.4	144.8	136.6	102.3	86.2	88.6	79.7	118.5	112.0
09/03/2005	88.88	72.5	81.5	68.3	191.2	170.2	139.6	104.7	93.5	75.1	147.3	121.6
10/03/2005	82.30	65.4	124.3	67.6	183.8	161.2	206.0	96.2	91.9	66.1	126.4	101.8
11/03/2005	76.54	60.9	133.3	63.2	144.3	126.6	146.7	81.9	99.8	55.0	104.2	86.6
12/03/2005	103.69	69.7	83.1	62.7	148.9	124.0	127.8	98.0	75.2	64.0	113.3	99.4
13/03/2005	96.83	70.1	80.1	59.0	124.3	116.3	659.5	96.2	71.9	61.0	111.6	97.1
14/03/2005	100.12	73.9	127.5	70.7	151.4	130.0	349.9	97.0	93.5	68.0	123.2	103.1
15/03/2005	97.10	70.8	89.2	66.7	145.4	128.5			78.7	60.2	112.2	94.2
16/03/2005	103.96	81.3	104.2	73.7	133.6	120.0			83.9	64.3	123.4	99.9
17/03/2005	122.06	92.7	100.9	79.6	135.5	118.7			95.5	74.8	133.9	109.1
18/03/2005	153.05	97.2	85.9	69.5	119.0	110.5			85.3	73.2	111.4	98.1
19/03/2005			73.8	65.3	106.2	101.5			82.0	70.8	97.9	86.9
20/03/2005					97.9	92.6			87.5	70.8	96.3	81.4

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
21/03/2005					96.8	88.6					89.7	77.5
22/03/2005					144.5	131.1						
23/03/2005	161.55	122.2	82.6	72.1	136.0	120.3	100.9	90.0	117.1	99.5	125.3	109.1
24/03/2005	162.37	125.8	104.5	72.5	116.6	103.1	80.9	75.2	131.7	103.3	113.0	96.0
25/03/2005	169.23	138.8			112.2	97.3	71.3	65.6			108.3	95.0
26/03/2005	185.95	152.6			189.5	163.8	146.7	125.4			139.6	120.6
27/03/2005	190.62	146.2			244.1	220.6	195.8	175.8			192.5	160.1
28/03/2005					208.4	193.9	148.7	137.2			159.6	132.6
29/03/2005					179.9	159.3	107.5	99.4			125.9	110.7
30/03/2005	172.24	142.2	129.7	104.1	263.3	230.3	209.5	181.2			205.7	171.8
31/03/2005	150.58	122.0	117.9	93.6	237.0	216.6	182.7	162.9			192.0	166.6
01/04/2005	148.66	115.8	105.3	78.8	201.0	186.8	142.9	130.5			159.4	139.7
02/04/2005	156.61	115.8	77.1	65.8	163.2	151.7	150.0	94.6			128.1	109.9
03/04/2005	160.18	117.4	85.0	68.6	144.0	128.5	88.1	74.2			113.6	99.2
04/04/2005	171.69	135.3	131.7	101.3	157.2	142.5	111.4	94.0			120.7	105.4
05/04/2005	194.18	121.2	110.8	92.2								
06/04/2005	228.18	132.9	163.2	105.3	164.0	144.8	263.6	198.9	325.8	177.8	222.4	158.0
07/04/2005			141.8	113.2	250.1	233.5	188.4	174.2			195.0	169.5
08/04/2005			114.7	96.4	196.6	178.6	150.9	144.4			157.7	140.7
09/04/2005			130.0	106.9	207.1	197.9	165.4	150.6			153.6	141.0
10/04/2005			123.2	100.8	212.8	204.2	158.3	142.8			157.7	144.4
11/04/2005					162.1	152.2	100.4	96.4			123.2	109.6
12/04/2005					139.9	133.5	79.3	75.8			109.4	95.5
13/04/2005					125.3	118.2	71.6	67.2			99.0	90.3
14/04/2005					155.5	140.9	130.3	110.9			141.8	118.2
15/04/2005			114.7	90.3	203.5	188.1	144.0	130.5			162.1	144.7
16/04/2005			176.9	123.3	242.4	222.4	196.9	162.9			204.6	166.4
17/04/2005			146.5	121.9	205.4	197.3	174.2	161.6			183.8	161.4
18/04/2005					257.3	233.8	214.5	191.4			225.7	198.0
19/04/2005	151.95	121.7	197.2	157.0	203.0	194.2	150.9	142.6	186.8	162.0	237.5	206.1
20/04/2005	157.71	121.0	59.5	55.5	179.1	166.7	137.1	121.6	92.2	75.6	158.0	129.2
21/04/2005	114.65	96.5	91.9	77.9	153.0	145.1	82.8	76.3	85.6	71.8	121.5	101.3
22/04/2005	113.01	90.6	112.7	88.9	130.6	123.4	62.8	60.8	82.8	76.2	96.3	89.5
23/04/2005	106.70	89.9	122.6	103.6	110.0	103.4	55.7	51.1	86.1	81.0	85.0	79.0
24/04/2005	106.98	91.5	76.3	72.3	97.9	93.4	45.6	42.8	91.1	84.0	80.1	74.8
25/04/2005	136.04	104.4	179.6	126.8	163.2	148.3	99.3	90.5	116.8	98.9	131.9	98.4
26/04/2005	137.96	108.6	160.7	135.7	186.0	172.8	140.2	125.9	115.8	93.8	151.7	119.8
27/04/2005	146.74	111.3	99.6	86.3	192.3	181.8	149.2	131.6	97.4	85.1	152.2	126.6
28/04/2005	140.16	111.5	102.9	83.5	141.8	136.6	100.1	85.2	98.5	87.3	109.4	91.6
29/04/2005	119.04	100.8	130.8	108.1	287.4	254.9	223.0	189.0	150.6	122.5	224.1	188.6
30/04/2005			179.4	144.1	243.8	233.0	207.6	190.6	127.0	109.5	212.8	183.9
01/05/2005			196.4	162.6	171.7	165.7	227.6	184.7	120.1	98.9	156.1	140.2
02/05/2005					139.3	120.8						

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
03/05/2005					130.6	122.1						
04/05/2005					144.3	137.2						
05/05/2005												
06/05/2005	204.33	157.6	173.9	150.0			244.4	220.6	194.7	159.1	252.3	215.8
07/05/2005	158.81	131.2	151.7	122.8	286.9	247.8	232.8	198.4	103.1	81.6	250.1	211.1
08/05/2005	167.85	125.5	121.8	97.8	267.1	238.5	224.6	209.9	115.8	100.6	239.2	205.0
09/05/2005	139.34	104.8	74.9	66.9	209.3	199.7	161.3	145.2	88.3	70.5	165.9	147.3
10/05/2005	121.78	100.1	60.4	56.2	198.6	182.0	96.0	91.6	87.5	73.5	137.1	119.6
11/05/2005	124.25	96.5	46.6	45.4			68.6	65.6	81.5	73.2	119.0	99.2
12/05/2005	133.03	105.1	45.0	41.0			63.4	56.7	83.1	74.5	90.2	84.8
13/05/2005	134.40	101.8	40.6	39.6			49.7	44.9	110.8	100.6	84.5	78.2
14/05/2005	152.50	107.7	37.0	36.5			46.9	43.3	114.9	99.7	99.0	83.7
15/05/2005	156.34	115.1	38.1	37.5			44.2	42.2	103.4	97.8	82.6	72.2
16/05/2005	168.40	117.2	44.7	40.0			43.9	42.2	107.0	94.1	79.6	70.4
17/05/2005									102.0	93.2	75.2	70.1
18/05/2005			43.9	39.1					108.9	99.7		
19/05/2005	224.34	141.5	56.8	53.4	74.1	68.8	42.5	39.0	108.1	98.4	90.0	80.3
20/05/2005			48.6	47.5	50.2	47.4	41.2	39.8	126.4	110.8	89.7	69.6
21/05/2005			53.5	51.7	52.4	50.3	43.4	41.7	131.4	116.3	91.9	77.5
22/05/2005			55.7	53.4	53.8	52.2	45.3	42.2	138.0	127.4	88.6	76.9
23/05/2005			56.0	52.4	53.0	50.9	43.1	39.0	172.5	145.5	98.5	86.9
24/05/2005			113.3	88.9	102.0	94.9	91.3	85.2	151.7	129.0	114.7	98.4
25/05/2005			94.9	86.6	113.3	106.0	103.4	98.3	161.3	139.8	132.8	105.2
26/05/2005			119.9	60.1	77.4	73.0	59.0	56.7	126.7	118.4	107.3	97.3
27/05/2005			62.0	58.0	59.0	57.2	56.0	50.0	141.5	128.2	108.6	85.6
28/05/2005	285.22	157.4	57.3	54.3	52.7	50.6	48.8	46.5	129.5	122.2	104.2	83.7
29/05/2005	324.71	176.4	56.2	54.5	85.0	79.1	50.8	44.1	130.3	122.5	96.6	86.1
30/05/2005	310.45	197.6					42.3	38.8	138.2	126.8		
31/05/2005	381.20	175.7					72.1	48.1	148.4	139.6		
01/06/2005	344.46	177.1							126.7	116.3	279.2	139.7
02/06/2005	236.68	183.3	192.0	146.9	356.0	308.5			182.7	157.2	232.3	204.3
03/06/2005	238.88	178.5			212.0	188.1			136.3	119.2	189.2	166.9
04/06/2005	328.00	199.9			291.8	263.3			166.2	148.0	235.9	203.2
05/06/2005	232.85	184.0			304.4	283.1			155.0	138.2	243.8	210.3
06/06/2005	196.37	152.6			215.0	206.1			119.3	107.3		
07/06/2005	201.31	155.5			139.3	127.4			117.1	108.1	105.3	99.4
08/06/2005	257.53	199.5			96.0	92.0	47.7	43.9	122.6	115.2	98.5	89.0
09/06/2005	245.19	188.5			77.1	74.1	41.2	38.8	134.4	126.0	90.2	82.2
10/06/2005	280.29	205.6			67.8	65.1	39.2	37.7	142.9	135.8	91.1	83.5
11/06/2005					64.2	61.2	40.6	38.0	148.9	140.1	89.2	84.8
12/06/2005					82.0	78.8	121.2	106.4	161.3	148.0		
13/06/2005					192.3	172.0	185.7	161.3	187.3	152.3		
14/06/2005					274.8	246.4	199.1	176.1	162.4	136.3		

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
15/06/2005	187.60	151.7	124.8	102.7	227.1	216.6	135.8	125.1	159.6	139.8	190.6	161.9
16/06/2005	192.53	132.2	114.1	93.4	159.9	150.4	102.9	98.6	101.5	85.1		
17/06/2005	267.40	192.1	90.0	80.7	139.9	132.9	74.3	69.1	113.3	100.6		
18/06/2005	237.78	180.2	63.9	61.1	108.9	104.2	190.6	168.6	126.7	107.1		
19/06/2005	254.24	182.8	190.3	143.4	226.0	205.8	151.4	139.9	185.1	152.6	288.5	222.3
20/06/2005	220.23	165.9	109.4	96.9	206.2	193.1	82.3	76.6	150.3	134.4		
21/06/2005	229.01	180.2	77.4	71.4	139.1	132.4			131.9	117.1		
22/06/2005	272.06	194.9	63.1	59.9	111.6	105.8	74.9	68.5	123.7	111.1	126.2	106.2
23/06/2005	292.90	226.1	61.5	58.3	96.3	91.5	57.3	54.6	154.4	132.2	104.2	87.7
24/06/2005	756.89	260.3	64.2	60.1	72.4	69.1	57.9	55.1	162.4	143.9		
25/06/2005	415.75	276.0	66.9	62.2	74.1	68.0	54.1	51.4	160.5	148.2		
26/06/2005	331.84	257.0	61.5	59.2	83.9	41.9	52.7	47.9	168.1	146.6		
27/06/2005	341.71	257.5	55.4	54.1			56.0	50.0	159.4	133.3		
28/06/2005	357.62	255.1	64.2	60.4			73.0	69.3	169.5	138.5		
29/06/2005	366.39	270.3	74.1	69.3			85.3	79.0	163.2	148.2		
30/06/2005	377.36	273.2	59.8	58.3			63.6	59.4	164.8	158.0		
01/07/2005	402.04	311.2	59.0	56.6			60.6	56.2	185.1	160.1		
02/07/2005	364.20	264.1	60.9	58.3			60.6	57.0	186.8	171.3		
03/07/2005							60.6	55.1				
04/07/2005							159.9	136.4				
05/07/2005							238.6	204.8				
06/07/2005							257.5	230.8				
07/07/2005	326.36	255.1	214.5	161.6	300.0	268.1			205.1	182.9	267.4	223.1
08/07/2005	280.29	216.3	132.5	93.1	233.1	86.0	149.5	140.4	159.6	139.0	180.5	159.6
09/07/2005	566.30	322.6	90.8	80.5			81.5	74.7	172.5	152.6	152.5	133.9
10/07/2005	485.41	332.6	75.4	70.4			68.0	65.0	188.1	163.1	123.2	111.5
11/07/2005	530.38	339.7	70.8	66.7			71.1	58.1	205.7	177.8	123.7	118.0
12/07/2005	553.41	333.1	72.1	66.0			60.4	58.6	205.7	191.0	127.5	107.0
13/07/2005	552.87	350.2	71.9	65.0			65.8	61.0	210.1	189.1	134.4	127.1
14/07/2005	499.67	336.9	71.3	62.0			66.4	63.2	215.6	201.9	135.5	120.6
15/07/2005	658.17	299.3	69.4	64.3			65.0	61.0	227.9	195.6	139.9	120.1
16/07/2005	567.67	325.9	65.6	62.5			64.2	57.0	223.2	210.8	136.3	116.2
17/07/2005			68.6	61.5			65.6	58.6	221.3	208.6	149.8	115.4
18/07/2005			72.1	66.0			62.8	58.6	213.9	205.4	129.7	110.7
19/07/2005							59.5	57.8	214.7	194.3		
20/07/2005							68.6	59.1				
21/07/2005												
22/07/2005	637.60	435.8	75.2	61.8	57.3	51.4	56.8	51.4	213.7	190.5	139.3	113.8
23/07/2005	522.70	349.2	77.1	65.5	33.8	31.9	56.2	54.0	176.9	144.2	126.4	101.5
24/07/2005	870.42	355.9	89.7	74.2	36.2	34.2	54.1	49.0	187.9	158.5	133.9	105.2
25/07/2005	611.55	444.3	80.4	68.1	34.3	32.4	56.0	51.9	191.4	163.9	138.2	103.6
26/07/2005	630.75	461.9	69.7	61.8	29.6	28.7	52.4	47.3	190.9	164.5	135.2	109.1
27/07/2005	559.45	402.5	80.7	65.0	33.5	31.9	52.7	46.5	184.3	162.0	136.6	108.8

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
28/07/2005	862.47	276.5	308.3	133.3	212.8	182.8	176.6	147.9	231.5	128.7	228.7	176.0
29/07/2005			236.4	129.4	166.8	157.0	131.7	119.8	124.3	107.6	177.2	151.2
30/07/2005			103.4	92.4	105.1	94.4	81.2	72.3	140.2	124.7	139.9	118.0
31/07/2005					77.6	68.0	79.0	67.7	159.6	141.5	124.5	107.0
01/08/2005					62.8	52.5	67.5	62.9	169.8	137.4	128.6	108.6
02/08/2005					48.3	45.1	63.9	59.4			139.3	116.2
03/08/2005	685.59	488.1	76.0	69.7	47.7	41.4	71.6	54.9	205.7	179.4	128.1	113.8
04/08/2005	640.34	442.9	87.8	75.3	41.2	37.7			182.9	160.1	100.9	80.6
05/08/2005	778.83	401.0	75.4	70.2	59.5	55.9			203.0	175.9	118.5	112.5
06/08/2005	606.07	416.3	81.7	73.5	51.0	45.6			209.3	186.1	126.2	109.6
07/08/2005	611.55	419.6	70.0	64.1	41.2	39.3			219.7	201.6	134.4	116.2
08/08/2005	628.00	409.1	67.5	60.8	38.7	35.0			215.3	202.9	119.9	100.2
09/08/2005	658.17	417.7	68.3	61.8	37.6	33.7			271.0	166.4	131.4	110.1
10/08/2005	710.27	411.0	72.7	64.3	37.0	32.7					117.4	99.2
11/08/2005	723.98	405.3	80.1	70.9	45.0	37.7					135.5	90.8
12/08/2005	784.31	368.7	77.4	69.5	164.6	132.2						
13/08/2005			102.3	86.1	213.9	184.1						
14/08/2005			215.0	163.7	210.6	192.3						
15/08/2005			167.0	142.5	131.4	123.4						
16/08/2005	521.60	393.4	99.6	87.0	92.2	84.4			152.2	139.8	120.4	102.824
17/08/2005	526.54	333.1	68.0	62.0	52.4	45.9	57.3	54.0	185.7	79.7	99.0	85.830
18/08/2005	669.14	413.4	67.2	62.2	43.4	39.8	56.8	51.6	175.5	135.8	99.0	87.137
19/08/2005	461.28	365.4	53.0	51.7	35.7	32.4	51.9	44.9	178.8	157.2	99.6	88.183
20/08/2005	751.41	413.4	51.6	47.3	26.1	25.3	49.7	45.5	181.8	162.6	105.3	92.889
21/08/2005	688.33	458.1	47.5	45.6	28.3	24.2	53.0	47.9	167.0	149.0	114.1	95.242
22/08/2005	421.79	278.4	131.1	101.3	53.5	47.7	127.3	111.4	169.0	126.0	198.3	158.774
23/08/2005	480.47	359.7	79.0	72.5	45.3	42.7	74.3	70.7	187.6	148.8	139.6	119.034
24/08/2005	365.84	277.9	186.0	138.0	159.6	147.2	193.9	167.8	188.7	151.7	248.8	204.265
25/08/2005	346.10	274.6	270.4	210.5	121.5	112.9	185.4	160.3	182.9	137.1	272.1	187.010
26/08/2005	324.71	254.1	244.9	202.6	275.6	254.6	239.2	212.0	149.2	118.4	246.8	214.723
27/08/2005	304.42	253.2	145.6	126.8	197.5	189.2	143.2	137.7	130.0	98.7	170.0	153.806
28/08/2005	365.30	290.7	97.4	88.7	126.7	121.1	85.9	81.1	144.5	120.3	134.1	119.295
29/08/2005	350.49	277.9	185.1	151.1	161.8	149.3	202.7	181.5	201.0	132.8	221.9	198.514
30/08/2005	372.43	288.8	126.4	111.1	145.6	138.5	122.1	117.9	250.7	122.0	159.1	140.734
31/08/2005	417.40	330.2	99.8	91.5	100.4	91.5	80.7	77.7			138.8	122.956
01/09/2005	400.95	311.2			77.9	75.2	99.0	90.8			156.1	137.074
02/09/2005					59.8	56.9	81.5	76.6			138.5	122.694
03/09/2005					50.5	47.2	72.7	67.5			115.2	105.177
04/09/2005					46.4	43.2	58.4	55.4			115.8	102.824
05/09/2005					42.8	40.1	59.0	55.7			128.9	104.916
06/09/2005					39.2	35.8						
07/09/2005	652.68	468.1	72.1	65.0	38.7	34.8	54.1	51.6	184.3	156.1	120.4	106.746
08/09/2005	478.28	358.7	212.6	157.4	178.5	157.0			216.7	165.8	224.1	181.781

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
09/09/2005	385.04	310.7	248.2	199.3	264.9	242.7			194.7	172.9	271.5	107.818
10/09/2005	401.49	322.1	345.0	272.0	396.0	354.9			244.1	224.6	356.5	308.844
11/09/2005	379.01	313.6	253.4	208.7	378.5	351.2			223.8	202.9	316.5	290.543
12/09/2005	392.72	293.1	140.7	126.3	251.8	236.1			167.9	150.1	213.9	197.729
13/09/2005			115.8	103.4	167.9	160.1			167.0	149.0	169.5	150.930
14/09/2005			281.4	209.4	237.0	219.5			217.8	187.0	241.6	208.187
15/09/2005					405.9	365.5			283.6	253.1	359.8	318.256
16/09/2005	361.46	256.5			329.6	312.7			218.0	199.7	306.1	275.902
17/09/2005					197.7	182.3			163.2	148.5		
18/09/2005					165.7	157.0						
19/09/2005												
20/09/2005												
21/09/2005												
22/09/2005												
23/09/2005	617.04	431.0	84.8	76.3	75.7	69.3			237.2	197.0	144.0	134.459
24/09/2005			75.4	68.8	71.1	65.1	65.3	58.9			128.9	113.544
25/09/2005			117.1	96.4	70.2	67.2	94.1	83.3			168.7	133.152
26/09/2005			98.7	88.2	68.6	65.9	79.6	73.1			167.9	136.028
27/09/2005	466.21	309.8	112.2	98.0	66.9	63.0	84.2	79.8				
28/09/2005	392.72	273.6	203.5	161.2	194.7	177.6	193.9	169.1				
29/09/2005	347.75	257.0	219.7	183.9	298.4	264.4	246.0	218.2				
30/09/2005	335.68	265.1	296.2	235.6	415.8	364.9	323.6	289.3				
01/10/2005	308.81	243.44	263.28	214.97			315.94	284.45				
02/10/2005	311.00	245.58	183.76	155.10			211.18	204.79				
03/10/2005	294.00	230.36	135.77	119.78			137.69	131.03				
04/10/2005	321.97	248.67					103.69	99.11				
05/10/2005	334.03	261.27										
06/10/2005												
07/10/2005			89.70	79.08	106.98	99.70	73.25	70.41	163.74	144.98	121.91	121.91
08/10/2005			202.13	163.75	246.83	232.45					234.33	234.33
09/10/2005			157.16	128.20	222.43	207.64					202.70	202.70
10/10/2005	362.83	287.42	101.22	92.18	153.87	144.03					149.36	149.36
11/10/2005	394.91	275.53	138.24	115.34	178.55	165.15					157.47	157.47
12/10/2005	357.07	293.60	275.08	225.50	356.52	322.70					286.88	286.88
13/10/2005	334.03	273.15	238.60	200.47	337.87	315.31					287.41	287.41
14/10/2005	320.32	249.38	160.45	132.88	234.77	223.74					196.16	196.16
15/10/2005	341.71	263.17	124.25	105.75							162.96	162.96
16/10/2005	387.78	292.17	116.57	89.61							144.39	144.39
17/10/2005	435.50	315.94	91.89	77.45							127.92	127.92
18/10/2005	434.40	304.53										
19/10/2005	349.39	279.33										
20/10/2005												
21/10/2005	338.97	268.40	328.55	246.31	485.41	422.46	383.40	331.12	267.95	236.80	306.75	306.75

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
22/10/2005	359.81	294.55	306.61	239.30	370.78	342.23	308.26	288.20			311.98	311.98
23/10/2005	362.55	293.60	317.03	243.74	360.36	322.18					290.54	290.54
24/10/2005			257.80	201.17	334.58	303.17	281.93	255.75			263.09	263.09
25/10/2005			229.28	167.02	323.61	283.12	228.46	202.64			220.21	220.21
26/10/2005			234.77	182.23			298.39	271.31			239.82	239.82
27/10/2005			179.65	150.65			148.93	139.88			214.20	214.20
28/10/2005			139.61	117.44			108.90	101.79			166.09	166.09
29/10/2005			110.54	93.58			91.35	87.31			153.81	153.81
30/10/2005			126.45	107.85			104.51	97.50			143.87	143.87
31/10/2005			110.27	95.46			93.81	89.99			138.64	138.64
01/11/2005							217.22	194.06			273.29	273.29
02/11/2005			307.71	242.57								
03/11/2005			327.45	261.75								
04/11/2005			314.29	257.54	298.93	283.12	319.78	285.52	243.81	220.28	282.18	282.18
05/11/2005			276.72	233.68	247.65	235.88	254.51	246.63	232.57	214.59	283.22	283.22
06/11/2005			257.80	212.63	264.93	249.34	261.64	236.17	148.11	139.83	265.97	265.97
07/11/2005	318.68	279.81	208.44	179.65	213.10	204.21	193.36	181.19	135.50	122.49	237.47	237.47
08/11/2005	291.80	237.02	266.30	212.63	295.64	272.03	268.22	238.32	139.34	126.56	265.97	265.97
09/11/2005	297.84	243.68	229.83	191.35	230.10	221.36	203.23	192.99	160.18	142.81	252.63	252.63
10/11/2005	337.33	281.71	271.51	226.20	255.33	241.42	238.88	217.13	160.45	151.21	241.91	241.91
11/11/2005	322.52	259.84	278.09	224.56	310.45	284.70	278.09	254.14				
12/11/2005	280.84	238.92	208.71	182.23	213.38	205.00	189.24	179.31				
13/11/2005	267.95	220.62			167.31	159.34	133.03	126.74				
14/11/2005	278.37	230.60			222.70	205.79	137.42	131.30				
15/11/2005	296.74	240.11			259.72	243.53	212.00	190.30				
16/11/2005	263.01	219.43	177.45	153.46	186.50	177.82	152.50	146.85	131.93	122.22	181.00	181.00
17/11/2005	168.95	137.65	109.72	90.31	144.55	129.25	86.96	82.75	79.01	75.36	125.05	125.05
18/11/2005	190.62	160.71	86.68	72.53	126.45	117.38	69.68	65.05	75.17	68.32		
19/11/2005	185.13	154.05	61.18	56.86	101.22	97.32	53.78	50.83	73.80	65.34		
20/11/2005	184.58	154.29	55.70	52.89	100.12	94.15	58.71	52.17				
21/11/2005	185.68	166.18	57.07	52.89	92.99	89.40	56.24	54.05				
22/11/2005	196.65	162.37	52.41	50.55	85.59	83.07	53.78	49.49				
23/11/2005	187.32	148.82	60.91	52.42	86.96	81.75	58.71	56.19				
24/11/2005	197.20	157.86			250.94	227.17	198.57	169.92				
25/11/2005					123.16	117.91	74.07	70.68				
26/11/2005					128.64	117.11	71.05	65.31				
27/11/2005					185.68	170.43						
28/11/2005												
29/11/2005												
30/11/2005												
01/12/2005												
02/12/2005	172.79	142.17	181.02	123.99	243.27	230.60	181.29	160.53	139.61	111.12	168.97	168.97
03/12/2005	168.68	141.93	171.42	139.19	222.43	196.82	181.57	164.56			173.68	173.7

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
04/12/2005	196.37	161.18	177.45	155.10	221.88	198.66	191.44	174.75			191.72	191.7
05/12/2005	185.13	153.34	173.06	147.38	229.83	207.90	192.26	176.09			200.87	200.9
06/12/2005	203.23	169.03	172.24	146.21	210.63	194.97	171.69	159.46			196.42	196.4
07/12/2005	196.65	162.14	142.90	121.18	209.26	194.18	158.81	151.41			189.36	189.4
08/12/2005	206.79	173.55			209.54	195.76	157.98	147.12			199.82	199.8
09/12/2005	192.26	163.32			171.42	165.15	125.90	117.35			165.83	165.8
10/12/2005	206.79	175.69			189.52	178.61	152.77	143.10			195.64	195.6
11/12/2005	192.26	158.81			164.84	158.29	121.51	117.62			160.08	160.1
12/12/2005	211.73	175.69			162.92	154.33	116.85	112.52				
13/12/2005												
14/12/2005												
15/12/2005												
16/12/2005	189.79	158.81	174.16	144.10	288.51	260.42	204.60	185.21	153.05	137.66	207.40	207.4
17/12/2005			137.69	113.93	255.06	185.20	139.61	134.25				
18/12/2005	116.85	101.52	102.04	87.50	172.24	163.30	109.44	103.40				
19/12/2005	123.16	107.93	77.36	72.53	205.97	192.86	86.68	73.90				
20/12/2005	135.22	113.40	56.79	52.89	193.91	183.09	62.83	58.88				
21/12/2005	126.45	109.84	53.50	51.25	246.28	225.85	70.23	61.29				
22/12/2005	121.78	108.17	62.83	52.19	251.77	236.93	60.91	53.24				
23/12/2005	123.70	102.23	113.56	88.67	252.59	235.08	132.75	117.08				
24/12/2005	251.22	116.73	164.56	127.50	222.70	207.37	190.89	164.29				
25/12/2005			168.40	119.08	182.66	176.23	185.13	164.02				
26/12/2005					178.82	170.43	135.77	124.86				
27/12/2005												
28/12/2005												
29/12/2005												
30/12/2005												
31/12/2005												
01/01/2006												
02/01/2006	146.46	117.92	91.89	76.042	165.386	157.0	97.9	93.7	86.7	79.693	131.583	131.6
03/01/2006	152.22	130.04			184.034	171.2	107.5	93.2			152.499	152.5
04/01/2006	140.43	124.10	77.36	69.260	169.500	160.7	93.8	91.1			135.505	135.5
05/01/2006	133.30	121.72	99.02	83.059	147.562	139.0	104.2	101.3			121.125	121.1
06/01/2006	133.85	111.74	104.78	91.011	129.737	124.5	124.8	118.7			102.824	102.8
07/01/2006	133.30	108.17	130.29	112.295	122.059	112.9	135.8	131.6			101.778	101.8
08/01/2006	140.16	115.78	125.08	109.254	120.139	110.0	134.4	129.2				
09/01/2006	151.68	134.56	141.80	116.505	201.310	182.3	147.0	140.7				
10/01/2006	165.11	122.67	121.78	107.851	260.817	240.4	133.6	129.7				
11/01/2006	152.22	116.25	103.69	90.684	206.794	198.7	100.1	96.4				
12/01/2006			50.76	45.169	179.920	168.1	94.1	90.5				
13/01/2006	145.92	114.83	83.39	77.680	148.933	141.7	116.0	112.0	83.9	77.256	118.772	118.8
14/01/2006	149.21	132.66	105.88	94.753	160.999	149.8	135.8	126.2	102.3	92.154	138.642	138.6
15/01/2006	136.87	112.93	79.55	73.938	151.401	141.4	93.8	102.1	83.4	78.881	122.694	122.7

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
16/01/2006	151.68	121.96	78.73	69.260	208.714	196.0	159.1	141.5	124.5	110.845	169.493	169.5
17/01/2006	157.16	133.37			224.345	201.8	170.9	163.8	131.9	118.971	170.539	170.5
18/01/2006	148.93	126.95			225.168	210.5	195.3	183.6	135.5	125.472	176.813	176.8
19/01/2006	171.15	131.94			199.390	192.9			125.1	109.490	174.983	175.0
20/01/2006	175.26	153.10			203.230	201.8			135.5	121.951	189.624	189.6
21/01/2006	151.95	131.94			164.015	160.4			102.3	94.863	154.329	154.3
22/01/2006					145.094	134.8			120.1	84.298		
23/01/2006					140.432	135.1						
24/01/2006												
25/01/2006	142.08	121.25	67.21	58.033			72.7	60.5	80.4	76.443	107.530	107.5
26/01/2006	130.01	112.45			97.379	93.4	43.6	41.2	80.4	74.818	85.830	85.8
27/01/2006	129.46	106.51			96.282	92.3	43.1	40.1			96.550	96.5
28/01/2006	121.24	103.89			88.055	84.7	48.8	46.3			85.830	85.8
29/01/2006	141.80	117.21			82.571	79.1	42.8	39.8			71.451	71.5
30/01/2006	138.51	117.68			76.812	73.0					60.731	60.7
31/01/2006	124.25	105.08			76.538	73.0					74.850	74.8
01/02/2006												
02/02/2006												
03/02/2006												
04/02/2006												
05/02/2006												
06/02/2006												
07/02/2006												
08/02/2006	116.03	93.20	105.61	90.08	196.10	183.89	125.62	116.54	69.13	83.49	125.31	125.31
09/02/2006	95.18	78.69			137.69	126.88	72.97	66.92	72.97	72.92	92.37	92.37
10/02/2006	111.36	89.87			102.04	95.21	52.68	51.10	68.59	61.82	83.48	83.48
11/02/2006	115.75	94.62			112.46	105.77	63.10	61.02	86.68	85.92	84.78	84.78
12/02/2006	136.59	88.68			222.15	181.77	148.38	132.37	153.59	90.26	127.92	127.92
13/02/2006	121.51	94.62			167.85	156.97	148.93	142.56	107.80	92.15	134.98	134.98
14/02/2006					221.05	194.97	189.52	164.56	149.76	111.93	158.77	158.77
15/02/2006					161.27	145.35	154.14	142.83	119.87	98.93	146.75	146.75
16/02/2006					168.95	152.22	161.55	130.49	121.78	104.61	139.69	139.69
17/02/2006	176.08	145.26	156.61	128.43	249.30	218.46	184.03	165.09	136.32	122.76	190.93	190.93
18/02/2006	106.15	90.34	76.54	71.83	124.25	116.06			73.52	69.13	114.85	114.85
19/02/2006	105.06	88.92	67.49	63.18	106.98	101.02			65.57	61.27	90.27	90.27
20/02/2006	111.91	92.72	58.99	56.86	100.94	96.27			65.57	62.09	90.01	90.01
21/02/2006	126.45	103.65	67.21	63.41	153.59	145.09			80.10	69.40	112.50	112.50
22/02/2006	104.78	92.72									110.41	110.41
23/02/2006	112.19	90.82									140.21	140.21
24/02/2006	97.93	88.68									138.64	138.64
25/02/2006											120.60	120.60
26/02/2006												
27/02/2006												

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
28/02/2006	96.01	80.60	85.31	78.62	111.36	107.35	132.75	123.25	69.68	63.17	114.59	114.59
01/03/2006	64.75	58.96	42.81	39.32	119.32	111.04			44.45	40.15	78.25	78.25
02/03/2006	69.68	64.43	36.77	36.28	104.78	101.02			43.08	40.96	81.91	81.91
03/03/2006	79.01	66.57	32.39	31.84	92.17	88.08			43.36	39.87	73.80	73.80
04/03/2006	84.49	74.18	47.47	45.40	90.52	84.13			47.74	45.29	71.71	71.71
05/03/2006	86.41	73.23	19.77	24.59	96.01	91.78			52.68	50.44	75.37	75.37
06/03/2006	88.88	73.46			99.02	94.42			59.26	52.88	84.26	84.26
07/03/2006					170.05	161.98			80.93	61.82	105.18	105.18
08/03/2006					142.08	133.48			82.30	73.46	98.12	98.12
09/03/2006					162.92	155.65			106.43	91.07		
10/03/2006					166.76	159.87			102.04	94.32		
11/03/2006									97.38	87.55		
12/03/2006												
13/03/2006												
14/03/2006												
15/03/2006												
16/03/2006												
17/03/2006												
18/03/2006												
19/03/2006												
20/03/2006	88.06	75.13	79.55	71.36	172.52	160.40	123.70	120.03	81.47	73.19	107.79	107.79
21/03/2006	75.99	63.24	5.51	11.96	150.03	140.34	112.46	105.82			100.21	100.21
22/03/2006	78.73	68.23	5.51	11.96	144.55	136.91	107.25	99.65			82.95	82.95
23/03/2006	90.52	78.22	5.51	11.96	141.80	135.32					78.25	78.25
24/03/2006	104.51	80.12	141.53	87.04	189.79	172.54					114.33	114.33
25/03/2006	120.41	92.72	116.57	94.05	163.19	154.33					117.47	117.47
26/03/2006	152.50	116.49	160.18	123.76	176.36	164.09					148.32	148.32
27/03/2006	168.13	131.71			199.94	188.11					175.51	175.51
28/03/2006	178.55	145.02			178.55	167.52					171.06	171.06
29/03/2006	157.71	130.28	117.95	104.11	151.13	134.01	132.21	127.81	116.30	107.32	151.98	151.98
30/03/2006	166.48	125.05			189.52	173.59	171.97	161.07	146.46	117.07	159.56	159.56
31/03/2006	190.34	138.13			196.10	175.97	173.61	164.82	141.25	121.95	170.02	170.02
01/04/2006	168.40	137.89			175.53	161.19	165.39	154.09	135.22	121.14	152.24	152.24
02/04/2006	180.47	142.88			181.57	170.69	176.08	155.44	144.55	122.76	132.89	132.89
03/04/2006	161.82	132.42			148.93	129.78	206.25	162.41	116.85	110.84	138.64	138.64
04/04/2006	133.85	114.59			123.70	115.27			98.75	85.38	120.34	120.34
05/04/2006					111.64	102.60			86.41	71.84	98.64	98.64
06/04/2006					167.03	147.73			127.27	104.34	130.01	130.01
07/04/2006					194.73	182.04			133.85	112.20	133.94	133.94
08/04/2006					206.79	192.33						
09/04/2006					188.15	171.22						
10/04/2006												
11/04/2006	115.48	100.56	99.85	86.80	157.43	144.30	120.41	115.47	96.01	84.03	143.61	143.61

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
12/04/2006	106.15	93.20	94.36	85.63	155.51	144.30	127.27	121.64			128.18	128.18
13/04/2006	98.20	84.64	63.65	60.61	139.88	134.53	105.88	99.65			118.77	118.77
14/04/2006	90.80	75.13	41.99	41.66	111.64	104.97	70.23	65.31			94.98	94.98
15/04/2006	100.67	82.74	41.16	42.13	100.12	95.47	71.88	62.90			80.34	80.34
16/04/2006	106.43	83.69	39.52	39.79	89.15	85.97						
17/04/2006	114.38	95.33	49.94	49.15	88.06	84.39						
18/04/2006	139.06	116.73	141.80	123.76	236.14	220.83						
19/04/2006	130.56	108.17	227.91	190.41	187.60	179.93						
20/04/2006												
21/04/2006	165.11	142.17	167.85	144.57	226.54	217.40	208.71	199.16	135.50	200.51	182.83	182.83
22/04/2006	109.72	89.39	87.23	79.08	137.69	127.14	128.64	121.10	86.14	81.32	124.26	124.26
23/04/2006	115.75	87.97	62.55	56.16	112.46	107.61			78.73	75.09	93.15	93.15
24/04/2006			50.21	48.68	97.10	91.78			80.10	76.98	81.12	81.12
25/04/2006	123.70	99.38	52.95	49.61	90.52	86.50			92.44	86.19	84.00	84.00
26/04/2006	120.96	97.95	50.21	49.15	78.46	73.04			94.64	90.26	75.90	75.90
27/04/2006	141.53	110.31	38.15	38.85	68.86	65.92	250.94	212.83	95.73	92.42	71.71	71.71
28/04/2006	147.84	118.87	43.63	42.60	61.73	60.11			104.78	100.28		
29/04/2006	153.87	120.53			64.20	60.37			106.98	101.09		
30/04/2006	117.95	94.15			56.52	49.55			109.44	100.82		
01/05/2006					106.15	101.54			174.16	131.16		
02/05/2006	160.45	120.53	87.78	80.72	103.14	98.11	84.49	78.73	129.74	118.97	107.01	107.01
03/05/2006	135.22	101.28	37.32	38.62	77.63	73.57	48.84	45.73	127.82	112.47	89.23	89.23
04/05/2006	166.21	110.79	37.60	36.05	68.31	65.65	34.31	32.32	137.96	121.95	82.95	82.95
05/05/2006	200.21	124.10	32.94	35.11	48.84	45.86	37.32	34.47	128.37	120.05	72.50	72.50
06/05/2006	204.60	119.34	40.61	40.96	50.76	48.23			125.90	115.45	74.85	74.85
07/05/2006	231.20	122.91	40.61	40.96	55.97	53.78			120.96	112.47	82.17	82.17
08/05/2006	242.17	118.87	37.05	38.39	54.87	52.98			123.98	113.01	80.08	80.08
09/05/2006			37.60	37.92	46.92	45.33			137.14	128.99	63.87	63.87
10/05/2006	292.35	204.21	35.68	37.22	45.55	42.69	34.03	32.59	120.96	107.86	92.37	92.37
11/05/2006			37.32	37.22	41.16	39.00	5.51	4.96	122.06	107.86		
12/05/2006	256.70	180.44	37.87	38.85	46.65	33.45	34.03	31.52	142.63	111.66	73.54	73.54
13/05/2006	218.59	144.78	67.76	60.14	75.71	72.25	69.96	62.63	155.79	129.81	87.14	87.14
14/05/2006	218.31	144.31	69.13	63.41	72.97	70.14	60.91	56.19	147.84	130.35	96.81	96.81
15/05/2006	232.30	163.09	160.18	125.16	188.15	171.22	132.48	128.08	182.11	132.79	99.16	99.16
16/05/2006	208.17	165.94	179.65	144.57	260.82	243.27	182.66	160.00	157.98	133.87		
17/05/2006	223.80	190.42	205.42	157.20	283.03	248.81	220.78	203.98	174.16	152.56		
18/05/2006	216.67	183.06	196.65	154.39			220.23	206.40	148.11	126.56		
19/05/2006	245.46	203.02	241.62	186.90			273.71	248.78	209.26	186.96		
20/05/2006	249.85	203.50	236.41	183.40			258.62	234.56	190.62	166.92		
21/05/2006			242.44	194.16			255.88	242.34	209.81	183.17		
22/05/2006			193.63	153.23			249.85	225.44	201.31	179.65		
23/05/2006	270.69	224.66	208.44	174.98	204.05	192.33	186.23	177.16	165.11	151.21	220.21	220.21
24/05/2006			185.68	157.90	229.83	206.58	117.12	112.52	150.85	143.08	210.54	210.54

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
25/05/2006			107.53	97.33	142.63	122.66	218.59	203.98	87.78	80.51	136.03	136.03
26/05/2006			235.04	194.86	295.09	237.99	145.37	139.61	192.53	174.23	239.04	239.04
27/05/2006			90.80	123.76	180.47	156.70	92.17	87.84	119.59	109.22	183.09	183.09
28/05/2006			110.27	77.21	121.51	116.32	115.48	109.03	88.06	79.42	131.58	131.58
29/05/2006			74.62	93.82			78.73	73.63	100.40	89.99	127.14	127.14
30/05/2006			80.65	68.79			56.24	51.90	95.18	91.34	96.29	96.29
31/05/2006							63.92	59.41	97.10	86.74	84.52	84.52
01/06/2006	188.42	148.59	75.99	67.62	84.22	79.11	56.52	52.98	101.77	88.63	96.55	96.55
02/06/2006	291.26	147.16	45.55	45.87	72.42	65.12	49.39	45.73	131.38	103.26	85.83	85.83
03/06/2006	271.51	155.72	49.39	40.02	59.26	57.47	44.73	42.78	131.38	107.86	80.08	80.08
04/06/2006	322.52	163.32	45.00	43.77	56.52	52.98	50.49	43.32	130.01	109.76	81.12	81.12
05/06/2006	297.84	169.51	45.28	40.49	52.13	50.34	43.63	38.49	133.85	109.76	73.80	73.80
06/06/2006			60.08	44.70	48.84	46.39	47.20	43.32	137.14	113.82	79.29	79.29
07/06/2006			60.36	43.06			49.12	43.59	135.77	115.99	77.46	77.46
08/06/2006			50.49	46.81			46.65	43.86	140.16	118.16	79.56	79.56
09/06/2006			46.65	42.13			49.39	45.73	152.50	127.64	79.29	79.29
10/06/2006			47.47	43.06			51.58	47.34	149.48	124.93	81.12	81.12
11/06/2006			68.04	59.90			57.89	52.17	148.38	118.16	84.78	84.78
12/06/2006	379.56	233.93	54.60	52.42	37.32	36.36	58.16	47.88	163.47	141.18	82.95	82.95
13/06/2006	393.27	111.02	60.63	53.82	37.05	35.57	50.76	47.08	172.79	130.89	83.22	83.22
14/06/2006	234.49	137.89	59.26	54.06	38.42	32.93	52.95	45.73	159.35	124.39	84.26	84.26
15/06/2006	288.51	151.44	54.60	52.89	36.77	35.57	55.42	48.15	155.79	127.91	82.43	82.43
16/06/2006	305.52	153.82	48.57	47.51	41.71	33.45	52.41	47.34	151.68	122.76	78.25	78.25
17/06/2006	392.72	178.54	50.76	46.11	34.31	32.66	55.70	49.22	140.98	118.43	83.48	83.48
18/06/2006			54.33	47.74	37.87	33.98	53.23	47.61	141.25	117.35	84.00	84.00
19/06/2006	1262.56	161.66	74.62	58.97	33.48	32.13	56.79	53.24	161.55	137.66	91.58	91.58
20/06/2006	1628.93	149.30	118.77	75.34	53.50	42.43	64.20	57.27	337.87	158.52	120.08	120.08
21/06/2006	1579.65	195.18	84.22	70.66	60.91	53.78	63.65	60.49	181.02	164.21	101.26	101.26
22/06/2006	1947.03	218.00	88.60	71.13	56.52	46.65	58.71	52.44	205.42	152.83	107.01	107.01
23/06/2006	1770.15	161.66	74.89	53.82	43.90	32.13	52.41	45.47	156.34	129.54	98.64	98.64
24/06/2006	1179.20	148.35	63.65	51.25	30.74	25.54	49.12	43.05	156.34	134.68	95.24	95.24
25/06/2006	1393.09	195.89			31.56	26.59	49.12	43.86	150.03	125.20	96.55	96.55
26/06/2006	1002.60	225.37			30.47	27.38	51.58	44.66	157.16	127.37	93.67	93.67
27/06/2006	952.14	243.68			34.86	25.80	56.24	45.47	157.71	130.35	98.12	98.12
28/06/2006	1168.23	247.48			28.55	26.86	51.58	45.20	160.45	134.41	102.56	102.56
29/06/2006	891.81	195.18			30.47	29.76	51.03	45.47	168.13	135.22	105.18	105.18
30/06/2006	879.74	299.78	67.49	55.23	33.76	28.18	54.05	47.08	190.34	128.45	104.39	104.39
01/07/2006	1398.58	190.90	49.94	36.28	24.16	22.90	47.20	44.39	137.96	117.89	94.20	94.20
02/07/2006	1234.04	223.94	103.96	79.32	92.99	82.01	85.04	69.07	113.28	88.90	134.46	134.46
03/07/2006	447.02	210.16			63.92	59.05	66.67	61.29	114.93	91.88	96.29	96.29
04/07/2006	472.24	277.91			35.95	31.87	63.92	59.41	153.59	125.74	90.80	90.80
05/07/2006	622.52	287.89			30.47	25.80	68.31	57.80	166.76	132.51	100.47	100.47
06/07/2006	651.31	271.25			30.47	21.84	66.94	58.61	178.82	143.62	109.36	109.36

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
07/07/2006	699.30	217.53			24.16	22.37	68.59	54.05	173.61	144.98	106.22	106.22
08/07/2006	800.77	232.26			25.26	21.31	56.52	50.83	172.24	144.43	107.53	107.53
09/07/2006	784.31	251.52			24.43	20.26	53.23	48.68	179.92	154.46	119.56	119.56
10/07/2006	596.47	259.84	72.97	58.03	25.26	21.58	53.50	51.10	180.19	150.66	123.74	123.74
11/07/2006	622.52	217.05	62.00	53.36	32.39	26.86	59.26	54.85	172.79	148.50	113.28	113.28
12/07/2006	659.54	238.45	58.99	53.36	28.27	24.48	59.26	53.24	175.26	147.68	118.77	118.77
13/07/2006	525.99	241.06	65.29	54.29	27.45	24.48	60.63	54.85	171.42	148.50	110.67	110.67
14/07/2006	789.80	248.91	55.70	51.48	24.71	23.16	58.71	54.85	167.85	146.06	109.36	109.36
15/07/2006	512.28	188.05	59.81	49.85	30.74	24.48	58.16	54.59	172.24	145.25	115.64	115.64
16/07/2006	702.04	294.55	57.89	49.85	28.00	25.01	61.46	55.66	178.82	150.12	105.18	105.18
17/07/2006	549.03	249.38	61.18	51.72	28.82	25.54	63.37	59.41	169.77	142.81	106.22	106.22
18/07/2006	626.63	283.14	60.91	51.48	30.19	26.59	62.00	59.68	164.84	139.56	109.36	109.36
19/07/2006	784.31	257.94	60.91	53.36	39.79	26.59	64.20	59.68	158.81	135.22	110.93	110.93
20/07/2006	658.17	318.80	63.10	54.76	34.58	26.33	92.17	65.85	164.84	135.22	110.14	110.14
21/07/2006	800.77	336.39	74.07	69.26	35.13	29.76	72.15	65.85	177.45	160.42	118.25	118.25
22/07/2006	800.77	387.26	99.57	83.76	35.68	28.70	76.26	66.92	210.63	166.10	128.71	128.71
23/07/2006	751.41	431.00	110.82	89.14	40.34	30.29	74.89	63.97	212.28	176.67	129.49	129.49
24/07/2006	795.28	487.11	81.47	69.49	37.60	26.59	74.62	63.44	202.68	167.73	129.49	129.49
25/07/2006	822.70	507.79	79.01	64.58	36.77	25.54	76.26	65.31	190.62	161.23	138.90	138.90
26/07/2006	1299.86	421.02	80.10	71.83	38.42	31.08	75.17	68.53	206.52	169.08	139.43	139.43
27/07/2006	1228.56	345.90	81.47	69.26	34.86	26.59	80.10	69.07	204.33	166.92	139.43	139.43
28/07/2006	1258.72	478.55	77.63	65.28	34.58	27.12	80.65	70.95	200.49	166.92	140.73	140.73
29/07/2006	1469.87	381.56	84.49	66.69	35.40	28.97	83.94	68.26	207.34	165.56	142.56	142.56
30/07/2006			87.23	69.26	32.39	24.74	88.33	73.36	243.81	193.19	148.05	148.05
31/07/2006	460.73	495.90	87.51	69.03	43.36	29.50	91.35	65.85	208.44	158.79	148.58	148.58
01/08/2006	302.77	169.74	140.43	98.50	31.56	17.88	29.10	22.67	186.50	143.62	35.89	35.89
02/08/2006	269.04	188.29	137.69	93.82	59.81	31.87	32.39	25.35	121.51	92.42	37.99	37.99
03/08/2006	432.76	295.50	96.83	70.20	29.10	22.37	34.86	22.94	103.41	80.24	26.74	26.74
04/08/2006	570.42	365.39	86.41	63.88	18.40	17.09	23.06	17.03	145.37	120.05	26.74	26.74
05/08/2006	604.69	380.61	81.75	61.78	21.69	14.72	23.34	14.89	168.13	140.91	33.54	33.54
06/08/2006	680.11	394.87	72.15	59.44	15.39	12.08	18.68	14.62	181.29	149.04	36.68	36.68
07/08/2006	630.75	334.49	85.04	60.84	14.01	10.49	20.87	16.77	188.15	148.50	41.12	41.12
08/08/2006			79.28	61.78	13.19	10.76	20.60	15.96	190.89	155.81	41.91	41.91
09/08/2006			96.28	65.28	12.92	11.02	20.60	16.23	202.41	164.21	44.78	44.78
10/08/2006					12.64	9.17	18.68	15.43	195.55	161.77	45.31	45.31
11/08/2006					12.92	9.17	20.60	14.89	196.10	155.81	48.44	48.44
12/08/2006					12.37	11.81	19.77	15.69			45.31	45.31
13/08/2006					16.21	14.98	22.79	15.96	259.72	162.58	40.86	40.86
14/08/2006	377.36	252.23	179.65	99.20	16.21	12.34	30.19	16.77	195.00	140.91	35.63	35.63
15/08/2006	669.14	239.87	71.05	64.11	37.05	31.61	55.15	45.73	160.72	132.79	93.15	93.15
16/08/2006	477.18	231.31	65.02	56.40	40.61	34.77	57.07	49.49	163.19	136.04	102.56	102.56
17/08/2006	377.36	205.40	136.04	103.41	123.70	101.02	106.70	83.02	134.40	104.89	119.56	119.56
18/08/2006	263.83	193.52	195.00	150.42	181.84	154.85	150.30	122.98	93.81	78.88	135.24	135.24

Date	DGC AC (°H)	DGC TC (°H)	UNG AC (°H)	UNG TC (°H)	NGC AC (°H)	NGC TC (°H)	UGC AC (°H)	UGC TC (°H)	RC AC (°H)	RC TC (°H)	WC AC (°H)	WC TC (°H)
19/08/2006	272.61	201.36	203.78	159.07	228.73	193.39	172.24	146.05	105.33	79.15	144.66	144.66
20/08/2006	286.87	209.21	239.15	181.99	217.22	186.26	192.26	164.82	108.90	87.28	166.36	166.36
21/08/2006	303.32	209.44	247.11	189.01	250.67	216.08	217.49	184.94	132.75	88.09	187.79	187.79
22/08/2006	284.67	213.48	137.96	114.17	158.26	139.28	136.59	122.18			133.15	133.15
23/08/2006	318.68	236.07	204.05	155.80	212.55	183.36	183.76	158.39			193.02	193.02
24/08/2006	286.87	213.48	144.00	109.72	175.81	157.23	135.50	122.18			166.88	166.88
25/08/2006					97.93	87.82	84.22	75.51			114.07	114.07
26/08/2006					92.17	82.01	134.95	115.20	170.60	134.95	133.94	133.94
27/08/2006					203.23	170.43	187.32	159.19			198.51	198.51
28/08/2006					275.08	243.00					228.32	228.32
29/08/2006	349.94	233.45	398.20	203.51	376.81	249.34	179.92	100.99	198.29	154.73	223.87	223.87
30/08/2006	257.25	201.84	156.61	131.94	137.14	120.81	140.71	131.03	90.25	80.78	153.54	153.54
31/08/2006	306.61	241.30	301.13	235.79	301.68	264.64	261.09	236.17	197.47	175.86	253.94	253.94
01/09/2006	302.77	247.72	292.35	228.30	190.89	170.69	189.52	176.89	155.24	137.39	221.26	221.26
02/09/2006	381.75	296.45			265.20	237.72	264.66	241.27	229.56	194.55	286.36	286.36
03/09/2006	368.59	294.55			267.12	219.25	232.02	216.32	204.33	181.00	263.35	263.35
04/09/2006	321.97	254.61			246.01	211.86	194.18	185.48	163.74	141.72	286.88	286.88
05/09/2006	343.36	283.61			270.96	250.13	221.33	206.13	202.13	175.31	275.90	275.90
06/09/2006	354.88	246.77			199.94	186.52	218.86	208.54	189.52	170.71	277.47	277.47
07/09/2006	331.84	274.10	188.97	165.62	200.76	167.52	175.26	165.63	170.05	149.31	244.79	244.79
08/09/2006	289.06	220.62							97.93	81.05		
09/09/2006	264.11	193.75										
10/09/2006	269.04	197.32										
11/09/2006	302.22	209.44										
12/09/2006	306.61	212.53			46.10	42.69					89.49	89.49
13/09/2006	336.23	219.67	72.15	61.78	49.94	44.01					81.39	81.39
14/09/2006	328.00	199.70	66.94	62.94	349.94	256.73					252.63	252.63
15/09/2006	317.58	231.55	359.26	264.56	196.92	160.66					178.91	178.91
16/09/2006					120.41	96.00					125.31	125.31
17/09/2006					101.77	71.19					99.69	99.69
18/09/2006					113.83	53.51					108.58	108.58
19/09/2006					74.89	58.26					111.97	111.97
20/09/2006					61.73	47.18					92.37	92.37
21/09/2006					47.20	37.94					89.49	89.49
22/09/2006	420.14	302.16	77.91	71.13	53.78	34.51	55.15	52.71	203.50	168.00	62.56	62.56
23/09/2006	348.84	247.95	126.17	105.04	68.04	62.75	94.36	90.26			118.77	118.77
24/09/2006	366.39	262.22	106.15	91.71	66.12	60.11	73.52	70.95			127.40	127.40
25/09/2006	379.01	267.92	86.68	78.15			66.67	62.63			129.49	129.49
26/09/2006	363.65	250.57	75.17	68.56	45.82	41.37	105.88	77.65			126.09	126.09
27/09/2006	393.27	236.78	72.15	65.05	44.73	39.26					122.96	122.96
28/09/2006	387.78	235.83	98.75	85.87	46.37	39.26					125.57	125.57
29/09/2006	379.56	255.09	141.80	118.38	48.02	44.80					135.50	135.50
30/09/2006	430.56	285.04	184.03	144.34	93.27	83.33					157.73	157.73

APPENDIX II: Cross-Laboratory Comparison aum^{-1} to °H

Sample Site	Date of Sample	STL ^{0} H	aum^{-1} (STL)	NTU (aum^{-1})	Sample Site	Date of Sample	STL ^{0} H	aum^{-1} (STL)	NTU (aum^{-1})
Jaggers Clough	20/08/03	7	0.24	0.95	**Jaggers Clough**	21/01/04	41	1.39	2.94
River Westend	20/08/03	20	0.68	1.21	**River Westend**	21/01/04	69	2.35	4.80
Linch Clough	20/08/03	22	0.75	1.56	**Linch Clough**	21/01/04	29	0.99	2.71
Derwent Res	20/08/03	60	2.04	4.79	**Derwent Res**	21/01/04	72	2.45	6.08
River Ashop Div	20/08/03	21	0.71	1.29	**River Ashop Div**	21/01/04	66	2.24	5.06
River Noe Div	20/08/03	20	0.68	0.59	**River Noe Div**	21/01/04	31	1.05	2.08
Howden Res	20/08/03	49	1.67	4.06	**Howden Res**	21/01/04	82	2.79	6.69
Mill Brook	20/08/03	9	0.31	0.58	**Mill Brook**	21/01/04	19	0.65	1.19
Upper Derwent	20/08/03	28	0.95	1.68	**Upper Derwent**	21/01/04	75	2.55	5.91
Ladybower Res	20/08/03	33	1.12	2.54	**Ladybower Res**	21/01/04	59	2.01	4.23
Jaggers Clough	17/09/03	13	0.44	0.95	**Jaggers Clough**	24/03/04	13	0.44	1.18
River Westend	17/09/03	18	0.61	1.20	**River Westend**	24/03/04	28	0.95	2.43
Linch Clough	17/09/03	20	0.68	1.58	**Linch Clough**	24/03/04	18	0.61	1.36
Derwent Res	17/09/03	89	3.03	5.23	**Derwent Res**	24/03/04	55	1.87	4.76
River Ashop Div	17/09/03	20	0.68	1.61	**River Ashop Div**	24/03/04	23	0.78	2.00
River Noe Div	17/09/03	18	0.61	1.04	**River Noe Div**	24/03/04	11	0.37	1.04
Howden Res	17/09/03	79	2.69	5.25	**Howden Res**	24/03/04	67	2.28	5.88
Mill Brook	17/09/03	6	0.20	0.86	**Mill Brook**	24/03/04			
Upper Derwent	17/09/03	24	0.82	1.80	**Upper Derwent**	24/03/04	36	1.22	2.91
Ladybower Res	17/09/03	50	1.70	2.83	**Ladybower Res**	24/03/04	55	1.87	4.36
Jaggers Clough	19/11/03	32	1.09	2.49	**Doctors Gate**	25/11/04	178	6.05	16.95
River Westend	19/11/03	38	1.29	3.41	**Upper North**	25/11/04	123	4.18	10.30
Linch Clough	19/11/03	26	0.88	1.98	**Nether Gate**	25/11/04	181	6.15	15.68
Derwent Res	19/11/03	85	2.89	5.70	**Upper Gate**	25/11/04	156	5.30	12.63
River Ashop Div	19/11/03	44	1.50	3.14	**Red Clough**	25/11/04	143	4.86	12.56
River Noe Div	19/11/03	26	0.88	1.56	**Within Clough**	25/11/04	227	7.72	20.23
Howden Res	19/11/03	72	2.45	6.23	**Doctors Gate**	26/01/05	26.1	0.89	5.59
Mill Brook	19/11/03	11	0.37	1.04	**Upper North**	26/01/05	62	2.11	5.56
Upper Derwent	19/11/03	65	2.21	4.60	**Nether Gate**	26/01/05	148	5.03	13.58
Ladybower Res	19/11/03	43	1.46	3.46	**Upper Gate**	26/01/05	97.1	3.30	8.29
					Red Clough	26/01/05	61.7	2.10	5.86
					Within Clough	26/01/05	117	3.98	10.86
					Jaggers Clough	21/01/05	41	1.39	2.94

APPENDIX III: True Colour (°H) and DOC (mgl^{-1}) Cross-Laboratory Analysis

Sample ref.	Date of sample	True Colour aum^{-1}	True Colour (°H)	DOC (mg l^{-1})	Sample ref.	Date of sample	True Colour aum^{-1}	True Colour (°H)	DOC (mg l^{-1})
DGC1	09/03/2004	8.35	97.10	9.16	UNG1	09/03/2004	3.525	44.18	4.14
DGC2	12/03/2004	8.775	101.77	6.99	UNG2	12/03/2004	4.8	58.16	5.68
DGC3	15/03/2004	7.05	82.84	8.1	UNG3	14/03/2004	7.025	82.57	9.46
DGC4	16/03/2004	6.825	80.38	7.1	UNG4	16/03/2004	4.05	49.94	5.17
DGC5	18/03/2004	7.675	89.70	7.16	UNG5	18/03/2004	6.85	80.65	8.23
DGC1	21/04/2004	12.480	142.40	11.17	UNG1	22/04/2004	8.519	98.96	8.80
DGC2	24/04/2004	10.009	115.30	7.55	UNG2	25/04/2004	3.594	44.94	3.81
DGC3	27/04/2004	12.827	146.21	8.87	UNG3	27/04/2004	3.850	47.74	3.49
DGC4	29/04/2004	16.836	190.19	15.53	UNG4	29/04/2004	13.722	156.03	14.65
DGC5	30/04/2004	13.065	148.82	10.75	UNG5	01/05/2004	6.984	82.12	7.01
DGC1	25/09/2004	18.483	208.25	16.47	UNG1	25/09/2004	15.471	175.21	14.95
DGC2	27/09/2004	25.137	281.24	24.08	UNG2	27/09/2004	23.275	260.81	23.28
DGC3	29/09/2004	23.186	259.84	20.09	UNG3	29/09/2004	16.942	191.35	16.09
DGC4	01/10/2004	25.873	289.32	23.23	UNG4	01/10/2004	20.460	229.94	20.18
DGC5	08/10/2004	20.932	235.12	16.66	UNG1	24/12/2004	10.588	121.65	11.49
DGC1	24/12/2004	10.443	120.06	11.12	UNG2	27/12/2004	7.731	90.31	8.5
DGC2	27/12/2004	7.712	90.10	8.23	UNG3	30/12/2004	8.839	102.47	9.28
DGC3	30/12/2004	8.752	101.52	8.75	UNG4	04/01/2005	11.419	130.77	12.33
DGC4	04/01/2005	10.443	120.06	5.92	UNG1	19/05/2005	4.350	53.23	5.14
DGC5	04/01/2005	9.879	113.88	10.75	UNG2	24/05/2005	7.600	88.88	10.03
DGC1	28/05/2005	13.850	157.43	13.03	UNG3	02/06/2005	12.900	147.01	15.92
DGC2	30/05/2005	17.500	197.47	13.74	UNG4	02/06/2005	18.925	213.10	26.3
DGC3	01/06/2005	15.650	177.18	13.23	UNG5	02/06/2005	12.900	147.01	16.44
DGC4	02/06/2005	8.550	99.30	10					
DGC5	02/06/2005	10.475	120.41	13.92					

Sample ref.	Date of sample	True Colour aum^{-1}	True Colour (°H)	DOC (mg l^{-1})	Sample ref.	Date of sample	True Colour aum^{-1}	True Colour (°H)	DOC (mg l^{-1})
NGC1	09/03/2004	7.775	90.80	7.44	UGC1	09/03/2004	4.6	55.97	5.89
NGC2	12/03/2004	6.425	75.99	6.28	UGC2	13/03/2004	7.175	84.22	8.83
NGC3	14/03/2004	12.775	145.64	12.43	UGC3	15/03/2004	7.525	88.06	9.49
NGC4	16/03/2004	11	126.17	10.49	UGC4	17/03/2004	4.525	55.15	5.99
NGC1	22/04/2004	12.773	145.62	9.94	UGC5	19/03/2004	9.375	108.35	11.58
NGC2	24/04/2004	8.081	94.15	6.14	UGC1	22/04/2004	11.907	136.12	10.35
NGC3	27/04/2004	6.228	73.83	4.78	UGC2	25/04/2004	3.765	46.81	3.78
NGC4	29/04/2004	14.529	164.88	11.48	UGC3	28/04/2004	15.649	177.16	14.65
NGC5	02/05/2004	6.686	78.85	5.12	UGC4	29/04/2004	16.040	181.45	14.11
NGC1	25/09/2004	16.478	186.26	12.70	UGC5	02/05/2004	3.789	47.08	3.77
NGC2	27/09/2004	31.131	346.98	26.48	UGC1	25/09/2004	14.695	166.70	12.26
NGC3	29/09/2004	24.297	272.03	20.61	UGC2	27/09/2004	26.848	300.01	23.87
NGC4	01/10/2004	27.425	306.34	21.79	UGC3	29/09/2004	20.001	224.90	17.23
NGC5	03/10/2004	27.233	304.23	24.28	UGC4	01/10/2004	24.036	269.16	20.17
NGC1	24/12/2004	18.932	213.18	17.84	UGC5	03/10/2004	22.104	247.97	18.15
NGC2	27/12/2004	15.588	176.50	14.38	UGC1	25/05/2005	9.500	109.72	9.73
NGC3	30/12/2004	19.726	221.89	19.18	UGC2	27/05/2005	4.200	51.58	5.33
NGC4	04/01/2005	13.880	157.76	11.87	UGC3	29/05/2005	3.525	44.18	4.68
NGC1	25/05/2005	9.175	106.15	8.58	UGC4	31/05/2005	3.875	48.02	5.01
NGC2	29/05/2005	6.700	79.01	6.28					
NGC3	02/06/2005	28.650	319.78	28.87					

Sample ref.	Date of sample	True Colour aum^{-1}	True Colour (°H)	DOC (mg l^{-1})	Sample ref.	Date of sample	True Colour aum^{-1}	True Colour	DOC (mg l^{-1})
RC1	09/03/2004	5.95	70.78	5.82	WC1	21/04/2004	11.565	132.	10.61
RC2	12/03/2004	6.175	73.25	4.52	WC2	24/04/2004	6.917	81.3	6.37
RC3	14/03/2004	5.775	68.86	7.61	WC3	27/04/2004	6.035	71.7	5.36
RC4	17/03/2004	5.6	66.94	5.54	WC4	29/04/2004	14.854	168.	13.60
RC5	20/03/2004	8.75	101.49	10	WC1	25/09/2004	23.196	259.	20.91
RC1	22/04/2004	8.911	103.26	7.87	WC2	27/09/2004	29.417	328.	28.08
RC2	25/04/2004	6.417	75.90	4.80	WC3	29/09/2004	24.603	275.	22.07
RC3	29/04/2004	13.702	155.81	12.50	WC4	01/10/2004	27.320	305.	23.55
RC4	07/05/2004	9.380	108.41	7.30	WC5	03/10/2004	25.794	288.	23.22
RC1	25/09/2004	13.332	151.75	10.98	WC1	24/12/2004	15.212	172.	15.05
RC2	27/09/2004	19.703	221.63	17.13	WC2	27/12/2004	11.612	132.	12.08
RC3	29/09/2004	16.468	186.15	13.46	WC3	30/12/2004	13.186	150.	12.91
RC4	01/10/2004	20.938	235.18	17.77	WC4	04/01/2005	12.947	147.	12.01
RC5	03/10/2004	19.975	224.61	16.90	WC1	23/05/2005	7.425	86.9	7.27
RC1	24/12/2004	8.911	103.26	11.81	WC2	24/05/2005	8.825	102.	8.55
RC2	27/12/2004	7.207	84.57	7.85	WC3	25/05/2005	9.075	105.	9.29
RC3	30/12/2004	6.590	77.80	7.13	WC4	26/05/2005	8.375	97.3	7.53
RC4	04/01/2005	5.750	68.59	5.58	WC5	27/05/2005	7.625	89.1	6.99
RC1	23/05/2005	13.025	148.38	7.63	WC6	28/05/2005	7.125	83.6	6.18
RC2	25/05/2005	12.500	142.63	10.35	WC7	29/05/2005	7.350	86.1	6.37
RC3	31/05/2005	12.225	139.61	7.33	WC8	01/06/2005	12.225	139.	13.2
RC4	02/06/2005	13.825	157.16	15.84					

APPENDIX IV: Monthly Descriptive Statistics of Hourly Stage (m)

Doctors Gate Clough Stage (m) Oct 2002-Sept 2006

Doctors Date Clough Stage Oct 2002 - Sept 2003								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	21	10	0.08721	0.00182	0.04037	0.044	0.073	0.278
Nov-02	30	0	0.07981	0.00122	0.03284	0.048	0.071	0.273
Dec-02	31	0	0.08384	0.00136	0.03701	0.043	0.076	0.295
Jan-03	31	0	0.074489	0.000965	0.026344	0.048	0.067	0.208
Feb-03	25	3	0.063346	0.000962	0.023755	0.044	0.057	0.17
Mar-03	15	16	0.040261	0.0000654	0.001242	0.039	0.04	0.043
Apr-03	30	0	0.05134	0.000892	0.02393	0.039	0.0425	0.298
May-03	743	0	0.07483	0.00122	0.03322	0.042	0.06	0.228
Jun-03	31	0	0.054018	0.000905	0.024286	0.039	0.047	0.204
Jul-03	31	0	0.06163	0.00132	0.03597	0.03	0.053	0.368
Aug-03	31	0	0.052753	0.000353	0.00963	0.036	0.053	0.079
Sep-03	30	0	0.048725	0.000486	0.013045	0.033	0.045	0.104
Doctors Date Clough Stage Oct 2003 - Sept 2004								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	0.053493	0.000642	0.017524	0.038	0.05	0.156
Nov-03	30	0	0.0661	0.00114	0.03054	0.039	0.055	0.326
Dec-03	31	0	0.06892	0.00125	0.034	0.037	0.055	0.202
Jan-04	31	0	0.08312	0.00155	0.04216	0.038	0.07	0.292
Feb-04	29	0	0.06151	0.00102	0.02693	0.036	0.052	0.254
Mar-04	31	0	0.053474	0.000572	0.015604	0.036	0.05	0.117
Apr-04	30	0	0.05807	0.00116	0.031	0.034	0.045	0.241
May-04	31	0	0.047251	0.000523	0.014264	0.035	0.045	0.191
Jun-04	30	0	0.05569	0.00127	0.03402	0.032	0.045	0.337
Jul-04	31	0	0.051427	0.000755	0.020591	0.033	0.043	0.174
Aug-04	31	0	0.0701	0.00168	0.04573	0.034	0.0525	0.337
Sep-04	30	0	0.06341	0.00118	0.03157	0.034	0.0505	0.187
Doctors Date Clough Stage Oct 2004 - Sept 2005								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	301	0	0.07322	0.00128	0.03486	0.038	0.062	0.236
Nov-04	23	8	0.07683	0.00185	0.04352	0.043	0.0615	0.295
Dec-04	30	1	0.07071	0.00126	0.03401	0.042	0.055	0.327
Jan-05	25	6	0.06632	0.00114	0.02839	0.04	0.058	0.264
Feb-05	12	16	0.051524	0.000632	0.010838	0.044	0.047	0.119
Mar-05	31	0	0.067528	0.000837	0.02282	0.045	0.059	0.154
Apr-05	30	0	0.064008	0.000784	0.021045	0.042	0.057	0.186
May-05	31	0	0.054335	0.000544	0.014845	0.042	0.05	0.155
Jun-05	30	0	0.056501	0.000844	0.022651	0.041	0.048	0.235
Jul-05	31	0	0.051595	0.000738	0.020125	0.042	0.046	0.33
Aug-05	31	0	0.056469	0.000692	0.018871	0.043	0.05	0.266
Sep-05	29	1	0.06876	0.00136	0.036	0.049	0.056	0.326
Doctors Date Clough Stage Oct 2005 - Sept 2006								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	30	1	0.07576	0.00173	0.04635	0.043	0.059	0.402
Nov-05	30	0	0.0612	0.00104	0.02779	0.036	0.054	0.249
Dec-05	31	0	0.06368	0.00107	0.02906	0.038	0.05	0.19
Jan-06	2	29	0.05934	0.00206	0.01319	0.046	0.055	0.085
Feb-06	0	29	*	*	*	*	*	*
Mar-06	0	31	*	*	*	*	*	*
Apr-06	14	16	0.06674	0.00103	0.01896	0.053	0.062	0.215
May-06	31	0	0.0739	0.00105	0.02863	0.049	0.06	0.233
Jun-06	30	0	0.047393	0.000139	0.003732	0.042	0.049	0.057
Jul-06	31	0	0.049148	0.000374	0.010211	0.043	0.049	0.193
Aug-06	31	0	0.07893	0.00148	0.04041	0.043	0.06	0.422
Sep-06	30	0	0.067062	0.000993	0.026676	0.048	0.058	0.447

Upper North Grain Stage (m) Oct 2002-Sept 2006

Upper North Grain Stage Oct 2002 - Sept 2003								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	21	10	0.15102	0.00425	0.09412	0.025	0.127	0.61
Nov-02	30	0	0.13877	0.00271	0.07259	0.072	0.122	0.552
Dec-02	31	0	0.14773	0.00312	0.08514	0.067	0.126	0.644
Jan-03	31	0	0.12671	0.0024	0.06539	0.062	0.106	0.448
Feb-03	28	0	0.09471	0.00203	0.05257	0.057	0.074	0.333
Mar-03	31	0	0.09103	0.00205	0.05584	0.052	0.071	0.46
Apr-03	30	0	0.06517	0.00193	0.05179	0.038	0.052	0.561
May-03	31	0	0.11949	0.00267	0.0729	0.057	0.0845	0.445
Jun-03	30	0	0.07148	0.00158	0.04243	0.053	0.061	0.367
Jul-03	31	0	0.09378	0.00265	0.07239	0.053	0.065	0.547
Aug-03	31	0	0.061831	0.000465	0.012052	0.049	0.058	0.128
Sep-03	30	0	0.055059	0.000603	0.016974	0.046	0.051	0.209
Upper North Grain Stage Oct 2003 - Sept 2004								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	0.07653	0.00179	0.04876	0.045	0.057	0.329
Nov-03	30	0	0.14195	0.00263	0.07069	0.07	0.122	0.643
Dec-03	31	0	0.16167	0.0027	0.07374	0.097	0.131	0.43
Jan-04	31	0	0.2014	0.00316	0.0862	0.102	0.172	0.596
Feb-04	28	0	0.14911	0.00235	0.06195	0.091	0.128	0.516
Mar-04	31	0	0.12522	0.0014	0.03814	0.089	0.117	0.278
Apr-04	30	0	0.1454	0.00253	0.068	0.095	0.118	0.559
May-04	31	0	0.10052	0.00133	0.03626	0.071	0.089	0.407
Jun-04	30	0	0.10646	0.00325	0.08725	0.053	0.069	0.732
Jul-04	31	0	0.11747	0.00181	0.04947	0.069	0.102	0.432
Aug-04	31	0	0.14719	0.00374	0.10201	0.072	0.111	0.713
Sep-04	30	0	0.12019	0.00263	0.07061	0.059	0.0915	0.404
Upper North Grain Stage Oct 2004 - Sept 2005								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	31	0	0.14576	0.00278	0.07586	0.074	0.117	0.465
Nov-04	30	0	0.154	0.00332	0.08912	0.082	0.12	0.6
Dec-04	31	0	0.13997	0.00295	0.0804	0.074	0.099	0.659
Jan-05	31	0	0.13892	0.00228	0.06216	0.08	0.119	0.591
Feb-05	27	1	0.10479	0.00241	0.06125	0.068	0.089	0.76
Mar-05	31	0	0.12291	0.00237	0.06468	0.07	0.097	0.366
Apr-05	30	0	0.11912	0.00204	0.05481	0.072	0.096	0.391
May-05	31	0	0.08844	0.00146	0.03979	0.055	0.075	0.342
Jun-05	30	0	0.09264	0.0019	0.05101	0.055	0.073	0.442
Jul-05	31	0	0.07159	0.00162	0.04408	0.049	0.06	0.611
Aug-05	31	0	0.07396	0.00152	0.04146	0.048	0.059	0.444
Sep-05	30	0	0.09595	0.00231	0.06204	0.054	0.074	0.551
Upper North Grain Stage Oct 2005 - Sept 2006								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	31	0	0.13384	0.00334	0.09112	0.073	0.093	0.73
Nov-05	30	0	0.12787	0.00269	0.07206	0.059	0.103	0.54
Dec-05	31	0	0.16056	0.0029	0.079	0.084	0.124	0.446
Jan-06	31	0	0.12769	0.00215	0.05872	0.08	0.104	0.382
Feb-06	27	0	0.13215	0.00254	0.06584	0.075	0.113	0.454
Mar-06	30	1	0.16429	0.00319	0.08515	0.106	0.124	0.569
Apr-06	30	0	0.12928	0.00182	0.04882	0.109	0.116	0.512
May-06	31	0	0.16633	0.00281	0.07658	0.111	0.134	0.572
Jun-06	30	0	0.10742	0.000309	0.0083	0.091	0.105	0.165
Jul-06	31	0	0.093435	0.000642	0.017516	0.087	0.091	0.376
Aug-06	31	0	0.16594	0.00321	0.08763	0.093	0.141	0.679
Sep-06	29	1	0.13237	0.00294	0.07758	0.072	0.105	0.872

Nether Gate Clough Stage (m) Oct 2002 – Sept 2006

Nether Gate Clough Stage Oct 2002 - Sept 2006								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	24	7	0.16125	0.00167	0.04029	0.126	0.152	0.43
Nov-02	30	0	0.1691	0.00138	0.03702	0.14	0.161	0.399
Dec-02	31	0	0.16891	0.00136	0.037	0.14	0.16	0.493
Jan-03	31	0	0.15938	0.000719	0.01961	0.139	0.153	0.254
Feb-03	28	0	0.14992	0.000757	0.01963	0.132	0.144	0.245
Mar-03	31	0	0.14389	0.00076	0.02073	0.13	0.138	0.32
Apr-03	30	0	0.13436	0.000795	0.02134	0.127	0.129	0.417
May-03	31	0	0.15564	0.000864	0.02357	0.134	0.146	0.28
Jun-03	30	0	0.13742	0.000431	0.01157	0.133	0.135	0.248
Jul-03	31	0	0.1519	0.0012	0.0326	0.137	0.141	0.479
Aug-03	31	0	0.14346	0.000144	0.00393	0.14	0.142	0.159
Sep-03	30	0	0.13971	0.0000749	0.00201	0.137	0.139	0.156
Nether Gate Clough Stage Oct 2003 - Sept 2004								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	0.14573	0.000509	0.01388	0.138	0.141	0.255
Nov-03	30	0	0.16117	0.0011	0.02946	0.136	0.155	0.443
Dec-03	31	0	0.17031	0.00116	0.03163	0.141	0.16	0.316
Jan-04	31	0	0.18498	0.00152	0.04138	0.148	0.168	0.422
Feb-04	28	0	0.16283	0.00105	0.02766	0.139	0.155	0.375
Mar-04	30	1	0.1537	0.000632	0.0171	0.138	0.145	0.223
Apr-04	15	15	0.16379	0.00115	0.02218	0.149	0.158	0.337
May-04	31	0	0.14943	0.000458	0.01254	0.141	0.146	0.265
Jun-04	30	0	0.15343	0.00115	0.03085	0.137	0.141	0.4
Jul-04	31	0	0.15376	0.000358	0.00976	0.146	0.151	0.213
Aug-04	31	0	0.17269	0.00138	0.03752	0.144	0.162	0.425
Sep-04	30	0	0.1608	0.000829	0.02223	0.143	0.15	0.273
Nether Gate Clough Stage Oct 2004 - Sept 2005								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	31	0	0.16937	0.000831	0.02266	0.147	0.162	0.278
Nov-04	30	0	0.17372	0.00122	0.03275	0.152	0.1625	0.388
Dec-04	25	6	0.16288	0.00101	0.025	0.144	0.153	0.39
Jan-05	27	4	0.15579	0.000775	0.01992	0.14	0.149	0.324
Feb-05	28	0	0.15156	0.000983	0.02547	0.139	0.144	0.397
Mar-05	31	0	0.14925	0.000562	0.01533	0.136	0.144	0.214
Apr-05	30	0	0.14794	0.000443	0.0119	0.138	0.144	0.208
May-05	31	0	0.142	0.000377	0.01027	0.133	0.141	0.2
Jun-05	30	0	0.15497	0.000689	0.01848	0.143	0.149	0.276
Jul-05	31	0	0.14647	0.000397	0.01082	0.14	0.145	0.286
Aug-05	31	0	0.14393	0.00057	0.01556	0.139	0.142	0.469
Sep-05	30	0	0.15063	0.000585	0.01569	0.14	0.147	0.289
Nether Gate Clough Stage Oct 2005 - Sept 2006								
Month	**N (Day)**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	31	0	0.17682	0.00199	0.0542	0.149	0.1585	0.659
Nov-05	30	0	0.15758	0.000834	0.02238	0.139	0.149	0.313
Dec-05	31	0	0.15746	0.000709	0.01935	0.139	0.149	0.228
Jan-06	31	0	0.14914	0.000507	0.01383	0.139	0.143	0.235
Feb-06	28	0	0.15203	0.000738	0.01912	0.136	0.144	0.246
Mar-06	21	11	0.16027	0.00104	0.02248	0.139	0.152	0.292
Apr-06	16	12	0.15494	0.000732	0.01533	0.14	0.152	0.248
May-06	29	2	0.15703	0.000949	0.0252	0.137	0.147	0.328
Jun-06	30	0	0.13937	0.000123	0.00329	0.135	0.139	0.147
Jul-06	31	0	0.13425	0.000112	0.00305	0.132	0.133	0.176
Aug-06	31	0	0.15289	0.00109	0.02969	0.135	0.141	0.439
Sep-06	29	1	0.1648	0.000971	0.02562	0.138	0.16	0.308

Upper Gate Clough Stage (m) Oct 2002 – Sept 2006

Upper Gate Clough Stage Oct 2002 - Sept 2003								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	24	7	0.13253	0.00254	0.06147	0.074	0.114	0.466
Nov-02	30	0	0.14237	0.00209	0.05611	0.097	0.128	0.502
Dec-02	31	0	0.14177	0.00227	0.06203	0.091	0.125	0.641
Jan-03	31	0	0.10867	0.00141	0.03843	0.069	0.096	0.305
Feb-03	28	0	0.09051	0.00148	0.03843	0.061	0.076	0.279
Mar-03	31	0	0.08994	0.00133	0.03636	0.069	0.08	0.438
Apr-03	30	0	0.08072	0.00147	0.03936	0.065	0.071	0.573
May-03	31	0	0.10676	0.00154	0.04187	0.074	0.088	0.332
Jun-03	30	0	0.073774	0.000912	0.024465	0.061	0.067	0.263
Jul-03	25	6	0.08153	0.00191	0.04636	0.062	0.07	0.626
Aug-03	24	7	0.063807	0.000101	0.002553	0.06	0.064	0.068
Sep-03	30	0	0.060861	0.000372	0.009986	0.049	0.06	0.14
Upper Gate Clough Stage Oct 2003 - Sept 2004								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	26	5	0.07213	0.00118	0.02975	0.052	0.059	0.233
Nov-03	30	0	0.10611	0.00179	0.04794	0.068	0.094	0.576
Dec-03	31	0	0.11883	0.00171	0.04665	0.079	0.0975	0.304
Jan-04	20	11	0.13436	0.00264	0.05732	0.074	0.1175	0.535
Feb-04	28.5	0.5	0.10607	0.00178	0.04639	0.052	0.092	0.432
Mar-04	31	0	0.078466	0.000929	0.025332	0.052	0.072	0.178
Apr-04	30	0	0.08678	0.00176	0.04731	0.055	0.069	0.426
May-04	31	0	0.089276	0.000718	0.01959	0.076	0.088	0.277
Jun-04	22	8	0.11309	0.00278	0.06341	0.068	0.0985	0.726
Jul-04	31	0	0.080196	0.000863	0.023533	0.06	0.072	0.217
Aug-04	31	0	0.11569	0.00217	0.05917	0.059	0.096	0.629
Sep-04	21	9	0.08077	0.00189	0.0429	0.029	0.07	0.304
Upper Gate Clough Stage Oct 2004 - Sept 2005								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	31	0	0.09642	0.00169	0.04608	0.051	0.0795	0.303
Nov-04	9	21	0.09325	0.00173	0.02513	0.062	0.091	0.173
Dec-04	31	0	0.10144	0.00178	0.04842	0.056	0.079	0.436
Jan-05	31	0	0.09741	0.0015	0.0408	0.042	0.087	0.333
Feb-05	2	27	0.055625	0.000657	0.004551	0.043	0.0555	0.063
Mar-05	22	9	0.08372	0.00175	0.0406	0.032	0.071	0.229
Apr-05	26	4	0.08011	0.00137	0.03448	0.035	0.069	0.232
May-05	11	20	0.06404	0.00227	0.03601	0.029	0.0525	0.204
Jun-05	27	3	0.06463	0.00138	0.03527	0.037	0.053	0.286
Jul-05	30	1	0.067321	0.000689	0.018396	0.047	0.065	0.216
Aug-05	91	0	0.071019	0.000926	0.025265	0.056	0.068	0.424
Sep-05	30	0	0.08093	0.0017	0.04642	0.055	0.063	0.408
Upper Gate Clough Stage Oct 2005 - Sept 2006								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	31	0	0.12562	0.00232	0.06305	0.078	0.097	0.568
Nov-05	30	0	0.11755	0.00196	0.05254	0.067	0.093	0.411
Dec-05	31	0	0.1222	0.00242	0.06588	0.063	0.091	0.324
Jan-06	719	25	0.09792	0.00231	0.06183	0.055	0.073	0.412
Feb-06	14	14	0.09296	0.00255	0.04771	0.054	0.071	0.452
Mar-06	23	10	0.13249	0.00345	0.08154	0.066	0.096	0.418
Apr-06	28	2	0.09487	0.00166	0.0434	0.057	0.085	0.471
May-06	31	0	0.09586	0.0019	0.05186	0.05	0.08	0.332
Jun-06	30	0	0.051326	0.000339	0.009091	0.042	0.045	0.073
Jul-06	30	1	0.046933	0.000531	0.014247	0.038	0.044	0.261
Aug-06	31	0	0.1039	0.0026	0.07079	0.039	0.076	0.536
Sep-06	30	0	0.10079	0.00147	0.03937	0.071	0.089	0.428

Red Clough Stage (m) Oct 2002 – Sept 2006

Red Clough Stage Oct 2002 - Sept 2003								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	25	6	0.27721	0.00333	0.08199	0.185	0.263	0.663
Nov-02	31	0	0.29142	0.00261	0.06997	0.221	0.278	0.641
Dec-02	31	0	0.2929	0.00282	0.07682	0.209	0.278	0.734
Jan-03	28	0	0.27558	0.00206	0.05619	0.205	0.2655	0.508
Feb-03	31	0	0.26857	0.00211	0.05479	0.219	0.2485	0.515
Mar-03	30	0	0.23843	0.00214	0.05831	0.194	0.211	0.613
Apr-03	31	0	0.22019	0.00192	0.05145	0.191	0.201	0.749
May-03	30	0	0.26109	0.00232	0.06324	0.204	0.2335	0.525
Jun-03	25	0	0.2205	0.00146	0.03915	0.202	0.207	0.503
Jul-03	24	0	0.23587	0.00305	0.08158	0.198	0.207	0.89
Aug-03	26	5	0.21351	0.000177	0.00446	0.209	0.212	0.243
Sep-03	30	0	0.21579	0.000464	0.01247	0.208	0.212	0.315
Red Clough Stage Oct 2003 - Sept 2004								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	0.23381	0.00147	0.04	0.209	0.218	0.469
Nov-03	30	0	0.28327	0.00231	0.06205	0.225	0.2685	0.826
Dec-03	31	0	0.29025	0.00243	0.06634	0.225	0.267	0.559
Jan-04	31	0	0.33866	0.00293	0.07997	0.238	0.309	0.803
Feb-04	28	0	0.29744	0.00185	0.04875	0.253	0.287	0.643
Mar-04	30	0	0.28273	0.000984	0.02683	0.25	0.281	0.435
Apr-04	30	0	0.29761	0.00212	0.0569	0.255	0.279	0.646
May-04	31	0	0.262	0.00104	0.02835	0.24	0.251	0.469
Jun-04	29	1	0.27624	0.00286	0.07632	0.226	0.25	0.885
Jul-04	31	0	0.28676	0.00121	0.03309	0.251	0.278	0.475
Aug-04	31	0	0.29182	0.00333	0.09088	0.221	0.2595	0.826
Sep-04	30	0	0.26393	0.00217	0.05826	0.209	0.251	0.576
Red Clough Stage Oct 2004 - Sept 2005								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	31	0	0.28207	0.00205	0.0559	0.221	0.265	0.56
Nov-04	30	0	0.29291	0.00251	0.0674	0.236	0.273	0.685
Dec-04	25	0	0.28004	0.0023	0.06277	0.228	0.2575	0.696
Jan-05	27	0	0.27898	0.00157	0.04285	0.239	0.269	0.559
Feb-05	28	0	0.26451	0.00228	0.05909	0.226	0.252	0.812
Mar-05	31	0	0.26788	0.00164	0.04472	0.228	0.257	0.477
Apr-05	30	0	0.25955	0.00134	0.03585	0.22	0.25	0.484
May-05	31	0	0.23258	0.00123	0.03345	0.198	0.219	0.456
Jun-05	30	0	0.24401	0.00196	0.0526	0.201	0.223	0.592
Jul-05	31	0	0.22533	0.00151	0.04108	0.202	0.211	0.824
Aug-05	31	0	0.23237	0.0016	0.04366	0.203	0.218	0.83
Sep-05	30	0	0.25223	0.00217	0.05825	0.211	0.231	0.78
Red Clough Stage Oct 2005 - Sept 2006								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	31	0	0.28753	0.00272	0.07423	0.233	0.272	0.834
Nov-05	30	0	0.28877	0.00206	0.05535	0.239	0.279	0.709
Dec-05	31	0	0.30027	0.00212	0.05775	0.246	0.279	0.61
Jan-06	31	0	0.27457	0.00144	0.03922	0.236	0.263	0.555
Feb-06	28	0	0.27709	0.00199	0.05171	0.233	0.263	0.573
Mar-06	31	0	0.30464	0.00253	0.06888	0.238	0.285	0.793
Apr-06	30	0	0.27874	0.00196	0.05256	0.231	0.27	0.701
May-06	31	0	0.27235	0.00218	0.05941	0.22	0.254	0.629
Jun-06	30	0	0.22321	0.000261	0.007	0.211	0.222	0.282
Jul-06	31	0	0.21433	0.000734	0.02001	0.204	0.21	0.514
Aug-06	31	0	0.26735	0.00265	0.07221	0.214	0.251	0.831
Sep-06	30	0	0.2665	0.00182	0.0488	0.233	0.249	0.79

Within Clough 1 Stage (m) Oct 2002 – Feb 2005

Within Clough 1 Stage (m) Oct 2002 - Sept 2003								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	25	6	0.18173	0.00401	0.09897	0.075	0.154	0.612
Nov-02	31	0	0.19393	0.00302	0.08106	0.125	0.168	0.592
Dec-02	31	0	0.19783	0.00318	0.08684	0.112	0.172	0.694
Jan-03	28	0	0.18192	0.0022	0.05993	0.123	0.159	0.469
Feb-03	31	0	0.15949	0.00234	0.06074	0.118	0.137	0.452
Mar-03	30	0	0.14884	0.00202	0.05523	0.115	0.13	0.545
Apr-03	31	0	0.11862	0.00158	0.04245	0.103	0.105	0.56
May-03	30	0	0.14454	0.00223	0.06091	0.092	0.123	0.44
Jun-03	25	0	0.12258	0.00127	0.03397	0.112	0.114	0.398
Jul-03	24	0	0.15006	0.00259	0.07058	0.116	0.123	0.732
Aug-03	26	0	0.12713	0.000412	0.01123	0.117	0.121	0.194
Sep-03	30	0	0.11799	0.000386	0.01035	0.113	0.116	0.201
Within Clough 1 Stage (m) Oct 2003 - Sept 2004								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	0.13126	0.00129	0.03505	0.112	0.118	0.371
Nov-03	30	0	0.17087	0.00194	0.05205	0.125	0.1605	0.624
Dec-03	31	0	0.18473	0.00177	0.04815	0.145	0.169	0.41
Jan-04	31	0	0.20747	0.00245	0.0667	0.152	0.183	0.602
Feb-04	28	0	0.1546	0.00219	0.05786	0.109	0.119	0.569
Mar-04	30	0	0.13278	0.00078	0.02127	0.113	0.125	0.236
Apr-04	30	0	0.15491	0.00188	0.05037	0.121	0.138	0.518
May-04	31	0	0.13034	0.000664	0.01813	0.114	0.125	0.259
Jun-04	29	0	0.13976	0.00234	0.06278	0.106	0.118	0.75
Jul-04	31	0	0.12741	0.00086	0.02346	0.106	0.12	0.299
Aug-04	31	0	0.15733	0.00303	0.0827	0.103	0.129	0.724
Sep-04	30	0	0.13479	0.00181	0.0486	0.102	0.117	0.386
Within Clough 1 Stage (m) Oct 2004 - Feb 2005								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	31	0	0.14779	0.00181	0.04938	0.112	0.128	0.431
Nov-04	24	6	0.15978	0.00299	0.07254	0.113	0.133	0.537
Dec-04	25	6	0.15326	0.00253	0.06192	0.113	0.123	0.585
Jan-05	31	0	0.14151	0.00135	0.03694	0.119	0.128	0.412
Feb-05	28	0	0.14433	0.00222	0.0576	0.117	0.122	0.708

Within Clough 2 Stage Jul 2004 – Sept 2006

Within Clough 2 Stage (m) Jul 2004 - Sept 2004								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Jul-04	31	0	0.1383	0.000372	0.01016	0.133	0.136	0.2
Aug-04	31	0	0.17656	0.0025	0.06831	0.127	0.152	0.615
Sep-04	30	0	0.15352	0.00168	0.04492	0.113	0.143	0.351
Within Clough 2 Stage (m) Oct 2004 - Sept 2005								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	31	0	0.17038	0.00161	0.04392	0.13	0.153	0.367
Nov-04	30	0	0.17644	0.00193	0.05185	0.137	0.16	0.487
Dec-04	25	0	0.16438	0.00175	0.04774	0.126	0.1455	0.541
Jan-05	27	0	0.16237	0.00114	0.03115	0.132	0.153	0.343
Feb-05	28	0	0.15618	0.00171	0.04442	0.129	0.146	0.598
Mar-05	31	0	0.16104	0.00122	0.03338	0.129	0.151	0.284
Apr-05	30	0	0.14864	0.0011	0.02952	0.113	0.141	0.321
May-05	31	0	0.15217	0.000813	0.02217	0.127	0.147	0.301
Jun-05	16	14	0.1561	0.00168	0.03299	0.129	0.1415	0.318
Jul-05	31	0	0.14289	0.00109	0.02987	0.127	0.133	0.532
Aug-05	31	0	0.14992	0.00118	0.03208	0.125	0.142	0.579
Sep-05	30	0	0.16931	0.00165	0.04414	0.138	0.155	0.56
Within Clough 2 Stage (m) Oct 2005 - Sept 2006								
Month	**N**	**N*(Day)**	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	31	0	0.18522	0.0023	0.06262	0.137	0.161	0.603
Nov-05	30	0	0.2026	0.00154	0.04121	0.175	0.188	0.507
Dec-05	31	0	0.20984	0.00163	0.04452	0.172	0.186	0.426
Jan-06	31	0	0.19101	0.00114	0.03102	0.161	0.18	0.33
Feb-06	28	0	0.18683	0.00137	0.03561	0.161	0.1715	0.371
Mar-06	31	0	0.19355	0.0018	0.04903	0.15	0.176	0.516
Apr-06	30	0	0.17207	0.00136	0.03641	0.14	0.162	0.502
May-06	31	0	0.16813	0.00154	0.04187	0.128	0.16	0.447
Jun-06	30	0	0.1386	0.000228	0.00613	0.126	0.135	0.159
Jul-06	31	0	0.13035	0.000546	0.01488	0.123	0.127	0.313
Aug-06	30	1	0.17526	0.00197	0.05311	0.131	0.1535	0.647
Sep-06	18	12	0.13157	0.00221	0.0463	0.114	0.12	0.68

APPENDIX V: Ashop Catchments Stream Velocity, Stage and Discharge

Ashop Catchments Flow Data for Discharge Calculation

Site	Date	Stage (m)	Mean Velocity	Q (ls^{-1})	Site	Date	Stage (m)	Mean Velocity	Q (ls^{-1})
DGC	25/10/2002	0.103	0.168	**21.00**	**UGC**	07/11/2002	0.139	0.157	**28.28**
	28/02/2003	0.045	0.017	**0.76**		28/02/2003	0.075	0.041	**8.31**
	17/03/2003	0.050	0.024	**1.45**		06/03/2003	0.085	0.028	**5.23**
	02/06/2003	0.055	0.028	**1.59**		03/06/2003	0.075	0.046	**6.65**
	08/07/2003	0.040	0.036	**2.17**		24/06/2003	0.068	0.059	**8.35**
	04/09/2003	0.050	0.029	**1.56**		02/07/2003	0.100	0.099	**17.37**
	16/10/2003	0.040	0.026	**1.51**		03/09/2003	0.061	0.030	**4.29**
	20/11/2003	0.070	0.152	**9.81**		11/09/2003	0.065	0.035	**3.66**
	18/12/2003	0.045	0.055	**2.83**		16/10/2003	0.065	0.043	**6.82**
	09/03/2004	0.070	0.107	**8.87**		20/11/2003	0.133	0.146	**27.24**
	02/11/2004	0.050	0.049	**2.98**		18/12/2003	0.085	0.070	**12.41**
	25/11/2004	0.058	0.060	**3.81**		19/03/2004	0.120	0.172	**30.03**
	23/05/2006	0.080	0.080	**9.59**		22/11/2004	0.095	0.126	**17.89**
						25/04/2005	0.025	0.011	**1.77**
UNG	03/11/2002	0.130	0.242	**62.57**		06/05/2005	0.060	0.078	**12.20**
	28/02/2003	0.070	0.117	**12.23**		22/06/2005	0.050	0.080	**13.65**
	17/03/2003	0.075	0.183	**18.26**		10/05/2006	0.055	0.038	**5.68**
	02/06/2003	0.065	0.112	**16.43**		23/05/2006	0.110	0.164	**22.98**
	08/07/2003	0.075	0.099	**17.02**		07/09/2006	0.090	0.113	**16.29**
	04/09/2003	0.050	0.048	**7.23**					
	03/10/2003	0.043	0.021	**1.45**	**RC**	28/02/2003	0.22	0.013	**3.72**
	16/10/2003	0.060	0.080	**11.03**		06/03/2003	0.27	0.055	**12.52**
	20/11/2003	0.175	0.169	**65.28**		12/06/2003	0.21	0.020	**2.70**
	18/10/2003	0.113	0.084	**16.38**		02/07/2003	0.31	0.160	**33.01**
	19/03/2004	0.170	0.186	**52.53**		03/09/2003	0.21	0.020	**2.00**
	02/11/2004	0.090	0.122	**35.25**		16/10/2003	0.21	0.036	**2.98**
	25/04/2004	0.070	0.049	**10.67**		20/11/2003	0.31	0.302	**44.03**
	02/11/2005	0.170	0.400	**72.38**		18/12/2003	0.24	0.063	**8.55**
	03/05/2006	0.060	0.159	**16.74**		19/03/2004	0.325	0.098	**16.51**
	10/05/2006	0.025	0.312	**13.70**		18/11/2004	0.355	0.203	**46.31**
	23/05/2006	0.120	0.387	**51.63**		25/11/2004	0.335	0.104	**22.03**
						25/04/2005	0.29	0.030	**2.38**
NGC	19/02/2003	0.141	0.036	**10.34**		06/05/2005	0.345	0.065	**11.36**
	28/02/2003	0.13	0.028	**9.67**		07/09/2006	0.34	0.068	**14.87**
	06/03/2003	0.14	0.038	**8.60**					
	03/06/2003	0.1325	0.023	**6.12**	**WC1**	28/02/2003	0.12	0.038	**9.224**
	24/06/2003	0.135	0.032	**10.29**		06/03/2003	0.14	0.120	**25.57**
	02/07/2003	0.148	0.041	**10.76**		12/06/2003	0.115	0.071	**8.694**
	03/09/2003	0.14	0.041	**8.61**		02/07/2003	0.15	0.232	**34.58**
	11/09/2003	0.145	0.027	**5.33**		20/11/2003	0.161	0.309	**47.25**
	16/10/2003	0.145	0.035	**8.32**		19/03/2004	0.165	0.203	**50.46**
	18/12/2003	0.165	0.052	**11.17**		18/11/2004	0.19	0.271	**67.31**
	19/03/2004	0.165	0.063	**12.29**		25/11/2004	0.132	0.155	**22.04**
	25/11/2004	0.17	0.083	**15.31**					
	25/04/2005	0.15	0.066	**11.71**	**WC2**	18/11/2004	0.195	0.359	**51.05**
	23/05/2006	0.18	0.196	**20.25**		25/11/2004	0.165	0.279	**30.23**
	07/09/2006	0.15	0.060	**10.06**		25/04/2005	0.14	0.159	**7.40**
						06/05/2005	0.16	0.265	**23.41**
						22/06/2005	0.14	0.148	**7.44**
						21/10/2005	0.27	0.628	**86.96**
						07/09/2006	0.18	0.308	**24.39**

APPENDIX VI: Descriptive Statistics Monthly Rainfall

Ashop Rainfall (mm) Oct 2002 – Sept 2006

Ashop Rainfall Oct 2002 - Sept 2003								
Month	N	N* (days with no rainfall)	Mean	SE Mean	St Dev	Sum	Median	Maximum
Oct-02	31	7	10.61	2.22	10.86	254.7	5.7	36.2
Nov-02	30	6	8.5	1.29	6.34	204.1	5.85	24.1
Dec-02	31	6	7.4	1.8	8.99	185.1	4.4	39
Jan-03	31	8	4.722	0.63	3.021	108.6	4.4	10
Feb-03	28	12	4.46	1.44	5.74	71.4	0.6	18
Mar-03	31	15	4.79	1.66	6.64	76.6	2.2	22
Apr-03	30	19	7.35	2.45	8.11	80.8	5.4	29.2
May-03	25	6	6.85	1.36	5.92	130.2	6.2	20.6
Jun-03	30	14	6.93	2.52	10.09	110.8	2.8	40.4
Jul-03	31	12	5.97	1.86	8.09	113.4	1.6	27.8
Aug-03	31	17	1.957	0.757	2.833	27.4	0.5	8.2
Sep-03	30	13	2.894	0.814	3.356	49.2	1.4	11.6
Ashop Rainfall Oct 2003- Sept 2004								
Month	N	N* (days with no rainfall)	Mean	SE Mean	St Dev	Sum	Median	Maximum
Oct-03	31	13	4.56	1.09	4.64	82	2.8	14.8
Nov-03	30	6	5.28	1.58	7.72	126.6	2.6	34.8
Dec-03	31	5	5.79	1.52	7.76	150.6	2.7	27
Jan-04	31	2	8.86	1.98	10.66	256.8	3.2	35.2
Feb-04	29	8	5.24	1.11	5.1	110	3.2	20.4
Mar-04	31	8	2.965	0.736	3.528	68.2	1.8	12
Apr-04	30	7	6.34	1.45	6.94	145.8	3	23
May-04	31	21	4.62	1.27	4.01	46.2	3.1	13.4
Jun-04	30	7	7.38	2.26	10.83	169.8	2	45
Jul-04	31	9	4.536	0.818	3.838	99.8	3.3	13.4
Aug-04	31	7	10.98	2.77	13.56	263.4	7.8	66
Sep-04	30	7	6.65	1.54	7.37	153	4.2	24.8
Ashop Rainfall Oct 2004- Sept 2005								
Month	N	N* (days with no rainfall)	Mean	SE Mean	St Dev	Sum	Median	Maximum
Oct-04	31	5	5.98	1.28	6.54	155.4	3.5	26.8
Nov-04	30	3	7.07	1.9	9.86	190.8	4.2	38.8
Dec-04	31	7	7.23	1.65	8.08	173.6	4.2	29.8
Jan-05	31	4	4.64	1.04	5.38	125.2	2.6	18.2
Feb-05	28	10	5.91	2.45	10.4	106.4	1.8	44
Mar-05	31	11	2.83	0.571	2.552	56.6	1.6	8
Apr-05	30	6	4.292	0.672	3.291	103	3.8	10
May-05	31	11	3.1	0.687	3.071	62	2.2	11
Jun-05	30	12	5.74	1.4	5.96	103.4	3.8	19
Jul-05	31	16	4.71	1.96	7.58	70.7	1.2	25.4
Aug-05	31	15	4.78	1.32	5.3	76.4	2.65	21
Sep-05	30	10	5.04	1.21	5.41	100.7	3	15.9
Ashop Rainfall Oct 2005- Sept 2006								
Month	N	N* (days with no Rainfall)	Mean	SE Mean	St Dev	Sum	Median	Maximum
Oct-05	31	13	9.17	2.29	9.71	165	6.2	35.1
Nov-05	30	9	4.957	0.916	4.196	104.1	3.7	19.1
Dec-05	31	6	5.34	1.19	5.93	133.4	2.4	19.8
Jan-06	31	16	4.21	1.29	5.01	63.2	2	16.6
Feb-06	28	11	7.24	1.71	7.04	123	5.6	20.4
Mar-06	31	5	6.42	1.08	5.52	167	5	14.6
Apr-06	30	6	4.98	1.34	6.59	119.6	2	26.8
May-06	31	7	6.43	1.32	6.49	154.4	4.1	24
Jun-06	30	17	2.354	0.64	2.307	30.6	1.8	8.6
Jul-06	31	19	3.73	1.43	4.95	44.8	1.5	16
Aug-06	31	4	7.05	1.36	7.08	190.4	4.6	22.4
Sep-06	30	11	4.92	1.13	4.91	93.4	4	15.4

APPENDIX VII: Descriptive Statistics Monthly Temperature

Ashop Catchment –Monthly Temperature (°C)

Ashop Temperature (°C) Oct 2003 - Sept 2004								
Month	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Oct-03	31	0	5.964	0.107	2.908	-0.2	6.4	10.6
Nov-03	30	0	4.913	0.107	2.886	$^{-2}$.2	5.2	10.1
Dec-03	31	0	2.07	0.114	3.117	-4.6	2	8.7
Jan-04	31	0	2.107	0.104	2.833	-5.6	2	7
Feb-04	29	0	2.44	0.139	3.678	-4.6	2.3	10
Mar-04	31	0	3.2121	0.097	2.6447	-3.3	3.2	9.8
Apr-04	30	0	6.839	0.116	3.124	1.2	6.4	15.5
May-04	5	26	8.413	0.513	5.694	-0.6	6.2	24.5
Jun-04	0	30						
Jul-04	0	31						
Aug-04	29	2	15.042	0.195	5.089	4.3	14.2	32.6
Sep-04	30	0	11.957	0.172	4.617	0.3	11.3	29.6
Ashop Temperature (°C) Oct 2004 - Sept 2005								
Month	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Oct-04	31	0	7.4009	0.0966	2.6336	-0.6	7.3	17.4
Nov-04	30	0	4.779	0.147	3.944	-8.2	6.2	14.2
Dec-04	31	0	2.839	0.132	3.596	-7.7	3.1	9.5
Jan-05	23	8	3.824	0.11	2.556	$^{-2}$.7	3.9	9.9
Feb-05	28	0	1.421	0.132	3.428	$^{-1}$1.2	1.9	8.8
Mar-05	31	0	4.672	0.175	4.766	-6.7	5	19.5
Apr-05	30	0	5.921	0.171	4.597	-5.3	5	20.9
May-05	31	0	9.497	0.206	5.611	-4	9.1	25.5
Jun-05	30	0	13.777	0.239	6.403	$^{-1}$	12	32.2
Jul-05	31	0	14.599	0.213	5.806	5.4	12.8	31.8
Aug-05	31	0	14.398	0.212	5.774	2.7	13.5	33.3
Sep-05	30	0	12.35	0.198	5.316	$^{-2}$.2	12	31.1
Ashop Temperature (°C) Oct 2005 - Sept 2006								
Month	N	N*	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Oct-05	31	0	10.116	0.112	3.062	0.7	9.9	22
Nov-05	24	6	2.404	0.235	5.582	-8.2	2.3	14.9
Dec-05	31	0	2.073	0.137	3.73	$^{-1}$1.2	3.1	12.8
Jan-06	31	0	1.664	0.105	2.859	-5.8	1.5	9.9
Feb-06	28	0	1.031	0.126	3.277	-8.2	0.7	8.8
Mar-06	31	0	1.894	0.181	4.928	$^{-1}$1.8	1.3	16
Apr-06	30	0	5.908	0.182	4.894	-7.7	5.4	21.3
May-06	2	29	5.514	0.401	2.862	-0.6	5.8	9.5
Jun-06	10	20	13.819	0.357	5.633	6.2	11.7	30.7
Jul-06	31	0	18.865	0.285	7.77	5	17	37.7
Aug-06	31	0	13.72	0.161	4.404	5.4	12.4	29.9
Sep-06	30	0	14.493	0.178	4.786	0.3	13.8	31.1

APPENDIX VIII: Descriptive Statistics Monthly MORECS Data

Climatic Data MORECS Square 106

Climate Data MORECS Square 106 Oct 2002 - Sept 2003									
Month	**Rain**	**PE**	**AE**	**SMD**	**EP**	**Sun**	**Temp**	**VP**	**Wind**
Oct-02	102.1	15.5	15.5	0.6	81.5	39	3.5	4.3	109
Nov-02	146.5	17.8	17.8	0	128	44.1	7.2	9.3	209
Dec-02	158.5	12.5	12.5	0	146	35.7	4.4	7.6	225
Jan-03	79	17.6	17.6	0.6	62	53	3.6	6.8	237
Feb-03	50.1	17	17	0	32.7	90.4	3	6.4	200
Mar-03	46.6	41.5	41.1	21.6	27.2	149.8	6.5	7.3	199
Apr-03	70	71.3	70.1	21.8	0	179.9	8.8	7.8	219
May-03	109.2	87.8	87.7	25.8	25.5	171	10.9	10	228
Jun-03	101.9	99.9	98.7	22.5	0	194.5	14.8	12.1	191
Jul-03	86.2	97.1	95.8	32	0	155.7	16.2	13.9	191
Aug-03	17.2	83.9	79.9	94.6	0	182.2	16.5	14.2	148
Sep-03	53.2	56.8	51.9	93.4	0	139.7	13	11.4	150
Climate Data MORECS Square 106 Oct 2003 - Sept 2004									
Month	**Rain**	**PE**	**AE**	**SMD**	**EP**	**Sun**	**Temp**	**VP**	**Wind**
Oct-03	57.6	38.9	36.6	72.3	0	118.5	7.9	8.5	214
Nov-03	76.6	19.5	19.2	14.6	0	59.9	6.8	9	225
Dec-03	111	11	11	0	85.4	39.3	3.8	7.2	197
Jan-04	135.5	16.4	16.4	0	119	26.6	4.4	7.4	245
Feb-04	61.2	23.5	23.5	6.1	43.9	98.3	4.4	6.8	230
Mar-04	48.7	39.7	39.7	7.2	10	94.6	5.4	7	236
Apr-04	114	54.9	54.9	2.4	54.2	102.3	8.4	8.6	199
May-04	60.7	82.5	82.2	40.7	16.6	183.9	11.1	9.9	157
Jun-04	80.8	87.8	86.7	46.6	0	160.7	13.7	12.1	194
Jul-04	84.7	86.8	86.1	47.9	0	142.8	14.2	12.4	176
Aug-04	233	81.3	80.8	6.9	111	150.5	16	14.8	173
Sep-04	104.6	62.6	62.4	1.2	36.6	141.3	13.2	12.1	227
Climate Data MORECS Square 106 Oct 2004 - Sept 2005									
Month	**Rain**	**PE**	**AE**	**SMD**	**EP**	**Sun**	**Temp**	**VP**	**Wind**
Oct-04	138.9	36.2	36.2	0.9	102	77.9	9.2	9.9	237
Nov-04	49.9	19.6	19.6	0.8	30.3	43.3	6.8	8.8	252
Dec-04	52	15	15	0.2	36.6	52.3	4.9	7.8	266
Jan-05	58.3	26.2	26.2	0.5	32.2	41.8	5.2	7.4	379
Feb-05	57.6	18.8	18.8	0	38.1	59	3.2	6.6	267
Mar-05	45.9	31.6	31.6	0.3	14.7	56.7	5.9	8.1	246
Apr-05	111.3	56.4	56.4	0	54.5	124.2	7.4	8.1	252
May-05	41.8	91.2	90.6	49.1	0.2	198.3	10	9.1	253
Jun-05	73.7	88	86.6	62	0	167.9	14.1	12.5	206
Jul-05	83	80.4	74.3	53.3	0	137.6	15.1	14.1	207
Aug-05	80.5	85.5	84.3	57	0	177.8	14.8	12.9	219
Sep-05	105.1	59.5	59.2	11.1	0	142.1	13.4	12.5	216
Climate Data MORECS Square 106 Oct 2005 - Sept 2006									
Month	**Rain**	**PE**	**AE**	**SMD**	**EP**	**Sun**	**Temp**	**VP**	**Wind**
Oct-05	134.9	34.1	34.1	0	89.8	55.5	11.6	11.9	230
Nov-05	91.1	19.8	19.8	0	71.3	98.1	5.2	8	243
Dec-05									
Jan-06	33.9	10.7	10.7	1.3	24.5	28.8	3.3	7	217
Feb-06	65.6	16.8	16.8	0.8	48.1	59.6	2.9	6.5	248
Mar-06	110.5	33.3	33.3	0	76.5	92.5	3.3	6.7	273
Apr-06	65.1	53.6	53.6	7.6	19.3	121.3	7	8	260
May-06	155.5	81.8	81.7	9.2	75.5	149.9	10.6	10.1	235
Jun-06	40.8	94.6	93.7	62.1	0	170.7	14.7	12.3	197
Jul-06	36.3	124.8	93.7	119.3	0	280.7	18.1	14.4	188
Aug-06	129.7	78.1	62.4	52.1	0	125.2	14.3	13.4	241
Sep-06	89.7	61.2	61.2	23.8	0	141.9	15	14.2	214

APPENDIX IX: Descriptive Statistics Monthly True Water Colour (°H)

Doctors Gate Clough Monthly True Colour Oct 2002 – Sept 2006

Doctors Gate Clough Monthly True Colour (°H) Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	19	12	220.6	11.2	49	161.6	219.1	391.1
Nov-02	22	8	181.3	11.5	53.8	93.5	200.5	255.6
Dec-02	23	8	115.91	8.8	42.19	40.34	114.38	197.47
Jan-03	24	7	107.05	6.17	30.23	61.46	112.46	150.85
Feb-03	26	2	75.81	2.48	12.67	56.24	74.48	117.4
Mar-03	26	5	104.2	10.7	54.7	42.5	83.4	210.4
Apr-03	18	12	118.22	8.04	34.11	52.68	129.05	162.37
May-03	22	9	144.12	8.83	41.43	81.47	145.23	215.02
Jun-03	20	10	197.13	7.79	34.86	130.01	197.47	266.58
Jul-03	14	17	256.3	20.7	77.4	139.6	247	416.3
Aug-03	7	24	289.2	34	89.8	191.9	298.4	460
Sep-03	18	12	320.5	10.7	45.6	215.2	330	383.9
Doctors Gate Clough Monthly True Colour (°H) Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	22	9	213.2	11.9	55.7	129.3	227.9	328.3
Nov-03	24	6	156.71	5.95	29.14	118.16	150.13	231.79
Dec-03	25	6	142.77	7.63	38.16	85.11	131.47	204.69
Jan-04	19	12	138.94	4.76	20.74	106.03	141.69	178.54
Feb-04	24	5	108	9.11	44.65	64.91	89.16	205.64
Mar-04	20	11	83.27	2.53	11.3	65.14	83.69	106.75
Apr-04	15	15	129.79	7.32	28.35	74.41	129.8	190.19
May-04	18	13	158.51	3.91	16.57	133.37	151.56	189
Jun-04	22	8	187.24	8.74	41.01	113.4	185.2	261.74
Jul-04	20	11	186.3	11.9	53.3	67.5	185.7	265.6
Aug-04	15	16	278.27	8.82	34.15	221.57	268.87	343.52
Sep-04	15	15	228.6	10.7	41.6	164.5	214.4	298.4
Doctors Gate Clough Monthly True Colour Statistics Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	21	11	218.86	4.98	22.8	188.05	215.86	289.32
Nov-04	14	16	181.51	4.91	18.36	143.59	185.91	204.21
Dec-04	26	5	132.63	7	35.69	84.4	139.32	197.32
Jan-05	19	12	93.72	3.23	14.07	77.27	91.06	135.51
Feb-05	18	10	111.51	2.34	9.91	95.57	108.65	126
Mar-05	18	13	99.69	7.49	31.78	60.86	91.41	152.63
Apr-05	17	13	110.95	3.37	13.88	89.87	111.5	135.27
May-05	16	15	131.95	8	32	96.52	121.37	197.56
Jun-05	26	4	203.08	8.31	42.38	132.18	190.31	276.01
Jul-05	19	12	337.5	14.8	64.4	216.3	333.1	461.9
Aug-05	26	5	363.2	13.6	69.3	253.2	381.1	488.1
Sep-05	13	17	320.8	17.9	64.5	256.5	310.7	468.1
Doctors Gate Clough Monthly True Colour (°H) Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	18	13	273.34	5.61	23.79	230.36	274.34	315.94
Nov-05	18	12	205.2	11.6	49	137.7	220	281.7
Dec-05	19	12	141.87	6.38	27.82	101.52	153.34	175.69
Jan-06	26	5	121.03	2.2	11.21	103.89	119.59	153.1
Feb-06	15	13	94.23	3.94	15.26	78.69	90.82	145.26
Mar-06	18	13	91.95	7.05	29.9	58.96	76.68	145.02
Apr-06	22	8	105.85	4.31	20.21	75.13	99.97	142.88
May-06	18	13	156.96	9.14	38.77	101.28	153.94	224.66
Jun-06	23	7	182.28	9.29	44.55	111.02	163.32	299.78
Jul-06	30	1	307.8	17.7	97	188.1	274.6	507.8
Aug-06	21	10	248.1	14.4	66.2	169.7	231.3	394.9
Sep-06	24	6	246.91	6.61	32.39	193.75	247.84	302.16

Upper North Grain Monthly True Colour Oct 2002 – Sept 2006

Upper North Grain Monthly True Colour (°H) Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	13	18	138.3	17.7	63.9	49.4	157.2	218.3
Nov-02	24	6	145.9	11.7	57.1	48.3	156.1	225.7
Dec-02	22	9	95.6	9.27	43.5	35.95	93.82	196.1
Jan-03	19	12	108.35	8.82	38.44	29.1	119.32	152.77
Feb-03	23	5	47.61	4.79	22.98	21.69	41.44	87.51
Mar-03	16	15	51.69	6.92	27.67	19.5	50.35	109.17
Apr-03	30	0	37.5	3.34	18.3	20.6	30.47	102.31
May-03	31	0	87.68	8.08	44.97	32.66	74.89	154.69
Jun-03	28	2	50.14	4.55	24.07	24.71	41.03	112.46
Jul-03	24	7	96	14	68.8	36.7	57.3	254.7
Aug-03	13	18	62.26	9.91	35.74	40.39	49.61	175.87
Sep-03	30	0	65.62	3.07	16.81	45.92	64.38	114.45
Upper North Grain Monthly True Colour (°H) Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	28	3	69.28	6.46	34.18	44.47	56.16	151.35
Nov-03	22	8	116.24	8.89	41.71	48.91	126.91	188.07
Dec-03	15	16	116.2	13.1	50.6	45.2	128.4	190.9
Jan-04	20	11	111.67	5.05	22.6	69.96	112.65	142.93
Feb-04	9	20	132.95	8.54	25.61	84.46	140.6	158.6
Mar-04	22	9	65.15	3.96	18.56	42.13	61.08	102.71
Apr-04	24	6	69.39	6.15	30.11	40.26	55.34	156.03
May-04	24	7	54.54	5.65	27.67	37.05	44.35	164.22
Jun-04	28	2	76.23	7.98	42.25	40.96	53.36	185.97
Jul-04	22	9	113.2	11.5	54	47.7	99.1	239.3
Aug-04	17	14	203.5	19.6	80.9	80.7	222.9	346.9
Sep-04	22	8	162.6	13.7	64.2	58.5	173.8	260.8
Upper North Grain Monthly True Colour Statistics Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	24	8	168.33	9.65	47.3	68.1	184.9	229.9
Nov-04	15	15	165.21	8.7	33.7	95.5	160	214.5
Dec-04	19	12	95.76	4.9	21.38	64.1	93.6	131.9
Jan-05	19	12	84.8	4.38	19.08	58.5	81.2	130.8
Feb-05	17	11	88.21	4.54	18.7	57.3	89.6	115.3
Mar-05	16	15	72.44	2.89	11.56	59	69.95	104.1
Apr-05	25	5	100.18	5.02	25.11	55.5	100.8	157
May-05	24	7	66.51	7.11	34.84	36.5	53.85	162.6
Jun-05	17	13	78.72	7.06	29.09	54.1	62.2	146.9
Jul-05	23	8	77.65	5.72	27.42	56.6	66	161.6
Aug-05	29	2	93.87	8.24	44.37	45.6	73.5	210.5
Sep-05	16	14	146.9	16.4	65.4	65	141.9	272
Upper North Grain Monthly True Colour (°H) Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	25	6	149.8	11.1	55.4	77.5	132.9	246.3
Nov-05	19	11	158.2	18.6	80.9	50.6	182.2	261.8
Dec-05	16	15	108.92	9.1	36.41	51.25	120.13	155.1
Jan-06	15	16	84.99	5.38	20.84	45.17	83.06	116.51
Feb-06	7	21	78.92	9.26	24.5	56.86	71.83	128.43
Mar-06	11	20	71.7	11.6	38.5	24.6	71.4	130.8
Apr-06	17	13	72.3	10.5	43.1	38.9	49.6	190.4
May-06	29	2	99.1	10.9	58.8	35.1	80.7	194.9
Jun-06	25	5	52.34	2.01	10.05	40.02	51.25	75.34
Jul-06	24	7	61.86	2.53	12.41	36.28	61.31	89.14
Aug-06	23	8	112.6	11.2	53.7	56.4	99.2	235.8
Sep-06	14	16	115.1	17.2	64.2	61.8	88.8	264.6

Nether Gate Clough Monthly True Colour Oct 2002 – Sept 2006

Nether Gate Clough Monthly True Colour (°H) Oct 2002 - Sept 2003

Month	N	N*	Mean	SE Mean	St Dev	Min	Median	Max
Oct-02	26	5	161.6	18	91.9	19.5	177.9	338.4
Nov-02	30	0	201.2	11.5	63.2	102	191.7	314.8
Dec-02	30	1	176.3	9.74	53.35	91.35	170.33	309.9
Jan-03	16	15	165.16	6.32	25.27	116.03	164.29	211.46
Feb-03	21	7	96.9	10.3	47.4	33.8	108.6	171.4
Mar-03	30	1	76.67	8.67	47.47	23.06	58.17	164.84
Apr-03	29	1	45.62	7.61	40.96	15.93	28.27	184.31
May-03	29	2	126.3	13.3	71.5	41.7	115.2	269.9
Jun-03	27	3	54.3	6.63	34.42	26.9	38.42	152.22
Jul-03	27	4	114.2	18.2	94.6	26.6	65.6	313.7
Aug-03	24	7	43.7	1.37	6.74	35.27	43.59	68.26
Sep-03	22	8	28.33	2.75	12.89	20.52	23.95	70.4

Nether Gate Clough Monthly True Colour (°H) Oct 2003 - Sept 2004

Month	N	N*	Mean	SE Mean	St Dev	Min	Median	Max
Oct-03	24	7	57.4	10.5	51.3	18.2	27.4	174.1
Nov-03	23	7	147.7	10.5	50.4	59.9	157.5	207.4
Dec-03	27	4	145.6	12	62.1	61.7	128.7	268.6
Jan-04	25	6	156.99	6.05	30.25	91.25	163.04	212.39
Feb-04	26	3	133.46	8.01	40.83	71.46	126.75	210.54
Mar-04	19	12	108.85	5.99	26.09	74.1	106.82	156.97
Apr-04	24	6	110	8.56	41.94	62.75	88.61	191.27
May-04	22	9	41.97	7.03	32.99	11.02	33.85	125.03
Jun-04	16	14	72.8	21.5	85.8	17.4	27.5	280.5
Jul-04	12	19	107.1	18.8	65	44.8	79.8	233.2
Aug-04	27	4	243.8	23	119.6	39	274.7	471
Sep-04	21	9	173	23.2	106.4	31.3	175.2	347

Nether Gate Clough Monthly True Colour Oct 2004 - Sept 2005

Month	N	N*	Mean	SE Mean	St Dev	Min	Median	Max
Oct-04	25	7	233	14.9	74.5	90.7	244.8	348
Nov-04	15	15	203.4	12.3	47.5	138.5	207.9	289.5
Dec-04	31	0	168.47	9.43	52.51	99.7	169.9	304.2
Jan-05	17	14	163.69	6.58	27.14	112.4	162	200.8
Feb-05	19	9	161.12	5.28	23.01	120.8	167.8	195.5
Mar-05	24	7	140.07	8.37	41.03	88.6	127.55	230.3
Apr-05	29	1	169.26	7.8	42.02	93.4	166.7	254.9
May-05	19	12	112.9	15.1	65.7	47.4	94.9	247.8
Jun-05	25	5	147.1	15.4	76.9	41.9	132.4	308.5
Jul-05	12	19	88.9	22	76.1	28.7	59.7	268.1
Aug-05	31	0	85	11.2	62.1	24.2	47.7	254.6
Sep-05	26	4	161.9	23	117.2	34.8	157	365.5

Nether Gate Clough Monthly True Colour (°H) Oct 2005 - Sept 2006

Month	N	N*	Mean	SE Mean	St Dev	Min	Median	Max
Oct-05	13	18	260.3	25.2	91	99.7	283.1	422.5
Nov-05	24	6	179.5	14	68.5	81.8	191	284.7
Dec-05	22	9	196	5.98	28.07	154.33	194.58	260.42
Jan-06	28	3	147.38	8.72	46.13	73	145.75	240.4
Feb-06	15	13	141.8	10.2	39.4	95.2	145.1	218.5
Mar-06	22	9	140.21	6.83	32.05	84.13	147.34	188.11
Apr-06	28	2	125.25	9.17	48.55	49.55	121.21	220.83
May-06	23	8	110.4	15.1	72.7	33.5	73.6	248.8
Jun-06	25	5	39.57	2.75	13.76	25.54	33.98	79.11
Jul-06	31	0	28.75	2.14	11.9	20.26	26.33	82.01
Aug-06	31	0	91	15.7	87.4	9.17	34.8	264.6
Sep-06	25	5	108.7	15.9	79.3	34.5	62.8	256.7

Upper Gate Clough Monthly True Colour Oct 2002 – Sept 2006

Upper Gate Clough Monthly True Colour (°H) Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	20	11	126.6	13.2	59.2	37.9	127.7	249.6
Nov-02	28	2	175.5	12.2	64.7	64.8	177.7	279.5
Dec-02	28	3	116.02	8.15	43.11	35.13	120.55	179.1
Jan-03	25	6	132.58	8.49	42.46	57.89	136.87	211.18
Feb-03	27	1	66.22	6.62	34.38	19.77	64.47	121.24
Mar-03	29	2	48.53	6.43	34.6	17.85	26.08	112.46
Apr-03	27	3	41.92	7.36	38.23	18.68	26.63	164.56
May-03	27	4	98.3	13.3	68.9	28.6	68	209.3
Jun-03	27	3	55.3	4.39	22.83	35.68	45.28	117.4
Jul-03	22	9	98.8	16.2	76.1	39	51.6	256.3
Aug-03	24	7	43.7	1.37	6.74	35.27	43.59	68.26
Sep-03	23	7	53.98	5.25	25.19	33.66	46.81	144.98
Upper Gate Clough Monthly True Colour (°H) Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	20	11	61.95	9.85	44.07	26.96	37.55	155.7
Nov-03	23	7	118.9	11	52.6	35.5	127.3	211
Dec-03	18	13	121.3	13.1	55.6	46.5	115.3	202.9
Jan-04	1	30	145.24	*	*	145.24	145.24	145.24
Feb-04	22	7	104.8	12.3	57.6	30.5	84.1	224.9
Mar-04	20	11	69.7	6.24	27.93	36.35	67.19	143.37
Apr-04	16	14	97.4	12.2	48.9	36.1	91.7	181.5
May-04	15	16	69.9	13.6	52.6	33.7	47.1	186.8
Jun-04	29	1	70.98	9.07	48.86	29.37	44.39	197.55
Jul-04	29	2	128.9	13.7	73.6	47.9	109.6	304.8
Aug-04	23	8	224.7	24.1	115.7	51.4	206.7	436.3
Sep-04	21	9	202.2	13.4	61.2	40.9	200	300
Upper Gate Clough Monthly True Colour Statistics Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	11	21	171.5	24.9	82.5	62.4	202.4	269.2
Nov-04	14	16	175.49	9.42	35.26	120.8	168.45	250.9
Dec-04	20	11	123.36	8.98	40.17	66.9	122.05	214.4
Jan-05	21	10	113.9	4.32	19.82	79	116.3	150.9
Feb-05	18	10	131.7	10.6	44.8	60.5	123.8	258.7
Mar-05	16	15	110.81	8.88	35.53	65.6	97.5	181.2
Apr-05	29	1	121	8.42	45.32	42.8	125.9	198.9
May-05	25	6	80.6	12	60.2	38.8	48.1	220.6
Jun-05	22	8	82.51	9.49	44.5	37.7	68.8	176.1
Jul-05	29	2	80.04	8.83	47.54	46.5	58.6	230.8
Aug-05	18	13	96.6	12.7	53.7	44.9	74.2	212
Sep-05	13	17	105.3	20.5	73.8	51.6	76.6	289.3
Upper Gate Clough Monthly True Colour (°H) Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	15	16	177	23.2	89.7	70.4	139.9	331.1
Nov-05	24	6	147.4	15.9	77.8	49.5	158.4	285.5
Dec-05	22	9	130.22	8.55	40.11	53.24	138.68	185.21
Jan-06	22	9	103.33	8.51	39.94	39.8	101.7	183.6
Feb-06	11	17	117.9	12.2	40.4	51.1	130.5	165.1
Mar-06	6	25	129.9	11.2	27.5	99.7	123.9	164.8
Apr-06	11	19	133.6	14.7	48.7	62.9	121.6	212.8
May-06	25	6	121.6	15.2	76.2	31.5	109	248.8
Jun-06	30	0	47.201	0.837	4.585	38.49	45.73	60.49
Jul-06	31	0	60.3	1.3	7.21	44.39	59.68	73.36
Aug-06	30	1	75.4	12	65.8	14.6	47.6	236.2
Sep-06	12	18	146.2	20.1	69.7	52.7	171.3	241.3

Red Clough Monthly True Colour Oct 2002 – Sept 2006

Red Clough Monthly True Colour (°H) Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	26	5	106.53	4.7	23.97	68.04	100.54	165.93
Nov-02	26	4	134.73	9.75	49.71	59.81	139.34	209.81
Dec-02	11	20	60.51	8.35	27.68	29.37	55.15	112.46
Jan-03	4	27	88.9	28.4	56.8	28.3	90.9	145.4
Feb-03	27	1	46.18	3.38	17.54	20.05	39.79	83.94
Mar-03	31	0	48.64	1.84	10.26	34.31	45.28	72.97
Apr-03	30	0	52.19	2.37	12.96	33.21	52.68	85.59
May-03	29	2	90.3	6.31	34	38.42	90.8	149.21
Jun-03	18	12	72.82	8.13	34.51	26.08	83.39	116.03
Jul-03	25	6	128.34	6.69	33.44	80.24	120.69	218.31
Aug-03	25	6	134.87	3.83	19.17	112.74	128.18	176.13
Sep-03	30	0	143.87	4.28	23.46	101.91	149.04	193.19
Red Clough Monthly True Colour (°H) Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	112.29	3.31	18.46	76.98	112.47	149.58
Nov-03	9	21	74.43	8.01	24.03	53.96	65.88	129.81
Dec-03	24	7	86.13	7.34	35.96	43.67	74.55	152.83
Jan-04	15	16	106.28	5.92	22.95	66.42	106.24	138.2
Feb-04	23	6	75.62	8.89	42.64	24.7	56.94	153.37
Mar-04	20	11	68.38	2.58	11.56	50.71	68.32	101.36
Apr-04	23	7	85.05	6.39	30.62	51.79	75.9	155.81
May-04	22	9	98.35	6.48	30.41	32.29	104.48	162.85
Jun-04	29	1	115.54	5.12	27.58	39.06	126.28	149.58
Jul-04	17	14	140.05	8.32	34.3	99.47	135.77	225.16
Aug-04	28	3	241.3	14.9	78.6	130.6	253.7	412.3
Sep-04	15	15	177.82	9.05	35.07	110.03	166.1	239.24
Red Clough Monthly True Colour Statistics Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	21	11	165.86	6.15	28.17	129.8	163.4	235.2
Nov-04	23	7	140.75	3.47	16.66	114.6	139.8	166.9
Dec-04	27	4	111.58	6.51	33.82	65.3	112.7	168.5
Jan-05	25	6	77.3	2.13	10.65	62.1	76.4	96.2
Feb-05	14	14	86.92	2.48	9.27	74.3	85	106
Mar-05	15	16	72.39	3.48	13.46	55	70.8	103.3
Apr-05	13	17	101.96	9.28	33.47	71.8	87.3	177.8
May-05	27	4	108.96	4.58	23.81	70.5	100.6	159.1
Jun-05	30	0	131.49	3.42	18.71	85.1	136.05	158
Jul-05	25	6	169.18	5.61	28.07	107.6	164.5	210.8
Aug-05	23	8	147.38	6.36	30.5	79.7	148.8	202.9
Sep-05	12	18	183.89	9.56	33.13	148.5	179.95	253.1
Red Clough Monthly True Colour (°H) Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	2	29	190.9	45.9	64.9	145	190.9	236.8
Nov-05	11	19	131.7	15.7	52	65.3	126.6	220.3
Dec-05	2	29	124.4	13.3	18.8	111.1	124.4	137.7
Jan-06	13	18	95.78	5.29	19.07	74.82	92.15	125.47
Feb-06	15	13	83.32	5.12	19.84	61.27	83.49	122.76
Mar-06	15	16	73.16	7.41	28.68	39.87	73.19	121.95
Apr-06	18	12	100.97	6.87	29.15	71.84	96.35	200.51
May-06	31	0	126.78	5.27	29.34	79.42	121.95	186.96
Jun-06	30	0	125.98	2.88	15.75	88.63	126.29	164.21
Jul-06	31	0	147.95	3.92	21.84	88.9	148.5	193.19
Aug-06	24	7	127.89	6.62	32.44	78.88	138.48	175.86
Sep-06	9	21	155.4	11.2	33.6	81.1	168	194.6

Within Clough Monthly True Colour Oct 2002 – Sept 2006

Within Clough Monthly True Colour (°H) Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-02	25	6	167.7	14.8	73.8	62.6	189.8	354.3
Nov-02	24	6	204.7	11.7	57.3	89.4	222.3	280
Dec-02	21	10	149.12	9.82	45.01	64.47	156.89	203.23
Jan-03	16	15	134.3	10.1	40.2	56	145	173.9
Feb-03	28	0	74.57	6.99	36.98	27.45	60.77	140.16
Mar-03	31	0	58.7	5	27.82	27.73	41.99	113.28
Apr-03	30	0	39.12	3.6	19.7	23.61	31.7	112.74
May-03	30	1	120.1	11.2	61.2	42.5	103	220
Jun-03	25	5	61.45	6.61	33.06	14.56	50.76	159.9
Jul-03	31	0	104.1	11.4	63.7	52.6	69.7	273.8
Aug-03	31	0	63.41	2.53	14.07	40.08	60.73	115.64
Sep-03	30	0	82.14	3.11	17.04	52.89	80.34	138.9
Within Clough Monthly True Colour (°H) Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-03	31	0	70.33	5	27.84	42.17	64.91	133.15
Nov-03	25	5	133.86	9.47	47.35	60.21	138.12	210.02
Dec-03	26	5	142.07	9.87	50.32	63.61	142.3	212.63
Jan-04	20	11	150.19	6.35	28.42	65.18	153.28	195.11
Feb-04	21	8	116	11.5	52.6	24.1	97.9	200.6
Mar-04	12	19	73.98	5.4	18.69	53.15	71.06	115.37
Apr-04	16	14	92.27	8.12	32.47	54.98	80.74	168.45
May-04	24	7	39.31	8.44	41.35	22.3	25.31	208.97
Jun-04	29	1	89.23	6.73	36.23	27.27	79.56	173.94
Jul-04	12	19	175.8	19.7	68.2	77.5	161.7	286.9
Aug-04	14	17	275.9	27	101.2	91.3	307.3	391.5
Sep-04	12	18	218.4	27.5	95.3	89	229.4	329.2
Within Clough Monthly True Colour Statistics Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-04	21	11	220.5	14.5	66.4	102.3	223.1	306.2
Nov-04	21	9	228.78	6.66	30.53	176.03	222.83	280.08
Dec-04	27	4	150.73	5.6	29.11	104.92	148.32	229.36
Jan-05	23	8	129.87	5.09	24.42	85.57	132.37	166.88
Feb-05	10	18	129.18	7.35	23.25	96.81	124	180.21
Mar-05	23	8	110.05	5.37	25.74	77.46	101.78	171.85
Apr-05	29	1	130.37	6.85	36.9	74.85	126.62	206.1
May-05	24	7	106.05	9.21	45.14	69.62	85.83	215.77
Jun-05	14	16	138.7	14.6	54.6	82.2	123	222.3
Jul-05	22	9	125.33	6.17	28.93	101.52	115.77	223.09
Aug-05	27	4	123.29	7.37	38.29	80.6	112.5	214.72
Sep-05	19	11	170.3	17.2	74.8	102.8	136	318.3
Within Clough Monthly True Colour (°H) Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Min**	**Median**	**Max**
Oct-05	22	9	205.5	13.5	63.4	121.9	199.4	312
Nov-05	10	20	240.9	16	50.5	125.1	259.3	283.2
Dec-05	11	20	186.34	4.89	16.23	160.1	191.7	207.4
Jan-06	22	9	124.71	8.08	37.9	60.7	121.9	189.6
Feb-06	19	9	121.95	6.39	27.85	83.48	120.6	190.93
Mar-06	20	11	112.3	8.23	36.79	71.71	102.7	175.51
Apr-06	19	11	115.03	6.93	30.21	71.71	120.34	182.83
May-06	22	9	115	11	51.7	63.9	94.3	239
Jun-06	30	0	89.73	2.05	11.21	73.8	84.52	120.08
Jul-06	31	0	119.22	2.93	16.34	90.8	115.64	148.58
Aug-06	31	0	106.1	12.8	71.1	26.7	102.6	253.9
Sep-06	26	4	161.2	14.6	74.2	62.6	126.7	286.9

APPENDIX X: Heavy Metal Analysis

	5/5/2006				7/7/2006				9/5/2006			
	Fe (mgl^{-1})	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**	**Fe (mgl^{-1})**	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**	**Fe (mgl^{-1})**	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour**
DGC	2.897	0.084	1.106	124.10	7.454	0.113	2.556	217.53	4.234	0.039	1.291	180.44
UNG	0.486	0.039	3.336	35.11					0.512	0.036	3.683	37.92
NGC	0.151	0.035	4.454	45.86	0.062	0.018	5.49	22.37	0.099	0.029	4.106	45.33
UGC	0.132	0.034	2.196	34.47	0.249	0.065	3.138	54.05	0.512	0.036	3.683	37.92
RC	4.135	0.083	2.524	116.02	4.091	0.107	3.598	137.89	4.199	0.083	2.641	123.86
WC	1.572	0.081	3.741	72.50	1.861	0.102	3.619	106.22	1.477	0.06	3.117	63.83

	12/5/2006				15/5/2006				19/5/2006			
	Fe (mgl^{-1})	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**	**Fe (mgl^{-1})**	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**	**Fe (mgl^{-1})**	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour**
DGC	4.234	0.039	1.291	180.44	2.286	0.149	1.69	163.09	2.072	0.198	1.219	203.02
UNG	0.583	0.043	3.41	38.85	0.641	0.168	2.983	125.16	0.947	0.249	2.2	186.90
NGC	0.087	0.022	3.983	33.45	0.42	0.185	3.838	171.22				
UGC					0.625	0.178	2.495	128.08	1.016	0.303	2.04	248.78
RC	2.859	0.06	3.372	108.65	2.164	0.11	2.818	127.19	1.205	0.217	2.038	174.73
WC	1.953	0.064	3.007	73.54	1.505	0.096	3.286	99.16				

	3/7/2006				23/7/2006				27/7/2006			
	Fe (mgl^{-1})	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**	**Fe (mgl^{-1})**	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**	**Fe (mgl^{-1})**	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour (°H)**
DGC	6.071	0.135	2.472	210.16	10.64	0.227	2.988	431.00	13.08	0.366	3.641	345.90
UNG					0.912	0.053	6.212	89.14	0.793	0.043	6.361	69.26
NGC	0.121	0.037	4.755	59.05	0.113	0.025	5.657	26.59	0.113	0.025	5.657	26.59
UGC	0.23	0.11	2.778	61.29	0.282	0.065	3.985	63.97	0.324	0.071	3.887	69.07
RC	1.877	0.107	2.791	91.29	4.569	0.11	4.932	165.70	3.089	0.072	4.948	157.14
WC	0.866	0.099	3.132	96.29	2.421	0.093	5.18	129.49	2.528	0.096	5.254	139.43

	1/9/2006			
	Fe (mgl^{-1})	**Al (mgl^{-1})**	**Mg (mgl^{-1})**	**True Colour**
DGC	3.194	0.239	1.507	247.72
UNG	1.347	0.346	1.889	228.30
NGC	0.523	0.306	3.023	170.89
UGC	0.833	0.26	2.639	189.52
RC	1.226	0.204	2.35	131.23
WC	1.496	0.349	2.149	221.26

APPENDIX XI: Descriptive Statistics Monthly Area Specific Discharge

Doctors Gate Clough Area Specific Discharge ($l^{s-1}.km^2$) Oct 2002 – Sept 2006

Doctors Gate Clough Area Specific Discharge Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	21	10	75.9	10.4	47.4	9.18	69.8	174
Nov-02	30	0	64.06	6.66	36.49	14.28	54.38	148.07
Dec-02	31	0	69.03	8.23	45.82	4.66	64.43	147.73
Jan-03	31	0	53.01	6.47	36	12.76	41.8	151
Feb-03	24	4	36.74	7.3	35.75	6.22	25.43	138.59
Mar-03	15	16	3.82	3.43	13.3	0	0	51.85
Apr-03	30	0	17.84	5.73	31.39	0.03	3.81	132.35
May-03	31	0	53.16	8.78	48.87	3.45	29.28	197.51
Jun-03	30	0	26.98	7.56	41.41	0	10.85	202.74
Jul-03	31	0	28.98	6.4	35.62	0	20.12	161.76
Aug-03	31	0	20.03	2.53	14.11	0	22.37	47.87
Sep-03	30	0	14.62	3.16	17.33	0	6.94	58.09
Doctors Gate Clough Area Specific Discharge Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	21.85	4.07	22.66	0	16.81	103.21
Nov-03	30	0	43.77	7.18	39.31	1.39	30.77	133.36
Dec-03	31	0	44.26	7.34	40.89	0.05	27.8	140.55
Jan-04	31	0	68.41	9.31	51.81	0.18	64.23	244.02
Feb-04	29	0	31.11	6.24	33.6	0	24.06	148.91
Mar-04	31	0	21.16	3.72	20.69	0	18.02	68.04
Apr-04	30	0	29.97	7.33	40.17	0	12.17	157.48
May-04	31	0	11.89	3.2	17.81	0	7.7	83.07
Jun-04	30	0	24.99	8.3	45.44	0	7.48	182.67
Jul-04	31	0	19.36	4.27	23.76	0	12.35	85.07
Aug-04	31	0	48.5	10.1	56.5	0	41	230.9
Sep-04	30	0	39.29	7.4	40.53	0	30.85	132.89
Doctors Gate Clough Area Specific Discharge Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	31	0	51.68	8.4	46.76	0	49.55	175.15
Nov-04	22	8	57.5	14.3	67	10.8	33.7	328.2
Dec-04	30	1	49.89	8.53	46.71	4.23	38.41	164.76
Jan-05	24	7	40.94	7.58	37.15	0.58	43.35	157.31
Feb-05	13	15	16.74	4.06	14.64	6.59	11.27	55.19
Mar-05	31	0	43.47	6.36	35.4	10.87	29.39	143.85
Apr-05	30	0	38.9	5.32	29.14	4.39	34.48	123.45
May-05	31	0	21.09	3.41	19	3.21	16.06	86.96
Jun-05	30	0	23.96	5.3	29.06	1.26	12.09	127.9
Jul-05	31	0	17.33	4.07	22.65	1.8	7.5	95.05
Aug-05	31	0	25.92	3.73	20.76	4.12	17.24	90.03
Sep-05	28	2	49.5	10.2	54	14.2	26.7	228.6
Doctors Gate Clough Area Specific Discharge Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	29	2	51.51	9.48	51.05	5.31	30.47	225.98
Nov-05	30	0	35.27	6.05	33.14	0	32.66	92.62
Dec-05	31	0	35.97	7.07	39.38	0	21.09	152.05
Jan-06	0	31						
Feb-06	0	28						
Mar-06	0	31						
Apr-06	14	16	48.49	8.06	30.15	32.56	34.06	122.74
May-06	31	0	50.43	6.84	38.08	13.53	31.78	162.17
Jun-06	30	0	10.35	1.02	5.6	1.8	13.13	21.09
Jul-06	31	0	13.27	1.68	9.35	5.31	12.29	51.27
Aug-06	31	0	64.2	7.84	43.64	21.22	58.69	163.21
Sep-06	29	1	40.59	5.32	28.63	15.63	28.71	126.08

Upper North Grain Area Specific Discharge ($l^{s-1}.km^2$) Oct 2002 – Sept 2006

Upper North Grain Area Specific Discharge Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	21	10	39.53	4.52	20.69	8.95	37.47	79.45
Nov-02	30	0	35.39	2.79	15.3	16.75	33.27	72.2
Dec-02	31	0	37.92	3.47	19.34	13.39	33.78	76.13
Jan-03	31	0	30.69	2.98	16.61	13.07	25.49	74.55
Feb-03	28	0	22.19	2.73	14.44	10.56	15.92	66.84
Mar-03	31	0	20.52	2.57	14.32	8.85	14.83	77.67
Apr-03	30	0	13.2	2.31	12.63	4.6	8.82	57.48
May-03	31	0	28.47	3.58	19.92	10.75	19.74	92.19
Jun-03	30	0	16.83	2.61	14.29	9.15	11.99	80.33
Jul-03	31	0	19.8	2.85	15.84	9.28	13.12	69.22
Aug-03	31	0	11.176	0.493	2.747	8.4	10.29	21.2
Sep-03	30	0	9.779	0.699	3.83	7.03	8.28	23.71
Upper North Grain Area Specific Discharge Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	16.98	2.29	12.76	6.73	10.51	58.47
Nov-03	30	0	37.44	3.22	17.65	15.14	33.26	77.08
Dec-03	31	0	41.65	3.04	16.9	23.73	35.41	81.96
Jan-04	31	0	54.31	3.56	19.85	29.42	50.6	118.41
Feb-04	29	0	36.84	2.81	15.12	21.48	33.41	84.87
Mar-04	31	0	31.06	1.75	9.76	20.5	28.8	55.54
Apr-04	30	0	37.26	3.15	17.26	23.03	31.17	90.93
May-04	31	0	23.28	1.74	9.71	14.81	19.16	56.96
Jun-04	30	0	25.61	4.3	23.57	10.23	15.29	109.44
Jul-04	31	0	28.4	1.99	11.1	14.93	25.48	59.64
Aug-04	31	0	37.69	4.28	23.82	14.91	30.45	115.98
Sep-04	30	0	29.99	3.22	17.62	11.71	26.83	69.88
Upper North Grain Area Specific Discharge Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	31	0	36.92	3.37	18.74	15.63	34.15	91.21
Nov-04	30	0	39.8	4.41	24.13	20.5	31.2	145.65
Dec-04	31	0	36.14	3.8	21.13	15.77	30.05	85.63
Jan-05	31	0	34.75	2.63	14.63	18.1	31.82	81.18
Feb-05	26	2	24.35	2.89	14.75	14.91	19.32	78.23
Mar-05	31	0	30.47	3.4	18.92	14.61	21.73	85.15
Apr-05	30	0	29.94	2.47	13.55	14.91	28.06	67.78
May-05	31	0	19.31	1.64	9.15	9.96	16.05	52.08
Jun-05	30	0	20.81	2.23	12.19	12.14	15.82	67.66
Jul-05	31	0	14.74	1.6	8.93	8.11	11.47	40.95
Aug-05	31	0	15.66	1.63	9.09	7.64	11.36	42.65
Sep-05	30	0	23.8	2.95	16.15	9.89	15.6	73.14
Upper North Grain Area Specific Discharge Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	31	0	32.64	4.06	22.61	16.45	23.52	113.92
Nov-05	30	0	32.75	3.26	17.85	11.29	28.08	66.58
Dec-05	31	0	41.17	3.75	20.86	19.25	33.34	90.4
Jan-06	31	0	30.91	2.82	15.68	16.65	24.14	70.52
Feb-06	28	0	33.56	2.98	15.76	16.18	28.84	66.92
Mar-06	27	4	45.26	4.34	22.58	25.41	30.86	112.24
Apr-06	30	0	31.2	1.38	7.55	26.41	28.41	52.26
May-06	31	0	43.59	3.63	20.19	26.91	34.8	100.22
Jun-06	30	0	25.311	0.395	2.164	20.67	24.75	30.3
Jul-06	31	0	21.709	0.598	3.327	18.76	20.67	33.39
Aug-06	31	0	44.57	3.82	21.25	21.88	40.39	98.47
Sep-06	27	3	32.54	3.67	19.08	14.9	28.85	71.98

Nether Gate Clough Area Specific Discharge ($l^{s-1}.km^2$)Oct 2002 – Sept 2006

Nether Gate Clough Area Specific Discharge Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	21	10	48.28	4.31	19.77	24.83	47.04	91.18
Nov-02	30	0	48.45	3.06	16.78	29.88	45.42	102.51
Dec-02	31	0	48.44	2.93	16.29	29.23	46.18	89.46
Jan-03	31	0	41.49	1.92	10.71	29.31	37.69	68.96
Feb-03	28	0	35.84	2.21	11.69	24.36	32.24	71.02
Mar-03	31	0	31.56	2.04	11.34	22.64	28.36	80.08
Apr-03	30	0	25.96	1.86	10.17	21.18	21.9	63.7
May-03	31	0	38.97	2.57	14.33	26.25	33.3	87.88
Jun-03	30	0	29	1.9	10.38	24.7	26.29	78.73
Jul-03	31	0	36	2.47	13.75	27.33	30.48	82.13
Aug-03	31	0	31.174	0.375	2.087	29.22	30.43	38.12
Sep-03	30	0	28.997	0.206	1.129	27.84	28.91	33.59
Nether Gate Clough Area Specific Discharge Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	33.48	1.4	7.77	27.9	30.19	66.7
Nov-03	30	0	43.98	2.58	14.13	27.2	41.76	87.14
Dec-03	31	0	49.22	2.87	16	30.06	44.44	91.11
Jan-04	31	0	59.03	3.62	20.14	36.06	51.41	124.54
Feb-04	29	0	42.9	2.82	15.2	28.57	37.54	94.58
Mar-04	27	4	36.72	1.78	9.26	28.16	32.66	57.66
Apr-04	16	14	44.48	2.77	11.06	35.47	39.45	73.36
May-04	31	0	35.36	1.26	6.99	30.42	32.69	63.92
Jun-04	30	0	38.26	3.34	18.32	27.42	30.5	101.49
Jul-04	31	0	38.183	0.862	4.802	32.97	36.26	49.57
Aug-04	31	0	50.9	3.44	19.17	32.52	47.15	126.82
Sep-04	30	0	43.24	2.19	12.02	31.46	38.4	77.16
Nether Gate Clough Area Specific Discharge Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	31	0	48.41	2.31	12.89	34.03	44.9	83.9
Nov-04	30	0	51.46	3.61	19.76	37.47	46.83	144.75
Dec-04	23	8	44.52	2.84	13.62	31.89	37.32	82.02
Jan-05	28	3	39.38	2.09	11.05	29.85	35.83	79.59
Feb-05	28	0	36.72	2.75	14.56	28.56	31.57	98.64
Mar-05	31	0	35.42	1.65	9.19	27.24	32.07	66.12
Apr-05	30	0	34.84	1.24	6.77	28.25	32.72	53.53
May-05	31	0	30.34	1.04	5.76	24.91	30.06	52.53
Jun-05	30	0	38.97	1.5	8.21	33.18	35.18	72.07
Jul-05	31	0	33.416	0.808	4.499	29.22	32.23	49.51
Aug-05	31	0	31.818	0.938	5.224	28.56	30.68	57.73
Sep-05	30	0	37.29	1.67	9.15	29.53	33.84	66.26
Nether Gate Clough Area Specific Discharge Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	31	0	53.4	5.51	30.71	35.18	43.17	187.26
Nov-05	30	0	40.56	2.34	12.83	28.56	35.91	70.69
Dec-05	31	0	40.64	2.13	11.86	29.22	36.14	68.43
Jan-06	31	0	34.73	1.41	7.85	28.56	31.53	57.91
Feb-06	28	0	37.37	1.92	10.14	26.73	34.19	57.66
Mar-06	18	13	42.93	3.33	14.14	28.98	39.01	83.65
Apr-06	15	15	40.34	2.25	8.73	30.19	39.39	59.22
May-06	30	1	40.35	2.69	14.74	27.87	34.35	80.01
Jun-06	30	0	28.577	0.378	2.073	25.92	28.6	32.84
Jul-06	31	0	25.471	0.247	1.375	24.14	24.6	30.33
Aug-06	31	0	38.62	2.52	14.05	26.58	33.44	77.87
Sep-06	27	3	45.66	2.78	14.47	28.09	45.35	76.29

Upper Gate Clough Area Specific Discharge ($l^{s-1}.km^2$) Oct 2002 – Sept 2006

Upper Gate Clough Area Specific Discharge Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	21	10	54.84	4.89	22.4	26.59	51.1	98.34
Nov-02	30	0	53.66	3.45	18.89	31.77	51.21	111.91
Dec-02	31	0	52.96	3.59	19.99	28.29	48.23	100.49
Jan-03	31	0	36.46	2.79	15.53	18.47	30.78	76.74
Feb-03	28	0	28.2	3.21	16.96	14.04	21.97	79.73
Mar-03	31	0	27.68	2.47	13.74	19.2	23.87	92.46
Apr-03	30	0	23.7	2.47	13.51	15.88	18.64	78.1
May-03	31	0	35.13	3.35	18.64	20.15	25.72	98.39
Jun-03	30	0	21.7	2.49	13.64	13.74	17.46	82.98
Jul-03	24	7	21.2	2	9.81	14.04	18.12	58.13
Aug-03	27	4	14.851	0.237	1.232	13.06	15.22	16.36
Sep-03	29	1	13.494	0.717	3.861	7.65	13.06	26.59
Upper Gate Clough Area Specific Discharge Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	26	5	20.05	2.44	12.46	11.77	14.15	62.01
Nov-03	30	0	36.74	3.15	17.25	16.99	32.34	78.85
Dec-03	31	0	41.87	3.11	17.31	23.1	33.53	79.24
Jan-04	18	13	47.14	3.64	15.43	21.51	44.89	74.17
Feb-04	29	0	34.74	3.96	21.31	9.12	28.32	88.79
Mar-04	31	0	22.2	1.95	10.85	9.12	20.42	44.13
Apr-04	30	0	26.61	3.36	18.4	11.85	20.39	91.28
May-04	31	0	27.73	1.43	7.98	20.92	28.29	60.95
Jun-04	19	11	35.92	4.59	20.01	16.99	28.77	83.08
Jul-04	31	0	22.67	1.56	8.67	13.06	18.74	44.75
Aug-04	31	0	40.69	3.74	20.82	13.06	36.77	120.12
Sep-04	19	11	22.34	3.12	13.62	1.71	19.7	48.42
Upper Gate Clough Area Specific Discharge Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	31	0	30.67	3.36	18.71	8.75	24.4	83.27
Nov-04	8	22	30.26	3.92	11.08	18.99	26.82	50.42
Dec-04	31	0	33.43	3.51	19.56	16.19	22.98	81.63
Jan-05	31	0	31.16	3.07	17.09	10.15	27.72	88.82
Feb-05	1	27	9.26	*	*	9.26	9.26	9.26
Mar-05	23	8	24.39	3.76	18.02	6.2	19.3	78.55
Apr-05	26	4	22.7	2.85	14.55	2.91	19.05	61.63
May-05	8	23	15.59	5.11	14.45	0.85	12.35	45.34
Jun-05	29	1	14.98	2.46	13.24	6.71	9.77	70.48
Jul-05	28	3	16.92	1.18	6.25	7.43	15.45	40.19
Aug-05	31	0	18.22	1.47	8.16	11.58	16.99	54.3
Sep-05	30	0	25.18	3.58	19.63	11.22	15	83
Upper Gate Clough Area Specific Discharge Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	30	1	45.09	5.12	28.03	22.42	35.78	147.94
Nov-05	30	0	41.59	4.14	22.7	18.48	32.52	85.64
Dec-05	31	0	42.79	5.34	29.72	18.64	30.63	132.21
Jan-06	28	3	26.78	4.07	21.55	11.76	18.96	90.61
Feb-06	7	21	22.81	6.23	16.48	11.06	13.73	50.52
Mar-06	21	10	49.68	8	36.68	17.23	39.45	152.87
Apr-06	29	1	28.3	2.63	14.15	12.05	27.22	62.88
May-06	31	0	30.76	4.17	23.19	8.44	21.55	93.13
Jun-06	30	0	8.377	0.77	4.219	4.21	5.68	15.58
Jul-06	29	2	6.76	0.833	4.484	2.43	5.15	26.08
Aug-06	31	0	36.46	5.59	31.13	13.55	24.27	140.7
Sep-06	30	0	31.57	2.72	14.88	18.46	27.21	68.44

Red Clough Area Specific Discharge ($l^{s-1}.km^2$) Oct 2002 – Sept 2006

Red Clough Area Specific Discharge Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	26	5	36.16	5.5	28.05	0	36.41	96.53
Nov-02	30	0	41.06	4.08	22.34	12.34	39.14	101.18
Dec-02	31	0	41.02	4.58	25.51	5.22	36.4	90.21
Jan-03	31	0	33.81	3.86	21.5	4.04	30.27	85.48
Feb-03	28	0	31.01	4.04	21.39	9.2	23.2	92.86
Mar-03	31	0	17	3.96	22.04	0	5.55	98.91
Apr-03	30	0	10.89	3.44	18.86	0	2.27	73.58
May-03	31	0	26.01	4.6	25.6	3.11	13.81	105.49
Jun-03	30	0	12.32	3.45	18.9	1.67	5.1	91.91
Jul-03	29	2	13.85	4.46	24.01	0.04	3.41	91.41
Aug-03	27	4	6.468	0.339	1.763	5.05	5.83	13.25
Sep-03	30	0	7.501	0.777	4.253	4.1	5.885	23.94
Red Clough Area Specific Discharge Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	16.29	2.84	15.8	4.53	8.82	71.95
Nov-03	30	0	38.7	3.93	21.55	11.92	35.91	92.82
Dec-03	31	0	39.69	4	22.29	12.23	33.42	87.14
Jan-04	31	0	61.99	4.71	26.24	32.66	57.25	154.09
Feb-04	29	0	41.81	3.16	17.04	24.8	38.07	101.19
Mar-04	31	0	37.04	1.89	10.53	23.09	36.86	65.41
Apr-04	30	0	43.54	3.79	20.76	25.65	36.31	106.54
May-04	31	0	27.92	2	11.15	18.32	23.44	64.75
Jun-04	29	1	31.74	4.41	23.75	13.1	24.71	133.19
Jul-04	31	0	38.17	2.13	11.86	22.77	35.16	62.83
Aug-04	31	0	40.72	5.32	29.65	10.92	35.67	160.83
Sep-04	30	0	29.2	3.8	20.81	5.04	27.31	81.52
Red Clough Area Specific Discharge Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	31	0	36.37	3.73	20.75	9.81	31.86	97.82
Nov-04	30	0	41.51	4.74	25.97	21.1	34.19	162.11
Dec-04	31	0	36.34	4.04	22.51	14.5	30.91	91.17
Jan-05	31	0	35.01	2.79	15.55	19	33.42	92.63
Feb-05	28	0	28.46	4.26	22.54	13.76	23.26	125.85
Mar-05	31	0	30.77	3.3	18.38	13.48	25.97	99.79
Apr-05	30	0	27.35	2.47	13.51	10.72	24.71	66.13
May-05	31	0	14.3	2.24	12.47	0.42	9.06	57.27
Jun-05	30	0	19.43	3.46	18.96	3.64	12.06	89.79
Jul-05	31	0	11.74	2.35	13.09	2.81	5.97	53.2
Aug-05	31	0	14.96	2.46	13.69	2.71	11.7	67.92
Sep-05	30	0	25.01	3.66	20.03	5.77	15.18	77.97
Red Clough Area Specific Discharge Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	31	0	38.56	4.67	25.98	15.75	34.4	133.22
Nov-05	30	0	40.32	3.21	17.56	18.52	35.38	75.81
Dec-05	31	0	44.17	3.88	21.6	22.12	37.32	105.18
Jan-06	31	0	32.4	2.65	14.75	16.4	28.64	73.12
Feb-06	28	0	35.01	3.33	17.62	15.51	30.63	75.22
Mar-06	31	0	47.67	4.63	25.79	18.09	39.06	147.43
Apr-06	30	0	34.09	2.92	15.98	14.58	31.95	74.95
May-06	31	0	32.01	4.02	22.38	10.22	23.36	101.3
Jun-06	30	0	10.396	0.459	2.513	5.75	10.08	16.64
Jul-06	31	0	7.149	0.971	5.404	2.84	5.64	29.04
Aug-06	31	0	31.63	4.5	25.08	7.76	27.54	105.52
Sep-06	29	1	42.34	2.87	15.45	18.24	50.99	69.96

Within Clough Area Specific Discharge ($l^{s-1}.km^2$) Oct 2002 – Sept 2006

Within Clough Area Specific Discharge Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	26	5	38.34	6.41	32.7	0	32.25	107.26
Nov-02	30	0	42.23	4.32	23.66	14.05	38.16	102.16
Dec-02	31	0	43.16	4.77	26.58	8.32	38.52	103.77
Jan-03	31	0	36.41	3.69	20.54	13.6	27.74	95.33
Feb-03	28	0	27.56	4.23	22.37	10.73	19.56	96.97
Mar-03	31	0	22.72	3.35	18.63	9.18	15.57	100.63
Apr-03	30	0	7.94	2.62	14.37	0	0	57.27
May-03	31	0	20.2	4.14	23.03	0	11.92	102.02
Jun-03	30	0	14.78	3.15	17.24	7.84	8.86	97.5
Jul-03	31	0	21.72	3.45	19.22	9.45	12.45	86.33
Aug-03	31	0	13.46	0.595	3.315	10.13	11.66	22.06
Sep-03	30	0	10.228	0.531	2.908	8.2	9.35	20.63
Within Clough Area Specific Discharge Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	16.36	2.17	12.1	8.19	10.26	61.32
Nov-03	30	0	33.26	3.05	16.69	13.38	31.91	86.38
Dec-03	31	0	37.98	2.66	14.79	22.01	33.66	72.43
Jan-04	31	0	47.19	3.63	20.19	26.73	41.2	116.97
Feb-04	29	0	23.98	3.93	21.17	9.16	11.01	89.47
Mar-04	31	0	16.49	1.42	7.91	8.45	14.11	37.97
Apr-04	30	0	25.65	3.05	16.73	12.11	18.99	79.6
May-04	31	0	15.28	1.18	6.59	9.01	12.94	35.99
Jun-04	30	0	20.5	4.65	25.46	2.26	11.32	118.29
Jul-04	31	0	14.27	1.38	7.66	5.27	11.91	31.02
Aug-04	31	0	27.78	4.98	27.72	0.79	24.24	134.73
Sep-04	30	0	17.34	3.34	18.3	0	13.57	61.85
Within Clough Area Specific Discharge Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	31	0	24.38	3.64	20.29	2.95	16.52	81.32
Nov-04	30	0	27.79	4.42	24.22	6.64	19.66	136.46
Dec-04	31	0	21.87	3.86	21.51	1.28	13.89	76.59
Jan-05	31	0	19.99	2.43	13.54	5.62	16.89	63.36
Feb-05	28	0	17.54	3.85	20.39	2.4	11.5	100.52
Mar-05	28	3	19.98	3.29	17.41	2.4	13.89	73.87
Apr-05	30	0	13.84	2.34	12.83	0	10.74	56.56
May-05	31	0	14.8	1.92	10.71	2.29	12.14	56.01
Jun-05	15	15	16.21	4.05	15.69	3.7	7.25	56.71
Jul-05	28	3	10.22	2.17	11.49	2.13	4.67	45.86
Aug-05	29	2	14.37	2.22	11.93	2.07	12.67	58.75
Sep-05	29	1	25.2	3.33	17.91	7.57	17.73	68.37
Within Clough Area Specific Discharge Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	31	0	31.86	4.97	27.69	9.93	20.9	124.36
Nov-05	30	0	43.08	2.99	16.39	27.07	36.35	81.19
Dec-05	31	0	45.02	3.69	20.55	27.19	37.55	108.5
Jan-06	23	8	39.22	2.93	14.03	25.32	33.73	71.23
Feb-06	21	7	36.52	3.04	13.95	22.37	32.53	61.99
Mar-06	31	0	37.71	4.08	22.7	15.36	29.63	117.94
Apr-06	30	0	24.24	2.5	13.68	8.62	19.68	62.7
May-06	29	2	24.67	3.54	19.07	3.59	21.38	75.88
Jun-06	29	1	7.163	0.566	3.046	1.28	5.62	12.59
Jul-06	31	0	3.45	1.05	5.83	0	1.32	29.68
Aug-06	26	5	25.51	4.24	21.61	7.22	19.25	92.41
Sep-06	18	12	15.63	4.04	17.16	6.69	10.03	79.49

APPENDIX XII: Descriptive Statistics Monthly DOC Flux

Doctors Gate Clough DOC Flux ($Ct.km^{-2}.yr^{-1}$) Oct 2002 – Sept 2006

Doctors Gate Clough DOC Flux Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**StDev**	**Minimum**	**Median**	**Maximum**
Oct-02	18	13	245.7	38.6	163.8	26.7	233.5	604.2
Nov-02	22	8	181.2	27.9	131	20.7	182.3	486.7
Dec-02	22	9	124.3	19.4	90.8	11.7	118.8	319
Jan-03	23	8	91.4	12.5	60	18.7	78	233
Feb-03	22	6	48.2	11.5	53.9	7.59	20.6	185.1
Mar-03	10	21	0.856	0.328	1.037	0	0.205	2.39
Apr-03	18	12	35	10.9	46.4	0.48	14.2	141.6
May-03	21	10	97.8	26.5	121.7	4.72	45.9	522.5
Jun-03	20	10	101.7	32.9	147.3	6.09	50.9	632.4
Jul-03	13	18	165.8	53.9	194.4	0	113.8	750.9
Aug-03	9	22	71.2	22.9	68.7	0	56.3	204.7
Sep-03	18	12	75.2	21	89	0	30.1	240.9
Doctors Gate Clough DOC Flux Oct 2003 - Sept 2004								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	22	9	66.9	10.7	50.4	0.5	59	200.3
Nov-03	24	6	90.6	18.4	90.3	2.71	61.6	368.4
Dec-03	25	6	99.1	20.6	102.9	0.1	63.9	362.1
Jan-04	19	12	121.7	17.4	75.9	0.71	109.9	244.7
Feb-04	23	5	78.8	21.5	103.2	0	37.6	444.7
Mar-04	20	11	18.31	4	17.89	0	15.35	49.76
Apr-04	14	16	45.4	14.5	54.4	0	13.9	159.7
May-04	18	13	18.79	5.75	24.39	0	17.56	88.34
Jun-04	22	8	53.2	24.8	116.5	0	8.44	522.7
Jul-04	20	11	66.1	17.5	78.2	0	39.8	253.9
Aug-04	15	16	234	80.1	310.1	0	146	1018.5
Sep-04	15	15	160.2	28.2	109.4	12.9	160	426.4
Doctors Gate Clough DOC Flux Oct 2004 - Sept 2005								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	21	10	170.4	29.9	137.2	0	157.4	564.1
Nov-04	8	22	156.1	29.9	84.7	67.6	135.1	262
Dec-04	26	5	85.2	14.1	71.8	9.15	61.7	268.8
Jan-05	13	18	47.14	9.79	35.31	8.65	38.91	103.7
Feb-05	4	23	53.6	12.7	25.4	21.6	54.6	83.5
Mar-05	18	13	77.8	10.4	44.1	23.9	74.9	159.9
Apr-05	17	13	55.9	11.1	45.9	6.23	38.1	158
May-05	16	15	41.2	13.3	53	4.99	19.9	202.6
Jun-05	26	4	53.9	11.8	60	3.53	27.7	251.1
Jul-05	19	12	58.6	18.9	82.2	8.61	28.5	323.3
Aug-05	26	5	132.4	19	96.8	31.5	93.8	470
Sep-05	12	18	343	73.4	254.4	80.8	307.8	843.9
Doctors Gate Clough DOC Flux Oct 2005 - Sept 2006								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	17	14	197.3	42.2	173.9	64.4	114.6	768.4
Nov-05	18	12	97.6	28.8	122.2	0	60.4	367.2
Dec-05	19	12	78.8	17.5	76.5	8.49	44	273.5
Jan-06	0	31						
Feb-06	0	28						
Mar-06	0	31						
Apr-06	11	19	73.9	15	49.7	45.3	55.3	217.1
May-06	18	13	136.3	31.3	132.7	38.5	60.2	478.5
Jun-06	22	8	26.96	3.64	17.09	3.01	30.83	48.72
Jul-06	29	2	52.34	4.88	26.3	30.17	45.61	166.08
Aug-06	19	12	208.2	24.7	107.5	100.4	181.6	482.9
Sep-06	23	7	155.4	24.1	115.7	48.1	92.1	400.7

Upper North Grain DOC Flux ($Ct.km^{-2}.yr^{-1}$) Oct 2002 – Sept 2006

Upper North Grain DOC Flux Oct 2002 - Sept 2003								
Month	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	13	18	793	163	589	122	590	1916
Nov-02	24	6	628	83.2	407.5	141.9	615.7	1412.7
Dec-02	22	9	447.6	74.1	347.7	65.6	394.8	1175
Jan-03	19	12	426.4	59.2	258	48.6	428.3	994.7
Feb-03	23	5	158.5	35.1	168.2	33	90.3	672.5
Mar-03	16	15	204.2	51.9	207.7	24.9	131.3	743.1
Apr-03	30	0	79.1	21.6	118.5	13.6	33.9	488.7
May-03	31	0	368.7	70	389.5	45.1	237.9	1672.8
Jun-03	28	2	102.1	22.4	118.5	34.4	66.4	660.1
Jul-03	24	7	291.5	57.6	282.1	45.7	145.7	1060
Aug-03	13	18	98.2	25.4	91.6	42.1	60.8	368.9
Sep-03	30	0	81.37	8.06	44.14	43.08	64.74	216.88
Upper North Grain DOC Flux Oct 2003 - Sept 2004								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	28	3	177.9	43.6	231	47.4	63.4	990.2
Nov-03	22	8	617.2	93.6	438.8	93.7	581.7	1495.2
Dec-03	15	16	681	130	502	144	575	1808
Jan-04	20	11	751.8	63.6	284.6	276.5	786.9	1418.7
Feb-04	9	18	879	122	365	403	868	1602
Mar-04	22	9	259	33.1	155	107.1	217.5	667.8
Apr-04	24	6	319.3	54.4	266.6	120.9	216	1179.2
May-04	24	7	152.8	26.5	129.7	76.5	97.2	641.2
Jun-04	28	2	237.6	42.4	224.6	53.8	102.1	790.4
Jul-04	22	9	444.3	75.6	354.7	88.1	322	1340.8
Aug-04	17	14	960	183	755	161	721	3053
Sep-04	22	8	737	110	516	92.8	647	1809
Upper North Grain DOC Flux Oct 2004 - Sept 2005								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	24	7	836	109	533	131	773	2235
Nov-04	15	15	754	64.2	248.8	276.4	870.8	1097.3
Dec-04	19	12	417	57.3	249.9	137	363.7	944.2
Jan-05	19	12	339	35.2	153.5	147.3	332.9	662.2
Feb-05	15	12	340.6	64.9	251.2	122.6	228.4	1076.1
Mar-05	16	15	339.2	46.8	187.2	146.2	298.4	729.9
Apr-05	25	5	401.4	48.5	242.4	120.3	332.5	974.3
May-05	24	7	170.1	39.7	194.7	68.7	94.7	948
Jun-05	17	13	179.2	27.5	113.4	87.6	113.2	489
Jul-05	23	8	132.8	22	105.3	61.6	88.7	480.2
Aug-05	29	2	209.4	40.2	216.7	52.3	120.8	1087.2
Sep-05	16	14	641	144	575	115	448	2085
Upper North Grain DOC Flux Oct 2005 - Sept 2006								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	25	6	723	148	740	156	435	2776
Nov-05	19	11	796	150	652	70.5	796	1915
Dec-05	16	15	627	109	434	235	442	1524
Jan-06	15	16	344.8	56.2	217.7	135.7	276.8	895.8
Feb-06	7	21	267.1	40	105.9	186.5	241.7	494.9
Mar-06	13	18	314.3	90	324.6	47.9	134.3	900.9
Apr-06	17	13	266.9	46.7	192.6	130.7	174	719
May-06	29	2	657	116	626	119	351	2270
Jun-06	25	5	166.35	7.23	36.15	130.88	152.43	265.83
Jul-06	24	7	164.4	10.2	49.8	123.2	152.8	324
Aug-06	23	8	709	122	585	172	527	2139
Sep-06	11	19	435	165	548	119	233	1989

Nether Gate Clough DOC Flux ($Ct.km^{-2}.yr^{-1}$) Oct 2002 – Sept 2006

Nether Gate Clough DOC Flux Oct 2002 - Sept 2003								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	21	10	232.5	31.9	146.1	10.5	188.4	530.1
Nov-02	30	0	234.9	20.8	113.9	93.2	216.9	475.9
Dec-02	30	1	209.4	20	109.8	61.1	192.2	470.3
Jan-03	16	15	164	13.2	52.9	113.7	140.5	272.3
Feb-03	21	7	90.4	14.2	64.9	16.4	13.8	232.1
Mar-03	30	1	61.1	10.1	55.3	9.5	35.7	211
Apr-03	30	0	29.19	8.29	45.43	-0.95	11.16	203
May-03	29	2	127.2	21.8	117.2	22.6	83.6	528.6
Jun-03	27	3	35.95	6.56	34.08	12.02	19.76	145.97
Jul-03	27	4	116.4	24.7	128.5	13.4	43.6	413.3
Aug-03	21	10	22.61	3.29	15.08	10.5	17.17	76.19
Sep-03	22	8	15.02	2.02	9.45	9.45	11.94	46.86
Nether Gate Clough DOC Flux Oct 2003 - Sept 2004								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	24	7	43.8	10.3	50.6	7.92	16.6	189.7
Nov-03	23	7	170.6	21.6	103.4	35.1	158.5	407.5
Dec-03	27	4	179.8	24.9	129.1	46.4	141.8	522.7
Jan-04	25	6	220.3	19.4	97.1	74.5	207.6	508.3
Feb-04	26	0	150.1	19.9	101.5	51.8	112.7	446.1
Mar-04	17	14	93.66	8.21	33.83	48.14	93.95	163.36
Apr-04	16	14	131.3	18.8	75	58.1	108.2	331.4
May-04	22	9	30.51	6.68	31.35	2.75	22.81	118.26
Jun-04	16	14	85	42.9	171.6	7.37	14.4	680.6
Jul-04	12	19	87.2	17.4	60.3	30.3	60.2	197.8
Aug-04	27	4	325.4	48	249.6	25.3	280.9	1162.8
Sep-04	21	9	184.2	31	142.1	18.5	153	460.3
Nether Gate Clough DOC Flux Oct 2004 - Sept 2005								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	25	6	285.7	29.4	147.2	69.7	270.9	594.5
Nov-04	15	15	233.7	21.6	83.8	126.8	213.1	405
Dec-04	22	9	182	21	98.3	73.6	153.8	399.6
Jan-05	16	15	144.18	7.8	31.18	87.3	148.55	182.99
Feb-05	19	9	154.8	19.4	84.6	93.1	132.1	449.9
Mar-05	24	7	120.3	10.9	53.5	58.1	112.3	249.8
Apr-05	29	1	141.8	10.4	55.9	60.7	136.3	242.9
May-05	19	12	81.9	14	61	24.5	55	234
Jun-05	25	5	141.5	18.2	91.1	28.7	111.7	350
Jul-05	12	19	67.3	19.4	67.1	15.3	38.8	226
Aug-05	31	0	63.7	9.99	55.62	12.85	30.03	203.04
Sep-05	26	4	160.3	29.2	148.9	20.1	128.2	577.7
Nether Gate Clough DOC Flux Oct 2005 - Sept 2006								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	13	18	422	104	375	84.2	293	1360
Nov-05	24	6	169.3	20.5	100.3	53.1	147.1	351.4
Dec-05	22	9	189.9	14.7	69	118.3	172	375.2
Jan-06	28	3	127.4	13	68.8	46	106.4	278.1
Feb-06	15	13	131.5	15.7	60.9	60	127.3	264.7
Mar-06	10	21	131.1	28.2	89.3	55.1	83.4	317.6
Apr-06	13	17	147.9	20.9	75.4	59	135.7	310.3
May-06	22	9	103.4	20	94	18.9	47.6	298.2
Jun-06	25	5	23.08	2.36	11.79	11.75	18.24	57.88
Jul-06	31	0	13.63	1.61	8.96	8.03	11.41	55.61
Aug-06	31	0	102	22.2	123.4	1.2	23.5	412.9
Sep-06	10	20	197.7	33.6	106.4	83	196.3	367.6

Upper Gate Clough DOC Flux ($Ct.km^{-2}.yr^{-1}$) Oct 2002 – Sept 2006

Upper Gate Clough Oct DOC Flux 2002 - Sept 2003								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	18	13	354.9	56.3	238.8	79.8	271.2	878.6
Nov-02	28	2	429	42.5	224.6	143.9	429.5	1035.6
Dec-02	28	3	284.4	28.4	150.4	66	270.7	606
Jan-03	25	6	227.4	22.8	114.1	64.2	208.9	491.6
Feb-03	27	1	111.3	16.9	87.9	27.1	90.6	326.8
Mar-03	29	2	91.2	17.3	93.3	34.4	50.9	488.4
Apr-03	27	3	78.7	18.8	97.6	29.9	35.2	359.3
May-03	27	4	184.1	38.2	198.6	44.2	90.2	882.8
Jun-03	27	3	62.61	6.18	32.13	35.38	52.86	194.59
Jul-03	15	16	119.3	33.3	129.1	37.1	51.2	419
Aug-03	23	8	39.08	1.13	5.44	30.53	40.12	47.97
Sep-03	23	7	43.45	5.04	24.18	22.33	37	117.79
Upper Gate Clough DOC Flux Oct 2003 - Sept 2004								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	15	16	102.5	26.6	102.9	24.3	29	349.2
Nov-03	23	7	233.5	33.9	162.7	40.3	185.4	561
Dec-03	18	13	273.7	42.7	181.2	69.6	241.8	657
Jan-04	0	31						
Feb-04	22	6	232.3	45.2	211.8	35.5	118.8	699.8
Mar-04	20	11	79.5	14.4	64.6	25.9	61.1	285.1
Apr-04	16	14	125.2	32.8	131.3	28.1	91.1	535.5
May-04	15	16	110.6	15.5	60.2	62.7	72	248.7
Jun-04	18	12	138.5	30	127.4	45.6	94.2	506
Jul-04	29	2	142.9	20.2	108.8	40.4	88.7	395.8
Aug-04	23	8	436.9	64.4	308.7	38.5	354	1099.2
Sep-04	10	20	252.2	44.5	140.7	80	218.2	540.4
Upper Gate Clough DOC Flux Oct 2004 - Sept 2005								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	11	20	237.5	71.6	237.4	29.5	191.1	807.2
Nov-04	7	23	244.7	36.9	97.6	129.8	258.3	416.5
Dec-04	20	11	209	40.4	180.6	61.9	119.1	748.5
Jan-05	21	10	164.4	24.3	111.2	51.7	135.2	550.1
Feb-05	1	27	53.61			53.6	53.61	53.61
Mar-05	15	16	146.9	27.3	105.9	21.7	123.9	366
Apr-05	24	6	147.2	23.7	116	13.4	97.4	401.6
May-05	5	26	160.4	72.8	162.8	25.2	113.6	426.4
Jun-05	22	8	79.5	23.6	110.8	16.5	37	503.6
Jul-05	26	5	61.35	7.89	40.21	23.57	48.77	227.76
Aug-05	18	13	81.7	11.5	48.9	31.6	66.2	199.1
Sep-05	13	17	196.1	85.4	307.9	36.7	50.2	997.9
Upper Gate Clough DOC Flux Oct 2005 - Sept 2006								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	15	16	471	102	395	123	279	1590
Nov-05	24	6	294.9	50.2	246.2	60.7	195.5	776.8
Dec-05	22	9	243.7	32.7	153.6	87.5	175.8	686.5
Jan-06	19	12	165.2	44.3	193	31.5	99.7	640.9
Feb-06	3	25	59.8	16.1	27.9	39.1	48.7	91.6
Mar-06	3	28	134.1	16.3	28.2	117.2	118.6	166.7
Apr-06	10	20	160.6	29.9	94.4	67.2	137.3	377.4
May-06	26	5	251.2	53.6	273.3	10.3	120.1	975.9
Jun-06	30	0	23.22	2.06	11.3	11.73	15.51	46.94
Jul-06	29	2	22.16	2.95	15.87	8.74	17.97	94.63
Aug-06	30	1	175.5	39.9	218.7	22.1	71.1	842.7
Sep-06	12	18	278.5	59.1	204.6	55.8	296.8	591.8

Red Clough DOC Flux ($Ct.km^{-2}.yr^{-1}$) Oct 2002 – Sept 2006

Red Clough DOC Flux Oct 2002 - Sept 2003								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	25	6	171.3	30.4	151.9	0	161.1	628.4
Nov-02	26	4	250.5	33	168.3	42.3	248.9	701.9
Dec-02	11	20	109.2	30.3	100.5	12.1	88.5	347.8
Jan-03	4	27	137.3	61.8	123.5	62.6	82.5	321.7
Feb-03	27	1	81.4	13.9	72.1	19.2	39.3	252.4
Mar-03	31	0	46.7	12.6	70.1	0	12.6	337
Apr-03	30	0	32	11.3	61.8	0	6.11	218
May-03	29	2	125.3	28.5	153.3	7.35	60.6	660
Jun-03	18	12	62.9	24.3	103	3.94	17.7	393.9
Jul-03	23	8	79.3	26.5	127	0.19	22.6	471.9
Aug-03	24	7	39.11	3.24	15.86	26.69	33.38	98.02
Sep-03	30	0	46.75	5.09	27.88	23.23	37.04	132.14
Red Clough DOC Flux Oct 2003 - Sept 2004								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	77.5	13.1	72.8	24.8	39.4	300.7
Nov-03	9	21	88.8	26	78.1	35	47.9	245.4
Dec-03	24	7	167.9	27.6	135	30.9	133.7	532.1
Jan-04	15	16	273.1	23.2	89.9	134.9	282.9	462.4
Feb-04	23	6	180.7	33.3	159.6	46.8	112.7	659
Mar-04	20	11	119.5	11.6	52.1	63.4	109.1	294.6
Apr-04	23	7	152.5	19.1	91.7	67	129.4	469.4
May-04	22	9	114.1	12.1	57	37.3	106.4	297
Jun-04	28	2	156.4	23.3	123.3	48.6	118	670.9
Jul-04	17	14	261.6	29.1	119.9	140.1	217.8	503.8
Aug-04	28	3	435.9	62.4	330.4	61.5	394.4	1382.3
Sep-04	15	15	234.4	35.1	136.1	42.4	267.3	447.9
Red Clough DOC Flux Oct 2004 - Sept 2005								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	21	10	262.6	42.4	194.2	70.4	215.9	804.9
Nov-04	23	7	232.3	16.5	79	108.4	220.8	412.3
Dec-04	22	9	189.1	24.5	114.9	65.4	147.9	542.7
Jan-05	25	6	127.7	11.3	56.3	66.2	117.1	293.1
Feb-05	14	14	157.9	32.5	121.4	68.2	116.1	531.2
Mar-05	15	9	123.9	18.5	71.6	51.6	98.9	313.6
Apr-05	13	17	132.8	28	100.8	41.1	99.9	363.9
May-05	27	4	62.3	14.3	74.3	2.2	34.8	385.6
Jun-05	30	0	112.5	22	120.3	20.9	59.9	581.1
Jul-05	25	6	57.6	10.1	50.3	19.5	41.5	220.6
Aug-05	23	8	73.4	11.2	53.6	20.6	60.8	204.4
Sep-05	12	18	240.1	38.2	132.3	56.8	217.6	436.2
Red Clough DOC Flux Oct 2005 - Sept 2006								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	2	29	333	175	247	159	333	508
Nov-05	11	19	275.3	55.3	183.3	64.7	240.7	642.8
Dec-05	2	29	347	167	236	180	347	513
Jan-06	13	18	172.7	26.9	96.9	68.4	125.7	356.1
Feb-06	15	13	152	23.1	89.6	50	101.9	315.7
Mar-06	15	16	180.2	33.3	129.1	43.3	152.7	438.7
Apr-06	18	12	149.5	23.4	99.2	65	107.9	366.3
May-06	31	0	191.5	31.3	174.1	48.6	97.3	791.1
Jun-06	30	0	56.35	2.63	14.39	31.9	53.48	111.61
Jul-06	31	0	42.3	4.36	24.29	17	35.83	116.82
Aug-06	24	7	144.9	23.9	117	51.3	107.9	512.2
Sep-06	9	21	300.9	36.4	109.3	92.7	309.6	442.7

Within Clough DOC Flux (Ct.km^{-2}.yr^{-1}) Oct 2002 – Sept 2006

Within Clough DOC Flux Oct 2002 - Sept 2003								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-02	24	7	666	134	657	0	472	2122
Nov-02	24	6	857	112	549	149	824	2169
Dec-02	21	10	588.1	84.7	388.2	50.5	544.5	1348.8
Jan-03	16	15	485.8	71.3	285.3	79.2	382.7	1088.1
Feb-03	28	0	244.8	52.9	280.1	32.1	111.5	971.2
Mar-03	31	0	148.8	28.1	156.6	29.2	72	613.7
Apr-03	30	0	47.8	17.8	97.5	0	0	343.2
May-03	30	1	306.8	74.4	407.5	0	154.9	1813
Jun-03	25	5	62.9	10.5	52.6	12.1	49.1	262.4
Jul-03	31	0	273.2	66.9	372.4	51.6	85.3	1538.3
Aug-03	31	0	82.12	6.62	36.84	49.83	74.37	138.62
Sep-03	30	0	80.22	6.08	33.28	49.37	68.3	174.47
Within Clough DOC Flux Oct 2003 - Sept 2004								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-03	31	0	125.6	25.6	142.8	39	55.8	702
Nov-03	25	5	446.8	56.3	281.4	78.6	426.6	1204.3
Dec-03	26	5	505.1	60.7	309.4	164	432.1	1405.2
Jan-04	20	11	607.9	49	219	291.8	538	1008.3
Feb-04	21	7	395	100	458	36.7	114	1640
Mar-04	12	19	110.4	16.4	56.6	50.2	97.4	215.8
Apr-04	16	14	184.3	32.5	130	68.4	145.8	573.5
May-04	23	8	66.2	22.4	107.6	19.7	29.1	501.1
Jun-04	29	1	222.4	68	366.2	17.3	72.2	1491.9
Jul-04	12	19	284.9	64	221.7	49	193.7	735.3
Aug-04	14	17	681	233	872	9.88	357	3146
Sep-04	12	18	385.8	97.4	337.4	0	310	979.3
Within Clough DOC Flux Oct 2004 - Sept 2005								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-04	21	10	624	128	586	28.2	442	2045
Nov-04	21	9	544.6	51.4	235.6	197.9	517.8	1044.1
Dec-04	27	4	355.9	70.3	365.5	13.1	159.4	1493
Jan-05	23	8	225.7	27.3	130.8	45.1	200.6	494.3
Feb-05	10	18	202.8	54.2	171.5	68.4	135.6	555.7
Mar-05	22	9	234.2	39.9	187.1	55.8	179.7	704.2
Apr-05	29	1	193.1	36.7	197.6	0	112.1	764.2
May-05	24	7	191.5	51.2	250.9	38.7	93.7	1126.1
Jun-05	7	23	428	130	345	52.5	396	1074
Jul-05	19	12	105.1	30.5	132.7	21.7	45.6	552.6
Aug-05	25	6	157.7	29.8	148.9	20.3	98.9	494.7
Sep-05	18	12	442	112	477	79.9	200	1886
Within Clough DOC Flux Oct 2005 - Sept 2006								
Variable	**N**	**N***	**Mean**	**SE Mean**	**St Dev**	**Minimum**	**Median**	**Maximum**
Oct-05	22	9	810	184	862	125	461	3046
Nov-05	10	20	1183	154	486	339	1339	1793
Dec-05	11	20	897	108	357	485	767	1522
Jan-06	15	16	550.9	79.5	307.9	241.4	370.7	1126.4
Feb-06	19	9	421.5	47.9	208.7	175.3	355.7	879.3
Mar-06	20	11	470.4	79.4	355	117.5	409.6	1178.2
Apr-06	19	11	274.9	44.9	195.9	68.2	226.6	735.8
May-06	20	11	263	68.7	307.2	24.9	128.1	1196.1
Jun-06	29	1	58.91	4.55	24.5	12.54	46.94	114.68
Jul-06	31	0	37.5	12.6	70.3	0	13.6	373
Aug-06	26	5	327.9	90.4	461.1	28.2	79.5	1965.5
Sep-06	18	12	178.2	46.3	196.5	63	106.6	781.8

APPENDIX XIII: Manual Dipwell Measurements (Water Table Depth)

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
29/04/2003	1	-1.041	-0.236	-1.302	-0.849	-1.375	-0.325
	2	-0.719	-0.539	-0.801	-1.214	-0.803	-0.419
	3	-0.118	-0.870	-1.212	-0.834	-1.022	-0.316
	4	-0.144	-0.965	-1.516	-0.495	-0.371	-0.07
	5	-0.718	-1.183	-0.746	-0.742	-1.557	-0.564
	6	-1.129	-0.909	-0.667	-1.244	-0.135	-0.244
	7	0.019	-0.775	-1.540	-1.269	-0.929	-1.287
	8	-0.495	-0.015	-0.969	-1.338	-0.061	0.095
	9	0.009	-0.074	-1.282	-1.400	-0.141	-1.547
	10	-1.068	-0.754	-1.158	-0.895	-1.403	-0.932
	11	-0.187	-1.011	-1.133	-1.305	-1.405	-0.585
	12	-1.056	-0.192	-0.289	-1.040	-0.031	-0.072
	13		-0.178	-1.289	-1.336	-0.742	-0.033
	14		-1.111	-1.517	-0.320	-1.113	-0.402
	15		-1.154	-0.255	-2.012	-0.141	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
28/05/2003	1	-0.354	-0.216	-1.304	-0.698	-0.881	-0.203
	2	-0.497	-0.184	-0.781	-0.737	-0.269	-0.424
	3	-0.231	-0.366	-0.298	-0.605	-0.383	-0.278
	4	-0.143	-0.306	-0.949	-0.480	-0.42	-0.018
	5	-0.463	-0.613	-0.466	-0.547	-1.125	-0.063
	6	-0.854	-0.979	-0.374	-0.694	-0.193	-0.15
	7	-0.017	-0.502	-0.743	-0.659	-0.552	-0.704
	8	-0.042	-0.034	-0.103	-1.350	-0.023	0.099
	9	-0.099	-0.161	-0.335	-1.081	-0.275	-0.909
	10	-0.682	-0.504	-0.768	-0.638	-0.838	-0.218
	11	-0.120	-0.390	-1.092	-0.964	-0.986	-0.368
	12	-0.422	-0.220	-0.880	-0.748	-0.095	-0.107
	13		-0.221	-0.778	-0.791	-0.09	-0.052
	14		-0.644	-1.097	-0.554	-0.612	-0.231
	15		-1.100	-0.143	-1.846	-0.086	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
24/06/2003	1	-0.171	-0.194	-0.633	-0.428	-0.556	-0.253
	2	-0.536	-0.146	-0.799	-0.315	-0.101	-0.328
	3	-0.235	-0.299	-0.463	-0.401	-0.038	-0.241
	4	-0.171	-0.273	-0.822	-0.106	-0.293	-0.118
	5	-0.441	-0.543	-0.483	-0.238	-0.744	-0.08
	6	-0.665	-0.915	-0.428	-0.391	-0.26	-0.195
	7	0.065	-0.388	-0.397	-0.297	-0.445	-0.509
	8	-0.093	-0.010	-0.082	-0.008	-0.001	0.018
	9	-0.102	-0.053	-0.207	-0.350	-0.201	-0.722
	10	-0.566	-0.522	-0.748	-0.366	-0.6	-0.296
	11	-0.112	-0.373	-0.749	-0.539	-0.7	-0.312
	12	-0.391	-0.210	-0.683	-0.376	-0.084	-0.103
	13		-0.203	-0.677	-0.470	-0.148	-0.065
	14		-0.627	-0.744	-0.012	-0.582	-0.27
	15		-1.081	-0.095	-1.343	-0.101	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
28/07/2003	1	-0.275	-0.237	-1.512	-0.364	-0.146	-0.273
	2	-0.550	-0.264	-0.793	-0.266	-0.098	-0.185
	3	-0.081	-0.338	-0.303	-0.400	-0.126	-0.125
	4	-0.150	-0.251	-0.519	-0.045	-0.27	-0.118
	5	-0.437	-0.596	-0.402	-0.276	-0.569	-0.082
	6	-0.534	-0.994	-0.423	-0.240	-0.181	-0.21
	7	-0.075	-0.020	-0.245	-0.279	-0.314	-0.459
	8	-0.085	0.015	-0.037	0.004	-0.043	-0.027
	9	-0.112	-0.080	-0.197	-0.361	-0.184	-0.643
	10	-0.448	-0.552	-0.442	-0.371	-0.369	-0.292
	11	-0.134	-0.324	-0.614	-0.544	-0.518	-0.295
	12	-0.390	-0.219	-0.574	-0.384	-0.082	-0.084
	13		-0.250	-0.632	-0.449	-0.191	-0.034
	14		-0.684	-0.432	-0.007	-0.448	-0.303
	15		-1.090	-0.115	-0.990	0.042	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
27/08/2003	1	-0.139	-0.312	-1.480	-0.251	-0.413	-0.330
	2	-0.611	-0.294	-0.768	-0.261	-0.129	-0.194
	3	-0.274	-0.384	-0.473	-0.420	-0.231	-0.165
	4	-0.310	-0.291	-0.469	-0.162	-0.270	-0.207
	5	-0.459	-0.628	-0.490	-0.352	-0.513	-0.135
	6	-0.531	-1.065	-0.443	-0.469	-0.348	-0.281
	7	-0.102	-0.217	-0.150	-0.364	-0.335	-0.474
	8	-0.122	-0.030	-0.012	-0.011	-0.075	-0.043
	9	-0.127	0.070	-0.262	-0.383	-0.201	-0.661
	10	-0.482	-0.636	-0.741	-0.473	-0.270	-0.332
	11	-0.189	-0.371	-0.567	-0.538	-0.507	-0.325
	12	-0.467	-0.316	-0.603	-0.434	-0.315	-0.075
	13		-0.265	-0.658	-0.505	-0.225	-0.085
	14		-0.706	-0.397	-0.211	-0.164	-0.357
	15		-1.097	-0.309	-0.947	-0.130	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
25/09/2003	1	-0.315	-0.333	-1.470	-0.418	-0.390	-0.264
	2	-0.655	-0.339	-0.815	-0.285	-0.072	-0.182
	3	-0.357	-0.413	-0.593	-0.452	-0.287	-0.168
	4	-0.155	-0.322	-0.480	-0.125	-0.306	-0.116
	5	-0.547	-0.683	-0.470	-0.265	-0.430	-0.102
	6	-0.406	-0.945	-0.485	-0.510	-0.280	-0.283
	7	-0.095	-0.325	-0.155	-0.344	-0.335	-0.477
	8	-0.205	-0.045	-0.025	0.007	-0.053	-0.001
	9	-0.120	-0.077	-0.010	-0.594	-0.192	-0.670
	10	-0.508	-0.585	-0.760	-0.530	-0.079	-0.345
	11	-0.173	-0.479	-0.597	-0.571	-0.545	-0.352
	12	-0.516	-0.332	-0.601	-0.440	-0.066	-0.072
	13		-0.282	-0.685	-0.522	-0.220	-0.051
	14		-0.616	-0.460	-0.118	-0.120	-0.316
	15		-1.143	-0.240	-0.839	-0.069	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
23/10/2003	1	-0.360	-0.296	-0.215	-0.372	-0.389	-0.219
	2	-0.647	-0.297	-0.055	-0.301	-0.159	-0.114
	3	-0.400	-0.388	-0.652	-0.442	-0.218	-0.154
	4	-0.193	-0.308	-0.451	-0.118	-0.316	-0.094
	5	-0.493	-0.622	-0.484	-0.239	-0.294	-0.072
	6	-0.613	-0.942	-0.457	-0.490	-0.208	-0.261
	7	-0.043	-0.183	-0.097	-0.342	-0.280	-0.442
	8	-0.128	-0.060	-0.012	-0.030	-0.036	-0.032
	9	-0.137	-0.144	-0.209	-0.406	-0.228	-0.668
	10	-0.460	-0.621	-0.768	-0.554	-0.122	-0.322
	11	-0.160	-0.434	-0.638	-0.601	-0.528	-0.327
	12	-0.445	-0.358	-0.562	-0.377	-0.105	-0.071
	13		-0.280	-0.690	-0.477	-0.192	-0.031
	14		-0.699	-0.299	-0.002	-0.150	-0.298
	15		-1.074	-0.189	-0.811	-0.106	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
21/11/2003	1	-0.336	-0.240	-1.435	-0.430	-0.308	-0.131
	2	-0.590	-0.157	-0.751	-0.240	0.000	-0.020
	3	-0.051	-0.343	-0.090	-0.372	-0.035	-0.160
	4	-0.115	-0.256	-0.055	-0.045	-0.227	-0.035
	5	-0.463	-0.542	-0.438	-0.248	-0.398	-0.055
	6	-0.434	-0.766	-0.392	-0.436	-0.090	-0.161
	7	0.040	-0.123	-0.128	-0.238	-0.287	-0.450
	8	-0.075	-0.013	0.022	0.025	0.011	-0.011
	9	-0.065	-0.071	-0.160	-0.259	-0.112	-0.641
	10	-0.432	-0.557	-0.673	-0.462	-0.092	-0.275
	11	-0.074	-0.220	-0.550	-0.522	-0.391	-0.255
	12	-0.348	-0.197	-0.298	-0.237	-0.014	0.007
	13		-0.214	-0.638	-0.482	-0.022	0.026
	14		-0.603	-0.058	-0.067	-0.037	-0.233
	15		-1.102	-0.069	-0.760	-0.055	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
23/01/2004	1	-0.374	-0.176	-1.375	-0.265	-0.201	-0.134
	2	-0.495	-0.145	-0.782	-0.211	0.019	-0.019
	3	-0.040	-0.142	-0.262	-0.348	-0.011	-0.165
	4	0.008	-0.205	0.005	-0.097	-0.162	0.062
	5	-0.390	-0.514	-0.410	-0.221	-0.274	-0.015
	6	-0.245	-1.091	-0.334	-0.328	-0.073	-0.102
	7	-0.010	-0.110	-0.130	-0.212	-0.225	-0.357
	8	-0.048	-0.002	0.057	0.020	-0.003	0.230
	9	-0.073	0.003	-0.142	-0.229	-0.008	-0.506
	10	-0.425	-0.490	-0.608	-0.325	-0.053	-0.220
	11	-0.074	-0.209	-0.508	-0.431	-0.286	-0.180
	12	-0.306	-0.182	-0.085	-0.242	-0.007	0.007
	13		-0.238	-0.485	-0.200	-0.005	-0.042
	14		-0.565	-0.095	-0.096	-0.026	-0.152
	15		-1.107	-0.081	-0.660	-0.029	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
24/02/2004	1	-0.316	-0.220	-1.483	-0.354	-0.162	-0.162
	2	-0.450	-0.181	-0.770	-0.190	-0.017	-0.046
	3	-0.082	-0.210	-0.244	-0.296	-0.021	-0.127
	4	-0.186	-0.233	-0.055	-0.106	-0.007	-0.022
	5	-0.364	-0.491	-0.390	-0.196	-0.073	-0.038
	6	-0.270	-0.970	-0.333	-0.249	-0.196	-0.084
	7	-0.090	-0.102	-0.103	-0.176	-0.210	-0.323
	8	-0.153	0.005	0.000	0.001	0.060	0.220
	9	-0.082	0.008	-0.123	-0.267	-0.109	-0.522
	10	-0.422	-0.523	-0.586	-0.405	-0.207	-0.296
	11	-0.067	-0.281	-0.495	-0.498	-0.289	-0.178
	12	-0.282	-0.163	-0.088	-0.280	-0.028	0.028
	13		-0.258	-0.412	-0.331	0.014	-0.092
	14		-0.597	-0.131	-0.099	-0.347	-0.152
	15		-1.085	-0.073	-0.651	-0.042	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
29/03/2004	1	-0.328	-0.220	-1.491	-0.348	-0.187	-0.167
	2	-0.461	-0.159	-0.766	-0.191	0.005	-0.075
	3	-0.053	-0.242	-0.207	-0.339	-0.013	-0.084
	4	-0.155	-0.155	-0.027	-0.082	-0.096	-0.053
	5	-0.387	-0.518	-0.389	-0.209	-0.118	-0.024
	6	-0.368	-0.945	-0.369	-0.301	-0.203	-0.121
	7	-0.011	-0.155	-0.097	-0.200	-0.193	-0.134
	8	-0.021	0.005	-0.135	0.019	-0.007	0.515
	9	-0.105	-0.228	-0.130	-0.185	-0.223	-0.458
	10	-0.392	-0.542	-0.661	-0.489	-0.255	-0.252
	11	-0.086	-0.362	-0.507	-0.498	-0.300	-0.216
	12	-0.310	-0.248	-0.066	-0.333	-0.049	-0.022
	13		-0.257	-0.453	-0.374	-0.031	-0.009
	14		-0.612	-0.102	-0.113	-0.329	-0.162
	15		-1.100	-0.078	-0.658	-0.056	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
30/04/2004	1	-0.351	-0.191	-1.501	-0.377	-0.151	-0.160
	2	-0.458	-0.160	-0.775	-0.180	-0.056	-0.048
	3	-0.081	-0.251	-0.141	-0.326	0.014	-0.102
	4	-0.126	-0.207	-0.022	-0.096	-0.223	-0.053
	5	-0.392	-0.521	-0.404	-0.210	-0.117	-0.018
	6	-0.347	-1.129	-0.390	-0.308	-0.217	-0.070
	7	0.018	-0.072	-0.131	-0.192	-0.158	-0.106
	8	-0.091	0.006	-0.015	-0.002	0.018	0.478
	9	-0.067	-0.099	0.052	-0.210	-0.165	-0.375
	10	-0.378	-0.545	-0.437	-0.404	-0.238	-0.250
	11	-0.040	-0.286	-0.490	-0.515	-0.143	-0.231
	12	-0.258	-0.167	-0.090	-0.357	-0.022	-0.079
	13		-0.266	-0.441	-0.390	-0.034	-0.035
	14		-0.600	-0.122	-0.113	-0.406	-0.275
	15		-1.083	-0.046	-0.657	-0.052	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
26/05/2004	1	-0.375	-0.188	-1.107	-0.331	-0.143	-0.239
	2	-0.458	-0.236	-0.766	-0.152	-0.146	-0.149
	3	-0.120	-0.278	-0.299	-0.323	-0.079	-0.123
	4	-0.207	-0.222	-0.089	-0.105	-0.138	-0.116
	5	-0.398	-0.545	-0.401	-0.236	-0.140	-0.133
	6	-0.351	-1.110	-0.384	-0.318	-0.275	-0.117
	7	-0.184	-0.193	-0.078	-0.237	-0.216	-0.085
	8	-0.175	-0.013	-0.115	-0.004	-0.018	
	9	-0.142	-0.278	-0.140	-0.238	-0.251	-0.340
	10	-0.367	-0.556	-0.613	-0.443	-0.280	-0.377
	11	-0.097	-0.335	-0.492	-0.491	-0.220	-0.296
	12	-0.305	-0.342	-0.144	-0.328	-0.126	-0.133
	13		-0.266	-0.462	-0.370	-0.147	-0.094
	14		-0.628	-0.236	-0.164	-0.447	-0.232
	15		-1.079	-0.184	-0.617	-0.256	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
05/07/2004	1	-0.387	-0.116	-1.467	-0.368	-0.296	-0.165
	2	-0.518	-0.133	-0.789	-0.200	-0.017	-0.103
	3	-0.043	-0.309	-0.243	-0.376	-0.015	-0.142
	4	-0.115	-0.238	-0.041	-0.070	-0.060	-0.061
	5	-0.377	-0.562	-0.449	-0.211	-0.095	-0.088
	6	-0.305	-1.148	-0.418	-0.321	-0.164	-0.234
	7	-0.004	-0.111	-0.131	-0.066	-0.162	-0.108
	8	-0.033	0.002	0.002	0.005	0.018	0.505
	9	-0.070	-0.091	-0.128	-0.153	-0.165	-0.360
	10	-0.397	-0.573	-0.667	-0.401	-0.120	-0.171
	11	-0.063	-0.330	-0.542	-0.514	-0.172	-0.313
	12	-0.244	-0.160	-0.068	-0.362	-0.027	-0.076
	13		-0.203	-0.497	-0.441	-0.020	-0.032
	14		-0.513	-0.065	-0.048	-0.169	-0.181
	15		-1.090		-0.640	-0.002	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
27/07/2004	1	-0.373	-0.189	-1.505	-0.380	-0.311	-0.209
	2	-0.544	-0.182	-0.844	-0.205	-0.004	-0.095
	3	-0.087	-0.317	-0.304	-0.358	0.006	-0.124
	4	-0.146	-0.228	-0.135	-0.115	-0.081	-0.084
	5	-0.304	-0.567	-0.402	-0.226	-0.065	-0.025
	6	-0.238	-1.127	-0.396	-0.292	-0.222	-0.238
	7	-0.036	-0.192	-0.157	-0.082	-0.228	-0.185
	8	-0.116	-0.007	-0.019	0.026	-0.006	0.510
	9	-0.112	-0.133	-0.155	-0.172	-0.300	-0.328
	10	-0.432	-0.598	-0.691	-0.454	-0.118	-0.173
	11	-0.065	-0.394	-0.491	-0.529	-0.231	-0.134
	12	-0.258	-0.200	-0.105	-0.363	-0.047	-0.061
	13		-0.240	-0.486	-0.440	-0.015	-0.016
	14		-0.510	-0.087	-0.100	-0.297	-0.153
	15		-0.748		-0.668	0.008	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
03/09/2004	1	-0.365	-0.010	-1.410	-0.308	-0.198	-0.155
	2	-0.470	-0.125	-0.890	-0.140	-0.047	-0.093
	3	0.010	-0.131	-0.285	-0.170	0.005	-0.107
	4	-0.150	-0.200	-0.573	-0.054	-0.070	-0.082
	5	-0.322	-0.477	-0.230	-0.163	-0.031	-0.015
	6	-0.159	-1.088	-0.457	-0.240	-0.110	-0.150
	7	0.018	-0.140	-0.090	-0.100	-0.208	-0.050
	8	0.015	0.015	0.035	0.020	0.020	0.380
	9	-0.220	-0.168	-0.090	-0.096	-0.159	-0.381
	10	-0.371	-0.469	-0.180	-0.355	-0.175	-0.150
	11	-0.022	-0.225	-0.539	-0.310	-0.176	-0.230
	12	-0.150	-0.194	-0.060	-0.193	-0.127	-0.058
	13		-0.220	-0.637	-0.380	-0.065	-0.012
	14		-0.532	-0.090	-0.045	-0.373	-0.540
	15		-1.015		-0.592	0.080	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
01/10/2004	1	-0.162	-0.125	-1.490	-0.308	-0.216	-0.095
	2	-0.478	-0.115	-0.750	-0.113	-0.037	-0.065
	3	0.038	-0.188	-0.102	-0.251	0.005	-0.100
	4	-0.098	-0.205	-0.752	-0.148	-0.042	-0.080
	5	-0.382	-0.480	-0.185	-0.176	0.014	0.005
	6	-0.195	-1.085	-0.258	-0.237	-0.055	-0.100
	7	-0.005	-0.090	-0.050	-0.045	-0.206	-0.040
	8	0.035	0.005	0.050	0.030	0.040	0.395
	9	-0.050	-0.090	-0.100	-0.066	-0.095	-0.369
	10	-0.388	-0.467	-0.295	-0.348	-0.125	-0.102
	11	-0.038	-0.314	-0.661	-0.374	-0.049	-0.242
	12	-0.110	-0.160	-0.015	-0.247	-0.015	-0.025
	13		-0.195	-0.720	-0.260	0.035	0.025
	14		-0.517	-0.095	-0.008	-0.408	-0.610
	15		-1.062		-0.592	0.090	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
01/11/2004	1	-0.210	-0.140	-1.472	-0.293	-0.220	-0.083
	2	-0.470	-0.110	-0.765	-0.125	0.045	-0.042
	3	-0.020	-0.220	-0.100	-0.270	0.015	-0.035
	4	-0.105	-0.210	-0.040	-0.030	-0.020	-0.045
	5	-0.365	-0.490	-0.170	-0.140	-0.070	-0.080
	6	-0.245	-1.085	-0.180	-0.230	-0.066	-0.110
	7	0.005	-0.085	-0.065	-0.043	-0.168	-0.028
	8	-0.045	-0.005	0.045	-0.010	0.025	0.465
	9	-0.030	-0.140	-0.100	-0.132	-0.155	-0.252
	10	-0.385	-0.465	-0.327	-0.405	-0.200	-0.100
	11	-0.010	-0.200	-0.245	-0.367	-0.065	-0.210
	12	-0.070	-0.167	-0.035	-0.303	-0.012	0.013
	13		-0.215	-0.220	-0.314	0.015	0.005
	14		-0.480	-0.065	-0.020	-0.415	-0.118
	15		-1.075		-0.595	-0.008	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
01/12/2004	1	-0.060	-0.170	-1.495	-0.273	-0.223	-0.090
	2	-0.485	-0.100	-0.805	-0.128	0.048	-0.088
	3	-0.050	-0.210	-0.085	-0.280	0.015	0.013
	4	-0.113	-0.200	-0.040	-0.044	-0.020	-0.033
	5	-0.368	-0.320	-0.175	-0.130	-0.081	-0.035
	6	-0.295	-1.100	-0.195	-0.120	-0.100	-0.115
	7	0.000	-0.195	0.080	-0.010	-0.148	0.005
	8	-0.080	0.005	0.105	-0.020	0.040	0.400
	9	-0.052	-0.110	-0.065	-0.081	-0.135	-0.354
	10	-0.390	-0.450	-0.140	-0.350	-0.190	-0.087
	11	-0.010	-0.212	-0.230	-0.309	-0.053	-0.186
	12	-0.045	-0.165	-0.030	-0.273	-0.005	0.005
	13		-0.215	-0.210	-0.340	-0.060	0.025
	14		-0.509	-0.070	-0.025	-0.405	-0.080
	15		-1.060		-0.525	0.102	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
01/02/2005	1	-0.020	-0.155	-1.375	-0.290	-0.205	-0.11
	2	-0.430	-0.110	-0.770	-0.135	0.030	-0.04
	3	-0.015	-0.145	-0.110	-0.290	0.020	-0.047
	4	-0.102	-0.200	-0.020	-0.015	-0.040	-0.035
	5	-0.316	-0.215	-0.155	-0.150	-0.145	-0.025
	6	-0.376	-1.130	-0.180	-0.230	-0.130	-0.095
	7	0.035	-0.085	0.055	-0.095	-0.183	-0.06
	8	-0.050	0.000	0.045	0.060	0.040	0.38
	9	-0.037	-0.250	-0.075	-0.101	-0.100	-0.25
	10	-0.312	-0.475	-0.160	-0.350	-0.210	-0.145
	11	-0.028	-0.297	-0.205	-0.395	-0.045	-0.195
	12	-0.060	-0.210	-0.025	-0.275	0.004	-0.03
	13		-0.210	-0.195	-0.225	-0.045	0
	14		-0.472	-0.025	0.010	-0.425	-0.11
	15		-1.075		-0.570	0.005	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
30/03/2005	1	-0.130	-0.170	-1.465	-0.405	-0.205	-0.125
	2	-0.400	-0.120	-0.770	-0.160	0.020	-0.045
	3	-0.015	-0.175	-0.195	-0.310	0.010	-0.057
	4	-0.102	-0.170	-0.015	-0.005	-0.065	-0.04
	5	-0.341	-0.350	-0.260	-0.140	-0.185	-0.015
	6	-0.416	-1.130	-0.225	-0.300	-0.245	-0.13
	7		-0.115	0.060	-0.110	-0.258	-0.07
	8	-0.050		0.055		0.000	0.37
	9	-0.030		-0.075	-0.121	-0.330	-0.285
	10	-0.325	-0.520	-0.210	-0.370	-0.240	-0.155
	11	0.085	-0.337	-0.260	-0.425	-0.100	-0.23
	12	-0.085	-0.290	-0.030	-0.295	-0.016	0
	13		-0.235	-0.245	-0.285	0.010	0.01
	14		-0.517	-0.060	0.000	-0.325	-0.125
	15		-1.085		-0.575	0.010	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
03/05/2005	1	-0.110	-0.172	-1.480	-0.295	-0.200	-0.132
	2	-0.400	-0.133	-0.745	-0.150	0.010	-0.052
	3	-0.030	-0.210	-0.160	-0.295	0.030	-0.075
	4	-0.073	-0.192	-0.015	0.040	-0.040	-0.045
	5	-0.360	-0.318	-0.250	-0.125	-0.180	-0.01
	6	-0.438	-1.070	-0.700	-0.410	-0.300	-0.12
	7	-0.010	-0.095	0.030	-0.058	-0.210	-0.015
	8	-0.070	0.015	0.055	-0.048	0.010	0.39
	9	-0.030	-0.095	-0.165	-0.116	-0.188	-0.26
	10	-0.335	-0.490	-0.165	-0.340	-0.260	-0.153
	11	0.025	-0.325	-0.280	-0.488	-0.045	-0.213
	12	-0.130	-0.180	-0.075	-0.273	0.008	-0.035
	13		-0.215	-0.220	-0.320	0.000	0
	14		-0.510	-0.090	-0.057	-0.433	-0.125
	15		-1.062		-0.568	0.018	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
01/06/2005	1	-0.100	-0.190		-0.315	-0.220	-0.19
	2	-0.410	-0.210		-0.160	-0.050	-0.115
	3	-0.075	-0.245		-0.315	0.020	-0.105
	4	-0.140	-0.200		0.010	-0.080	-0.1
	5	-0.370	-0.395		-0.180	-0.175	-0.02
	6	-0.450	-1.070		-0.325	-0.350	-0.17
	7	0.030	-0.125		-0.110	-0.220	-0.05
	8	-0.075	0.015		-0.030	-0.050	0.35
	9	-0.065	-0.205		-0.186	-0.075	-0.28
	10	-0.345	-0.520		-0.380	-0.250	-0.24
	11	-0.035	-0.375		-0.460	-0.095	-0.267
	12	-0.200	-0.225		-0.285	0.000	-0.04
	13		-0.225		-0.350	-0.070	-0.01
	14		-0.540		-0.045	-0.480	-0.2
	15		-1.060		-0.565	0.010	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
06/07/2005	1	-0.090	-0.165	-1.480	-0.335	-0.242	-0.2
	2	-0.430	-0.190	-0.755	-0.165	0.030	-0.115
	3	-0.010	-0.248	-0.120	-0.330	0.010	-0.115
	4	-0.100	-0.155	-0.030	-0.030	-0.090	-0.087
	5	-0.405	-0.390	-0.375	-0.190	-0.115	-0.05
	6	-0.455	-0.955	-0.260	-0.355	-0.025	-0.165
	7	0.015	-0.090	0.025	-0.115	-0.200	-0.075
	8	0.013	-0.002	0.060	-0.025	-0.010	0.38
	9	-0.142	-0.030	-0.160	-0.130	-0.105	-0.265
	10	-0.365	-0.500	-0.130	-0.340	-0.265	-0.2125
	11	-0.005	-0.315	-0.040	-0.380	-0.115	-0.295
	12	-0.240	-0.280	-0.030	-0.315	-0.107	-0.095
	13		-0.210	-0.335	-0.385	0.012	-0.035
	14		-0.440	-0.175	-0.165	-0.560	-0.195
	15		-1.065		-0.560	-0.025	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
04/08/2005	1	-0.105	-0.220	-1.475	-0.260	-0.285	-0.29
	2	-0.410	-0.260	-0.755	-0.205	-0.065	-0.145
	3	-0.080	-0.308	-0.295	-0.385	-0.020	-0.29
	4	-0.165	-0.110	-0.035	-0.110	-0.160	-0.113
	5	-0.425	-0.260	-0.245	-0.260	-0.185	-0.03
	6	-0.470	-0.970	-0.325	-0.395	-0.225	-0.225
	7	-0.030	-0.110	-0.055	-0.110	-0.215	-0.135
	8	-0.027	0.015	-0.045	-0.055	0.105	0.21
	9	-0.082	-0.240	-0.120	-0.240	-0.160	-0.315
	10	-0.405	-0.545	-0.165	-0.490	-0.100	-0.3025
	11	-0.060	-0.335	-0.140	-0.320	-0.210	-0.355
	12	-0.325	-0.270	-0.080	-0.300	-0.045	-0.155
	13		-0.230	-0.360	-0.425	-0.178	-0.06
	14		-0.490	-0.240	-0.170	-0.130	-0.24
	15		-1.085		-0.600	-0.115	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
06/09/2005	1	-0.215	-0.185	-1.470	-0.275	-0.305	-0.200
	2	-0.500	-0.205	-0.760	-0.205	-0.030	-0.115
	3	-0.070	-0.333	-0.290	-0.375	-0.005	-0.105
	4	-0.150	-0.115	0.000	-0.070	-0.075	-0.185
	5	-0.440	-0.465	-0.300	-0.220	-0.060	-0.080
	6	-0.305	-0.975	-0.305	-0.375	-0.160	-0.205
	7	-0.005	-0.120	-0.055	-0.120	-0.230	0.020
	8	-0.022	0.010	-0.010	-0.040	0.005	0.425
	9	-0.062	-0.130	-0.110	-0.200	-0.180	-0.305
	10	-0.425	-0.495	-0.235	-0.490	-0.095	-0.223
	11	-0.050	-0.340	-0.125	-0.400	-0.265	-0.340
	12	-0.270	-0.285	-0.080	-0.330	-0.020	-0.065
	13		-0.230	-0.390	-0.450	-0.123	-0.050
	14		-0.530	-0.175	-0.130	-0.180	-0.220
	15		-1.075		-0.620	-0.075	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
03/10/2005	1	-0.270	-0.107	-1.455	-0.105	-0.295	-0.130
	2	-0.512	-0.140	-0.755	-0.122	0.025	-0.090
	3	-0.038	-0.323	-0.240	-0.360	0.010	-0.080
	4	-0.102	-0.075	0.015	-0.040	-0.090	-0.170
	5	-0.437	-0.390	-0.245	-0.190	-0.030	-0.050
	6	-0.345	-0.975	-0.205	-0.305	-0.050	-0.160
	7	0.015	-0.090	0.005	-0.055	-0.190	-0.003
	8	0.032	0.000	0.060	-0.010	0.020	-0.425
	9	-0.012	-0.040	-0.095	-0.120	-0.150	-0.290
	10	-0.435	-0.470	-0.135	-0.350	-0.110	-0.158
	11	0.020	-0.235	-0.115	-0.430	-0.295	-0.270
	12	-0.240	-0.155	-0.025	-0.315	0.005	-0.050
	13		-0.197	-0.350	-0.455	0.002	-0.045
	14		-0.518	-0.080	-0.070	-0.320	-0.160
	15		-1.070	-0.057	-0.620	-0.040	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
07/11/2005	1	-0.185	-0.136	-1.453	-0.088	-0.273	-0.118
	2	-0.511	-0.128	-0.753	-0.104	0.023	-0.068
	3	-0.042	-0.298	-0.210	-0.280	0.020	-0.073
	4	-0.104	-0.078	0.018	-0.035	-0.098	-0.052
	5	-0.431	-0.320	-0.210	-0.180	-0.048	-0.025
	6	-0.371	-0.995	-0.175	-0.240	-0.105	-0.130
	7	0.018	-0.085	0.055	-0.050	-0.140	-0.001
	8	0.013	-0.008	0.050	0.015	0.040	0.413
	9	-0.076	-0.045	-0.088	-0.115	-0.120	-0.265
	10	-0.435	-0.465	-0.130	-0.345	-0.148	-0.140
	11	0.018	-0.245	-0.100	-0.358	-0.285	-0.240
	12	-0.343	-0.193	-0.008	-0.260	0.008	-0.018
	13		-0.204	-0.270	-0.383	-0.003	-0.020
	14		-0.534	-0.070	-0.045	-0.390	-0.148
	15		-1.068	-0.037	-0.555	-0.033	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
06/12/2005	1	-0.095	-0.165	-1.460	-0.055	-0.250	-0.09
	2	-0.510	-0.110	-0.750	-0.115	0.020	-0.055
	3	-0.040	-0.275	-0.190	-0.195	0.030	-0.06
	4	-0.100	-0.120	0.020	-0.030	-0.105	-0.045
	5	-0.415	-0.250	-0.185	-0.150	-0.065	
	6	-0.402	-1.155	-0.150	-0.165	-0.160	-0.1
	7	0.005	-0.080	0.120	-0.040	-0.090	-0.015
	8	-0.010	-0.015	0.015	0.030	0.060	0.4
	9	-0.143	-0.050	-0.085	-0.115	-0.090	-0.245
	10	-0.440	-0.465	-0.125	-0.340	-0.185	-0.13
	11	0.010	-0.250	-0.085	-0.275	-0.275	-0.21
	12	-0.445	-0.225	0.000	-0.200	0.010	0.01
	13		-0.205	-0.215	-0.295	-0.008	0
	14		-0.555	-0.065	0.015	-0.460	-0.135
	15		-1.065	-0.015	-0.495	-0.025	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
05/01/2006	1	-0.245	-0.143	-1.470	-0.125	-0.318	-0.128
	2	-0.514	-0.160	-0.760	-0.189	0.028	-0.123
	3	-0.026	-0.375	-0.310	-0.515	0.000	-0.083
	4	-0.094	-0.110	0.010	-0.050	-0.083	-0.060
	5	-0.439	-0.530	-0.325	-0.190	-0.013	
	6	-0.298	-1.075	-0.270	-0.425	0.005	-0.190
	7	-0.005	-0.100	-0.080	-0.060	-0.240	-0.019
	8	-0.001	0.005	0.055	-0.070	0.000	0.438
	9	-0.125	-0.030	-0.115	-0.135	-0.180	-0.320
	10	-0.440	-0.485	-0.145	-0.360	-0.073	-0.183
	11	0.020	-0.210	-0.145	-0.565	-0.305	-0.300
	12	-0.302	-0.075	-0.070	-0.420	0.003	-0.088
	13		-0.179	-0.535	-0.585	0.007	-0.075
	14		-0.491	-0.105	-0.085	-0.250	-0.173
	15		-1.075	-0.095	-0.755	-0.048	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
10/03/2006	1	-0.270	-0.190	-1.470	0.000	-0.210	-0.120
	2	-0.450	-0.050	-0.770	-0.160	0.010	0.007
	3	-0.010	-0.270	-0.260	-0.300	0.000	-0.075
	4	-0.085	-0.085	0.010	-0.028	-0.150	-0.035
	5	-0.380	-0.280	-0.205	-0.160	-0.070	0.000
	6	-0.440	-1.125	-0.100	-0.240	-0.080	-0.115
	7	0.005	-0.075	0.100		-0.120	
	8	0.045	-0.020	0.020		0.030	
	9	-0.020	-0.010	-0.085	-0.105	-0.385	-0.270
	10	-0.395	-0.490	-0.135	-0.350	-0.240	-0.045
	11	0.035	-0.245	-0.245	-0.450	-0.235	-0.225
	12	-0.295	-0.150	-0.020	-0.305	-0.170	0.005
	13		-0.175	-0.255	-0.050	0.015	0.005
	14		-0.405	-0.145	-0.050	-0.330	-0.120
	15		-1.080		-0.490	0.010	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
07/04/2006	1	-0.010	-0.160	-1.470	-0.040	-0.190	-0.120
	2	-0.430	-0.120	-0.760	-0.160	0.030	-0.043
	3	-0.035	-0.255	-0.230	-0.280	-0.060	-0.045
	4	-0.090	-0.175	0.000	-0.043	-0.120	-0.030
	5	-0.360	-0.320	-0.205	-0.140	-0.050	
	6	-0.440	-1.125	-0.200	-0.260	-0.300	-0.135
	7	-0.040	-0.090	0.120	-0.050	-0.170	0.005
	8	0.035	0.010	0.065	-0.020	-0.010	-0.375
	9	-0.020	0.020	-0.075	-0.135	-0.445	-0.260
	10	-0.365	-0.450	-0.135	-0.350	-0.230	-0.145
	11	-0.005	-0.275	-0.165	-0.450	-0.215	-0.185
	12	-0.055	-0.190	-0.050	-0.305	-0.010	0.000
	13		-0.190	-0.200	-0.170	-0.005	0.005
	14		-0.445	-0.085	-0.060	-0.400	-0.100
	15		-1.100	-0.035	-0.490	0.000	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
02/05/2006	1	-0.100	-0.180	-1.510	-0.145	-0.190	-0.160
	2	-0.415	-0.160	-0.765	-0.160	0.020	-0.078
	3	-0.060	-0.250	-0.235	-0.290	0.020	-0.065
	4	-0.110	-0.170	0.000	-0.051	-0.135	-0.060
	5	-0.365	-0.310	-0.250	-0.160	-0.090	
	6	-0.445	-1.125	-0.260	-0.290	-0.230	-0.160
	7	-0.040	-0.100	0.070	-0.060	-0.200	-0.220
	8	0.025	0.040	0.025	-0.040	0.030	0.340
	9	-0.040	-0.180	-0.090	-0.185	-0.155	-0.285
	10	-0.450	-0.490	-0.185	-0.405	-0.240	-0.215
	11	0.035	-0.290	-0.175	-0.450	-0.205	-0.210
	12	-0.045	-0.220	-0.060	-0.290	-0.005	-0.015
	13		-0.220	-0.245	-0.245	-0.003	0.005
	14		-0.475	-0.100	-0.090	-0.400	-0.160
	15		-1.070	-0.065	-0.475	0.000	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
07/06/2006	1	-0.204	-0.175	-1.470	-0.147	-0.200	-0.113
	2	-0.416	-0.214	-0.758	-0.194	-0.085	-0.091
	3	-0.053	-0.260	-0.305	-0.310	-0.042	-0.108
	4	-0.084	-0.209	-0.010	-0.123	-0.156	-0.080
	5	-0.375	-0.357	-0.243	-0.182	-0.069	
	6	-0.416	-0.988	-0.250	-0.302	-0.278	-0.170
	7	-0.050	-0.185	0.062	-0.123	-0.204	0.015
	8	-0.100	0.008	-0.070	-0.132	-0.006	0.365
	9	-0.095	-0.232	-0.120	-0.180	-0.190	-0.280
	10	-0.365	-0.488	-0.195	-0.400	-0.250	-0.195
	11	-0.050	-0.350	-0.115	-0.355	-0.235	-0.250
	12	-0.100	-0.297	-0.100	-0.300	-0.052	-0.090
	13		-0.239	-0.235	-0.328	-0.106	-0.060
	14		-0.486	-0.138	-0.139	-0.423	-0.200
	15		-1.092	-0.105	-0.505	-0.088	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
30/06/2006	1	-0.181	-0.217	-1.392	-0.190	-0.249	-0.305
	2	-0.442	-0.261	-0.741	-0.180	-0.225	-0.190
	3	-0.170	-0.32	-0.310	-0.341	-0.135	-0.141
	4	-0.120	-0.182	-0.030	-0.200	-0.200	-0.110
	5	-0.390	-0.434	-0.265	-0.230	-0.132	
	6	-0.462	-0.947	-0.335	-0.335	-0.311	-0.220
	7	-0.114	-0.217	-0.170	-0.245	-0.234	-0.158
	8	-0.141	-0.059	-0.110	-0.050	-0.030	
	9	-0.075	-0.23	-0.211	-0.190	-0.195	-0.325
	10	-0.389	-0.545	-0.300	-0.482	-0.115	-0.316
	11	-0.085	-0.349	-0.155	-0.365	-0.255	-0.332
	12	-0.271	-0.312	-0.125	-0.346	-0.182	-0.101
	13		-0.247	-0.330	-0.390	-0.210	-0.073
	14		-0.3	-0.270	-0.164	-0.165	-0.195
	15		-1.062	-0.290	-0.541	-0.095	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
31/07/2006	1	-0.237	-0.311	-1.442	-0.288	-0.320	-0.419
	2	-0.453	-0.338	-0.770	-0.277	-0.246	-0.302
	3	-0.287	-0.386	-0.495	-0.418	-0.219	-0.290
	4	-0.336	-0.305	-0.253	-0.285	-0.286	-0.310
	5	-0.465	-0.484	-0.432	-0.348	-0.279	
	6	-0.454	-1.110	-0.460	-0.435	-0.315	-0.305
	7	-0.290	-0.327	-0.290	-0.325	-0.279	-0.110
	8	-0.271	-0.045	-0.280	-0.054	-0.150	0.277
	9	-0.260	-0.346	-0.350	-0.362	-0.291	-0.416
	10	-0.431	-0.596	-0.439	-0.510	-0.370	-0.410
	11	-0.279	-0.454	-0.056	-0.395	-0.337	-0.433
	12	-0.446	-0.323	-0.235	-0.425	-0.300	-0.293
	13		-0.363	-0.205	-0.472	-0.346	-0.267
	14		-0.473	-0.370	-0.187	-0.216	-0.365
	15		-1.050	-0.441	-0.579	-0.335	

Date	Dipwell No.	DGC	UNG	NGC	UGC	RC	WC
06/09/2006	1	-0.090	-0.175	-1.460	-0.063	-0.225	-0.163
	2	-0.400	-0.097	-0.735	-0.100	0.010	-0.085
	3	-0.379	-0.295	-0.440	-0.092	-0.010	-0.055
	4	-0.110	-0.140	-0.345	-0.040	-0.170	-0.005
	5	-0.457	-0.225	-0.195	-0.155	-0.080	
	6	-0.430	-1.155	-0.193	-0.250	-0.115	-0.095
	7	0.025	-0.067	-0.075	-0.055	-0.200	
	8	0.010	0.030	0.025	0.000	0.020	0.344
	9	-0.070	-0.052	-0.090	-0.087	-0.132	-0.302
	10	-0.454	-0.265	-0.130	-0.370	-0.075	-0.095
	11	0.017	-0.295	-0.055	-0.273	-0.260	-0.223
	12	-0.065	-0.230	-0.010	-0.315	-0.015	-0.015
	13		-0.210	-0.132	-0.413	-0.005	-0.005
	14		-0.125	-0.045	0.020	-0.015	-0.115
	15		-1.054	-0.065	-0.590	-0.040	
Date	**Dipwell No.**	**DGC**	**UNG**	**NGC**	**UGC**	**RC**	**WC**
06/10/2006	1	-0.125	-0.163	-1.465	-0.025	-0.215	-0.115
	2	-0.450	-0.095	-0.740	-0.080	0.020	-0.075
	3	-0.470	0.253	-0.225	-0.225	0.030	-0.070
	4	-0.085	-0.037	-0.355	-0.035	-0.175	-0.055
	5	-0.435	-0.266	-0.080	-0.195	-0.042	
	6	-0.415	-0.100	-0.190	-0.265	-0.080	-0.130
	7	0.065	-0.064	-0.100	-0.025	-0.190	
	8	-0.012	-0.155	0.070	-0.070	-0.205	0.449
	9	-0.160	-0.392	-0.070	-0.015	-0.090	-0.286
	10	-0.465	-0.368	-0.120	-0.320	-0.050	-0.100
	11	0.025	-0.290	-0.115	-0.252	-0.085	-0.222
	12	-0.235	-0.410	-0.025	-0.300	-0.010	0.037
	13		-0.288	-0.285	-0.285	0.005	0.015
	14		-0.796	-0.020	-0.065	-0.125	-0.095
	15		-1.208	-0.045	-0.575	-0.005	