UNIVERSITY
of
GLASGOW

Department of Civil Engineering

Morphological Sustainability of Barrage Impoundments

By

Lindsay C. Beevers

Thesis submitted to the University of Glasgow

in Fulfilment of the

Degree of Doctor of Philosophy

Glasgow

United Kingdom

September 2003

Even the weariest river winds somewhere safely to sea...

Swinburne

To my parents

Acknowledgements

I would like to express my sincere gratitude to both Prof. Gareth Pender for his supervision, support and encouragement and Dr. William Sloan, my pastoral supervisor, for his guidance, enthusiasm and constructive criticism throughout the course of this research. The research was supported by EPSRC grant GR/M42299 and GR/M42305 and I am grateful for the chance that this gave me to pursue my interest in environmental sustainability and the effects of climate change.

The research was completed as part of a larger project, and as such I would like to thank the other project partners, Dr. Sue White and Dr. Fred Worrall for their help, in particular with the suspended sediment data. I would like to acknowledge Jenni McCulloch, and my colleagues at Durham University, for their assistance during the survey of the Tees. I am also very grateful to my colleagues at Glasgow University for their helpful discussions and encouragement, in particular Kevin McGinty, Dr. Herve Morvan, Dr. Graeme Forbes, Dr. Colin Davie and Dr Eliane Guiny.

I would like to say thank-you to: Dr Nicole Augustin for her assistance and enthusiasm during the climate change work, the advice provided by Dr. Hayley Fowler and Prof. Roger Bettess; and the assistance given by Kenneth McColl regarding anything remotely computational. Additionally I am indebted to the Environment Agency (EA), the British Atmospheric Data Centre (BADC), the Climate Impacts LINK Project, the Met. Office, and the National River Flow Archive (NRFA) for all the data that they provided for the Tees catchment.

No small effort went in to the completion of this thesis: several of my friends and family were particularly instrumental in keeping me motivated, so a sincere thanks to; Stephen Smith for his understanding, proof-reading abilities and patience, my parents for their support and Lucy O'Donovan, Iona McCauley, Jan Beevers, Paul Hunter and Gordon Asher.

Abstract

Barrages built in estuaries fundamentally alter the dynamics of the river with regard to both flow and sedimentation patterns. Therefore it is essential to ensure that these structures do not affect the sustainability of the systems in which they are built. In recent years there has been increased emphasis on assessing the effect of climate change on river flows and the impact that this has on watercourses. Therefore, to investigate morphological sustainability of barrage impoundments, the effect of climate change must be included.

An assessment of the morphological sustainability of the River Tees impoundment is presented. The predictions were completed using the 1-dimensional software package ISIS, which modelled flow and sediment movement within the impoundment. Fifty-year simulations were completed to predict the sediment distribution through the system under differing future scenarios.

A method is proposed for extending the flow boundary for the numerical model, which uses a generic statistical modelling technique. It uses the historical flow data recorded on the Tees and forward predicts the series based on its statistical properties. Firstly, the Markov Chain method was used to predict a 50 year flow series which assumes a stable climate. The predicted series showed good correlation with the measured series in terms of both statistical properties and structure. Secondly, the method was further developed to enable climate change predictions to be incorporated. This means that the generated series can be modified to directly account for the possible influence of climate change on discharge. This technique uses a Markov model fitted in the framework of a multinomial logit model, enabling catchment precipitation and temperature values to be linked to the discharge. Climate change predictions available for the period 2070 to 2100 were then used to create 50-year modified flow series for the River Tees under a medium\high and medium\low emissions scenario.

During the period of sediment monitoring on the Tees a change to the sediment supply was noticed as a result of the high flows experienced in October/November 2000. Unfortunately, it is unclear whether the sediment supply will return to its original levels or if, as a consequence of higher flows resulting from climate change, the supply will remain at present levels. Hence three different sediment rating curves were created from the field data to deal with this uncertainty; representing high, medium and low sediment supply conditions.

Using the data generated for the flow and sediment boundaries, simulations were undertaken to assess the morphological sustainability of the Tees impoundment. Simulations using a flow boundary, which assumed both a stable climate and a changed climate, as well as three different sediment supply options for each, were considered. The results show that the impoundment reaches a dynamic equilibrium during the modelled period, irrespective of the sediment supply. From this it is possible to state that the Tees Impoundment is morphologically sustainable over the next 50-80 years. Climate change, while increasing the sediment supply, actually appears to improve the sustainability of the impoundment with regards to sediment. The increased number of high flows cause more steep water surface slopes which re-entrain sediments and partially flush the system.

In conclusion this thesis presents an assessment of the morphological sustainability of the Tees impoundment under differing future climate scenarios for both the fluvial and sediment inputs. Within the course of the work a different technique for extending flow series assuming both a stable and changed climate has been proposed. It is hoped that these methods will be of use in future sustainability assessments; however further investigations into these methods would be beneficial.

Table of Contents

List of Figures

List of Tables

List of Notation

a,b	constants
A	area
A	initial motion parameter
b,B	channel top width
B	backward shift operator
c	coefficient of the sediment transport function
cdf	cumulative distribution function
cpd	cumulative probability distribution
C_{gt}	coefficient of calibration for gated weir
d	water depth
D	sediment diameter
d	number of differencing passes
D	matrix with eigenvalues down the diagonal
D_{gr}	dimensionless sediment diameter
E_t	errors or residuals
F_{gr}	particle mobility
f_e	expected frequency
f_o	observed frequency
g	gravitational acceleration
G	volumetric sediment transport rate
G_{gr}	dimensionless sediment transport
h	depth of flow
h_I^*	total afflux
h_g	height of gate
i,j	states
K	conveyance

K	calibration factor
K^*	total backwater coefficient
l, L	increments in space
n,m	steps
M	exponent of the sediment transport function
n	Mannings coefficient
N	number of members in a sample
p,P	probability
p	autoregressive parameters
P	matrix of probabilities
pdf	probability density function
pacf	partial correlation function
q	moving average parameters
Q	discharge
Q_s	sediment concentration
Q	quartile
r, R	increments in time
R^2	coefficient of determination
s	specific gravity
s	series of states
S_0	riverbed slope
S	water surface slope
S	matrix of eigenvectors
$\mathbf{S}^{-1}$	inverse matrix of eigenvectors
t	time
tr_{ij}	transition from state i to state j
T	turbidity
V_*	shear velocity
v, V	velocity

V_s	particle settling velocity
w	vector
W	width of flow
x, X	variable
x	distance
y, Y	variable
y	depth of water over weir
Y	predicted response
z	bed level
α	kinetic energy coefficient
α, β	constants
β	momentum correction factor
$\{\gamma_{\lambda 1i}\}_{i=1}^{k}$	eigenvector relating to the corresponding eigenvalue
$\{\gamma_{\lambda new i}\}_{i=1}^{k}$	new eigenvector relating to the corresponding eigenvalue
$\hat{\gamma}$	skew
η	transition component
θ	scale factor
θ	weighting factor
$\hat{\kappa}$	kurtosis
λ	eigenvalues
Λ	variable
μ	mean of a sample
ξ	mode of distribution
π	invariant probability distribution
ρ	density of water
σ	standard deviation
τ	bed shear stress

υ	kinematic viscosity of water
$\phi(B)$	polynomial in B of order p
χ^2	chi-square statistic
$\psi(B)$	polynomial in B of order q
∇	differencing operator

Subscripts, Superscripts

d	differencing passes
i, j	states
k	number of chosen states
l	increments in space
n	number in a series
p	autoregressive parameters
q	moving average parameters
r	increments in time
t	time

Abbreviations

AR	autoregressive model
ARMA	autoregressive moving average model
ARIMA	autoregressive integrated moving average model
BIC	Bayes Information Criterion
OD	ordnance datum
POT	peaks over threshold
TBM	temporary benchmark

Chapter 1: Introduction

1.0 Problem Statement

Any construction built in a river or watercourse fundamentally alters the flow dynamics around it. This then has a direct impact on the sediment movement and distribution in the same area. While the effect on velocity patterns can be seen almost immediately, the influence on sediment transport may take years to determine. At a time when environmental sustainability is considered important it is essential to investigate the long-term impacts of any proposed or existing structure in watercourses with regard to sedimentation. Changes to sediment regimes can cause structures to become obsolete as sedimentation problems impede the use for which they were originally intended. An example of this can be seen on the River Wansbeck, where a partial exclusion barrage was built in 1975 (Worrall & Burt, 1998). Over a period of years the impoundment has become full of sediment effectively preventing the majority of boating activities. By silting up, the barrage is no longer fulfilling the principal amenity purpose for which it was built.

Computer modelling of fluvial and estuarine environments can be a very useful tool for investigating issues such as flood risk and long-term sedimentation. However, to gain useful predictions these models require detailed upstream flow and sediment boundary information. Assessing morphological sustainability of fluvial or estuarine areas requires long-term investigation as sedimentation patterns and deposits can take many years to establish. Therefore a realistic long-term flow boundary is required if morphological sustainability is to be investigated using a computer model.

Historical flow records exist for most major UK rivers, measured over the years by the Environment Agency. Detailed records for each site usually span from around 1970 to the present, but can go as far back as 1950. The problem of how to extend these historical flow records, for the purpose of investigating long-term sediment movement, has been tackled in many different ways over the years. Hydraulic modellers have tended to approach the problem in a different way to stochastic modellers who are interested in reproducing the statistical structure of the series. For hydraulic modellers the boundary dilemma has been part of the overall long-term sediment modelling problem. Therefore, they have historically approached it in a simple way, more conducive to computer modelling purposes. One method employed by Otto (1999), Havis Alonso & King (1996) and Zeigler & Nisbet (1996) was to simply recycle the historical flow data recorded at the site. Short term modelling with a long-term interpolation (HR Wallingford, 1992(b); Annadale, 1992) is another popular method used extensively in industry when using high dimensional models. Other simple methods have included regime theory (Spearmanet al. 1996; Denniset al. 2000), trapping efficiency estimations (Carvalho, 1999; Siyamet al. 2001) and the flow exceedence curve method (Meadowcroftet al., 1992; HR Wallingford, 1988; Bettess, personal communication, 2001). Similarly, stochastic modellers have investigated this problem for years. The techniques developed tend to be complicated and detailed. Autoregressive moving average models (ARMA) and autoregressive integrated moving average models (ARIMA) (Salas & Sin, 1999; Abrahart & See, 2000; Montanariet al. 1999; Schreideret al.. 1997) have been popular solutions to the flow series extension problem.

From a computer modelling viewpoint there appears to be a need for a method that is simple and robust, but does not oversimplify the problem. It is essential that the flow boundary is realistic when modelling sedimentation issues. Issues such as seasonality, time between peaks and periods of low flow are important to the structure of the flow series and have implications on sediment distribution and retention within the modelled system. Thus, when creating an upstream boundary it is important to reproduce the statistical properties and structure of the historical series, so that sedimentation is properly represented within the model. However, the method must not become over complicated.

In addition, it is now increasingly necessary to consider the effects of climate change on water resources, especially when dealing with long-term investigations. Changes to flow regimes will influence sedimentation patterns; therefore it is important that long-term morphological sustainability investigations incorporate the effect of climate change on water resources. Historically, climate change has been modelled in a very detailed way using statistical or dynamical downscaling. These results are then used in broad scale catchment models to model the runoff reaching the river. To make this process faster it would be beneficial to incorporate climate change predictions directly when extending the historical flow series, thereby creating a modified flow series quickly that can be used to investigate the effect of climate change on sedimentation processes.

In summary, a method of predicting the impact of climate change on long-term river flows would aid the long-term assessment of morphological sustainability of structures within fluvial or estuarine environments. The method would allow historical flow series to be extended simply, but realistically, and would have the capability to incorporate climate change predictions into the solution. This method could then be a powerful tool for long-term morphological sustainability investigations completed using computer models and would provide a useful aid for assessing the effect of climate change on sedimentation.

1.1 Research Aims

This research was completed as part of a larger project set up to investigate the sustainability of managed barrage impoundments called the SIMBa project. The project partners at Durham and Cranfield Universities were interested in investigating different aspects of the overall sustainability of barrage impoundments. Figure 1.1 shows the structure of the project with Cranfield University investigating the sediment inputs into the impoundment and Durham University concentrating on the sustainability of the barrage with regard to water quality. The sediment and fluvial inputs to the impoundments, monitored and analysed by Cranfield University, became essential boundary conditions to the modelling section of the research carried out at Glasgow University. The work completed for this thesis aimed to investigate the long-term sustainability of barrage impoundments with regard to sedimentation.

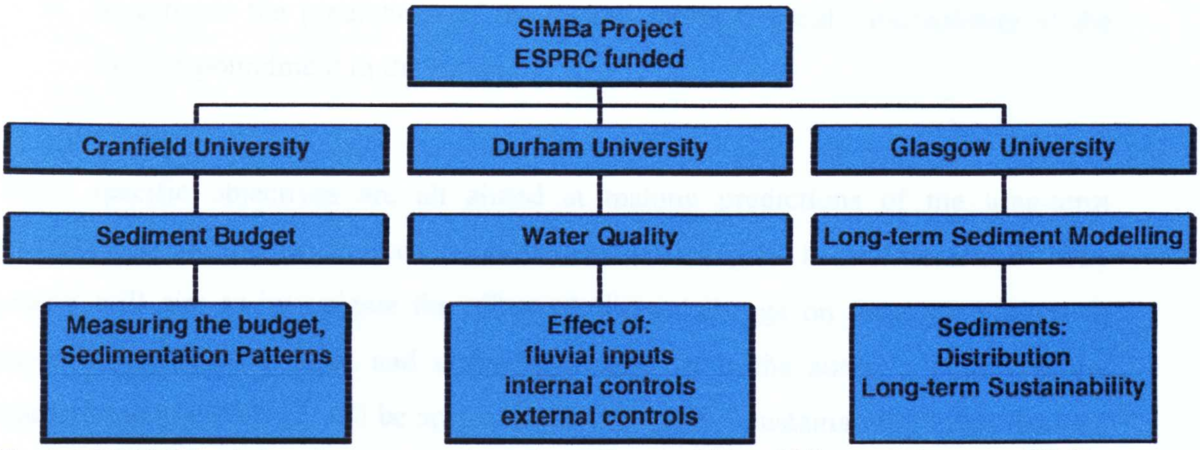


Fig. 1. 1 EPSRC funded project set up to investigate Sustainability of Managed Barrages (SIMBa Project)

Several barrage sites were used for the SIMBa project, however this research concentrated on the Tees barrage impoundment situated in the North East of England, UK. The barrage was built in 1994 and is a total exclusion barrage. The relative youth of the Tees barrage scheme means that an investigation into its long-term morphological sustainability is topical and interesting.

The focus of this project was to use a computer model to assess the morphological sustainability of the River Tees impoundment, within this several objectives were identified:

- Propose a method for extending historical flow series.
- Propose a technique that will allow the incorporation of climate change predictions into the extension of these flow boundaries.
- Using the flow series created assuming no climate change, predict long-term morphological change.

- Using the flow series created which accounts for climate change, predict long-term morphological change.
- Investigate the implications of a stable climate on sedimentation processes.
- Investigate the implications of climate change on sedimentation processes.
- Investigate the consequence of changed sediment supplies on sustainability.
- Investigate the predictions of the overall morphological sustainability of the Tees impoundment in the future.

These specific objectives are all aimed at making predictions of the long-term sustainability of the River Tees impoundment with regard to sedimentation. The project will aim to investigate the effect of climate change on these predictions in terms of both flow regime and sediment supply. It is the author's hope that the research completed here will be applicable to many other sustainability investigations and will not be site specific.

1.2 Numerical Work

All the computational work for this research has been completed using the 1-dimensional software package ISIS. This is a finite difference code, which models the water and sediment movement in river channels.

1.3 Layout of Thesis

This thesis contains seven chapters, which aim to describe the work completed. The following summarises the contents of each chapter.

Chapter 1 contains an introduction to the problem proposed along with an outline of the projects aims and objectives. In ***Chapter 2*** a literature review covering details on sustainability issues, the impact of barrages, climate change, numerical modelling and long-term sedimentation studies can be found. ***Chapter 3*** provides a description of the Tees catchment and details the data collection completed. This includes the topographical study of the impoundment and the sedimentation issues addressed in the research.

Chapter 4 describes the proposed method for extending flow series, firstly without accounting for climate change. This method is analysed statistically and then tested against other long-term sedimentation methods. Next a technique for extending and modifying flow series to account for climate change is proposed and the results of this method presented and analysed. In ***Chapter 5*** the details of the construction of the ISIS model of the impoundment are described. It explains the representation of the barrage, boundary conditions and the sediments within the model and shows the calibration of the model for both flow and sediment. It also provides details of the sensitivity test completed, which investigates the use of daily flows rather than hourly flows. ***Chapter 6*** presents the results of the long-term sediment modelling for the Tees impoundment. It details the results predicted for the impoundment under both a stable climate and assuming climate change with varying sediment supply scenarios. ***Chapter*** *7* discusses the overall conclusions from the research undertaken and provides some suggestions for further work. ***Appendix A*** contains details of an alternative method investigated to incorporate climate change, which was ultimately found to be a non-viable option, and finally ***Appendix B*** describes the gate rules used for the gated weir which represented the barrage in the ISIS model.

Chapter 2: Literature Review

2.0 Introduction

Estuarine barrages have been widely used in the UK, and indeed worldwide, as a method for controlling floods, generating power, regenerating urban areas and improving amenity. To ensure the ongoing sustainability of these structures it is crucial to understand their impact on patterns of sedimentation distribution and re-distribution in their impoundments. This chapter will present a summary of the work carried out to date on the investigation of estuarine barrages and their sustainability. In addition it will include, a historical overview of research to date on the effects of climate change on water resources, with particular reference to the sustainability of barrages.

This chapter will also review the methods available to examine the long-term effects of engineering works on fluvial and estuarine environments. It is split into two sections: one which examines how hydraulic models have been employed for post-construction monitoring and prediction, and the other which reviews the methods utilised for extending flow records for the upstream boundary condition for such long-term models.

2.1 The Impact of Barrages on Estuaries

Different countries define the word "barrage" in different ways. In the context of this thesis the term barrage is that defined by HR Wallingford (1999):

> "A barrage is a structure, built in an estuary, with the specific intention of preventing, or in some way modifying tidal propagation"

Barrages are built for many different reasons: for power generation (e.g. La Rance barrage in Brittany, France); flood control (e.g. the storm surge barriers on the Thames and in Hull); to improve water quality (like the proposed Venice tidal barriers (Berstein & Cecconi, 1996) and in the UK the Tees barrage, (Maskell & Barraclough, 1996)); water storage (such as the Morecambe Bay scheme which has been proposed but not built (HR Wallingford, 1999)); and, for urban regeneration and amenity purposes. There are many barrages in the UK that have been built to regenerate urban areas, for example those across the Tawe (1992), the Tees (1994) and more recently the Cardiff Bay Barrage.

Barrages that are constructed for urban regeneration generally impound water upstream creating stable conditions where water levels are held artificially high. These artificial lakes hide unsightly, but ecologically important, mud flats that are a common feature of tidal estuary areas and create pleasant waterside areas, which look similar to high tide conditions pre-barrage and attract developers. Barrages built for regeneration, or amenity purposes come in two different types; being either partial exclusion or total exclusion barrages. Fig. 2. 1 demonstrates the difference between the two types; partial exclusion barrages allow the tide to propagate upstream in overtopping cycles, thus allowing the mixing of fresh and saline water (for example the Wansbeck barrage permits tidal intrusion upstream for 10 to 16 days a month (Worrall, Wooff & McIntyre, 1998)), whereas total exclusion barrages allow no saline intrusion upstream, thereby creating a freshwater impoundment upstream. The Tees barrage is a total exclusion barrage.

Barrage construction fundamentally changes the dynamics within estuaries in terms of hydraulics, having implications on the sediment regime and on the water quality throughout the estuary. These implications necessitate studies to investigate the effects that barrages have on the original estuarine system. The review of this information is split into two corresponding sections as this thesis is interested in the long-term effect of the barrage in the estuary in terms of both the hydraulic and sediment regime.

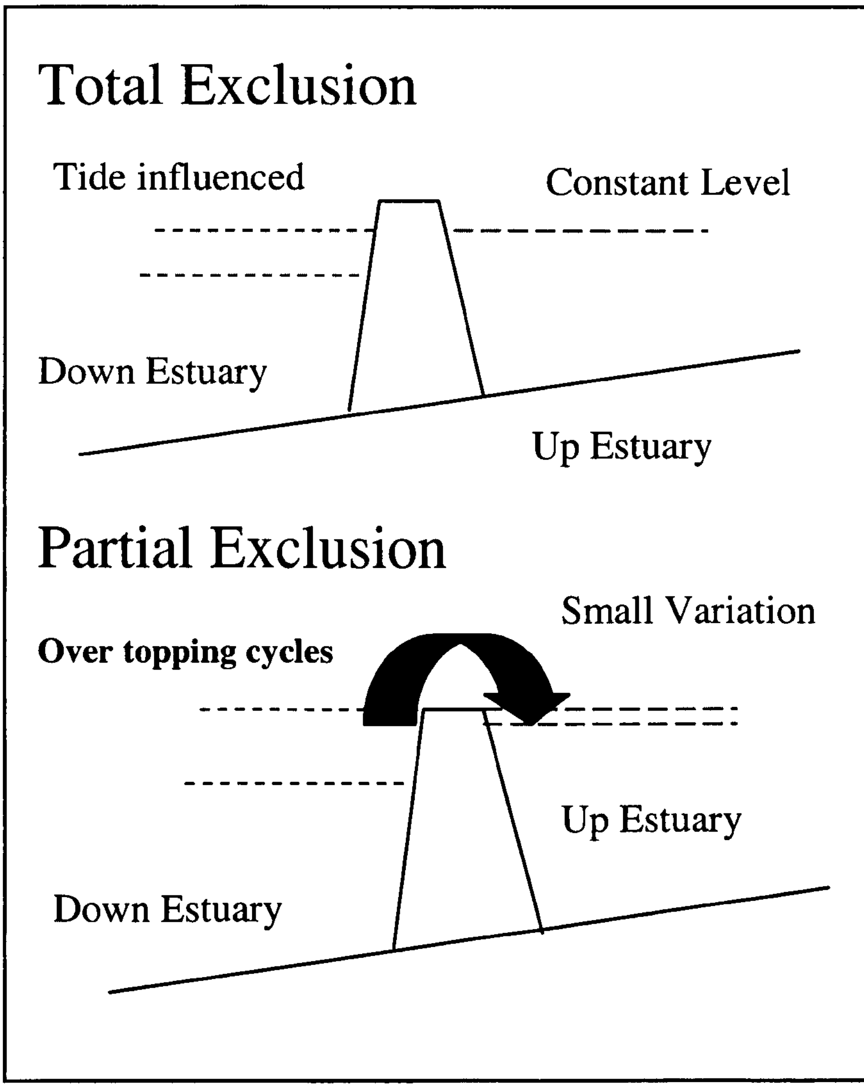


Fig. 2. 1 Amenity barrages: tide excluding – either partial or total

2.1.1 Water Regime

Any construction in an estuary will modify the flow regime. A barrage is no different. No matter what the purpose of the barrage, the post-construction tidal regime of the estuary will be modified. Each estuary will be affected differently as the change depends on the external tidal regime, the pattern and strength of the fluvial flows, the shape and roughness of the channel and the type of barrage constructed (HR Wallingford, 1999). If a barrage truncates an estuary completely then it is important to consider whether the tidal constituents are close to resonance downstream: however as this work is on the long-term effects of barrages upstream, this topic will not be reviewed.

For total exclusion barrages the effect on the flow regime in the estuary is similar to that resulting in the creation of a very narrow, long reservoir. The tide is effectively excluded from the estuary creating a freshwater impoundment with artificially high water levels. This results in the changing and slowing of velocity patterns throughout the impoundment. An implication of the high water levels upstream could be an increased risk of flooding (HR Wallingford, 1999), but as this tends to be accounted for at the pre-feasibility and design stage it should not have a long-term impact on the estuary. Nevertheless, the modified velocity patterns can have a large impact on flushing in the impoundment because, not only are the velocities lower than before, but the estuary is no longer flushed twice daily by the tide. In other studies, the flow patterns in total exclusion barrages have been found to be one of the major controls on water quality within the impoundment (Wright & Worrall, 2001). This study was completed on the River Tees and investigated the most significant controls on water quality parameters. The conclusions from the field studies were thought to be a result of the water's residence time in the impoundment. This is linked to the frequency of flushing.

In the case of a partial exclusion barrage, such as the Tawe or Wansbeck barrages, the intrusion of the tide upstream determines the ecological consequences for the impounded area. The impacts are related to the saline concentration upstream and the time delay before it is flushed through the impoundment (Shaw, 1995). Partial exclusion structures retain minimum water levels that hide the unsightly mud flats but still allow the intrusion of saline water, which is likely to cause a stable two layer stratified condition in the impounded section. This is especially noticeable during low fluvial flows and neap tides, and can lead to major water quality problems (HR Wallingford, 1999).

In general, the currents and flow patterns within estuaries determine the movement of solutes, bed load and suspended solids, and so investigation of the new velocity patterns created in estuaries have been an important part of barrage research and planning (Shaw, 1995; Burt, 2002). The changes to the hydraulic regime, in terms of small scale velocity fields, can be seen almost instantly thus making them simpler to predict using computer models, whereas changes to the sediment regime take a longer time to become evident. These two processes are inexorably linked because as the hydraulic regime dictates the sediment regime, so the long-term effects of sedimentation have implications on the future flow regime. Therefore, the hydraulic regime upstream of the barrage post impoundment has serious implications on the impounded water, and as such has been the subject of many investigations (Burt, 2002; Falconer & Riddell, 1992; HR Wallingford, 1992 (a) & (b))

2.1.2 Sediment Regime

Changes in the sediment distribution in the whole estuary are inevitable following the construction of a barrage: but this work concentrates on the impacts upstream of the barrage only. The Tees barrage is a total exclusion barrage and as a result it impounds freshwater with minimal saline intrusion occurring through the navigational locks. Consequently, the impoundment can be considered to behave like a long narrow reservoir, so research into the long-term impacts of reservoir sedimentation is relevant to this work. In addition to this, any investigation into the effect of tidal sediments can safely be ignored.

Sediment patterns within the new estuarine environment will be dictated by the new flow regime imposed by the barrage. While the new hydraulic regime takes a short amount of time to settle down, the new sediment regime within the impoundment takes longer; in fact the closing of the barrage marks only the beginning of a long-term adaptation. The process is known as siltation because with the water levels being held artificially high, the area in which the river flows has now become much larger than before the barrage was built. This change in the hydraulic gradient affects the sediment transport capacity of the channel. The transport capacity of the channel is reduced and sediment drops out of suspension as the water is effectively ponded upstream of the barrage (HR Wallingford, 1999). Sediment starts to drop out of suspension around the point in the impoundment where the backwater effect of the barrage starts to influence the river.

The effects of increased sedimentation within impoundments or reservoirs are well documented. There can be a number of detrimental impacts to the impoundment due to a build up of sediment, namely loss of amenity value of the impoundment, as with the Wansbeck barrage built in 1975 (Worrall & Burt, 1998). The amount of sedimentation that has taken place in this impoundment has prevented rowing boats from navigating the river in places (HR Wallingford, 1999). Indeed the local rowing club were persuaded to relocate upstream after the barrage was built, with the assurance that the new impoundment would make an ideal area for practice. However, since the relocation, the impoundment has become so shallow it is very difficult to row on it (Worrall, 2000, personal communication). An example of this occurred at the Haringvliet Dam in the Rhine-Meuse delta where, after construction, the cross section profile was reduced by 10-20% due to severe sedimentation (Huggett, 1996). The reduced or non-existent tidal currents in the new impoundment result in a reduction of water energy there, leading to sedimentation. These examples show the impact that large amounts of sedimentation can cause and, if the barrage is built for amenity purposes, it is important that this not allowed to happen. Another example of the impact of sedimentation is the loss of freshwater storage upstream of the barrage. Where water levels have risen as a result, this can lead to incidental flooding. Some studies into this have been completed for most proposed barrages at the design stage (Burt & Cruickshank, 1996; Burt & Littlewood, 2000), although the true long-term distribution of the sedimentation has not yet been realised within the impoundment.

For the Cardiff Bay barrage a detailed study was undertaken into the possibility of increased sedimentation occurring around the Alexandra Dock Channel. However, following the implementation of a fully tidal 1:250 scale model of the bay and barrage and a computer-aided calculation process (SAP) to predict the sedimentation in the channel it was shown that this was not the case (Hunter, 1996; Burt & Littlewood, 2000). It was important to investigate the effect of the barrage on the sedimentation distribution because it could have caused a large increase in maintenance dredging and therefore increased costs.

Increased sedimentation can also lead to problems with water quality (HR Wallingford, 1999) especially if the barrage traps polluted or organic sediments. For the organic sediments to break down and become stable compounds they demand oxygen from the water. This demand leads to depleted dissolved oxygen levels in the water and can impact on the species living in the impoundment. Another impact on species inhabiting the river can be the loss of spawning grounds, especially in feeder rivers. These spawning grounds can be drowned out by increased sedimentation, which was considered to be an issue for the Tees barrage (HR Wallingford, 1999)

From this review of the current literature it is clear that the impact of increased sedimentation in an impounded estuary can have many major implications in terms of the sustainability and long-term viability of an estuarine barrage. The issue of sustainability will be dealt with in section 2.2 as it is important to link sedimentation issues with the principles of estuarine barrage sustainability. Upriver siltation in an estuary impounded by a barrage can have the effect of:

- Loss of amenity value of the impoundment (McGarvey, 1996; Worrallet al. 1998)
- Water becoming too shallow for commercial navigation (Worrall et al. 1998)
- Loss of freshwater storage with impacts on flooding (Samuels, 1996)
- Water quality problems arising from increased oxygen demands (Burt & Cruickshank, 1996; Reynolds, 1996; Worrall & Burt, 1998)
- Impacts on aquatic life (Gough, 1996; HR Wallingford, 2002)
- Sediment blocking of sluice gates (HR Wallingford, 1999)

All these impacts lead to the need for detailed investigation at the design stage of the impacts of sedimentation upstream of barrages. This is routinely completed for all proposed schemes (HR Wallingford, 1988, 1992 (a & b), 1999); however in addition there is a need to continue monitoring the upstream impoundments post construction to ascertain the full long-term impact on the estuary (HR Wallingford, 1999). Indeed it is set out as one of the research priorities regarding estuarine barrages by HR Wallingford, and is linked to the sustainability of the construction itself. In terms of this body of work the most important research priorities highlighted in the HR Wallingford report (1999) were the sustainable development issues and sedimentological issues.

2.2 Sustainability Issues

Sustainability has become an important issue in the world over the past decade, with the particular aspect of sustainable development affecting civil engineering. One of the better-known definitions of sustainability comes from the 1987 Brundtland Report:

> "Humanity has the ability to make development sustainable – to ensure that it meets the need of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development, 1987, cited in Parkin, 2000)

Thus it is important that constructions of today are still serving their purpose in years to come, but if they are not then it is necessary to ensure that the impact of these obsolete structures does not compromise or prevent future generations from providing for themselves. An example of this is described in a paper by Palmieri, Shah and Dinar, (2001), on the topic of reservoir sedimentation. Common engineering practice to date has been to allow reservoirs to fill with sediment slowly, as part of the design and operating strategy. Once the sediment has filled the reservoir its useful life is over and it must be decommissioned. Until now this has not been considered a problem as the future generations have been left to take care of the decommissioning, while the present population enjoy the benefit of using the storage which exists for a finite period of time. However, this method is beginning to lose its appeal as more reservoirs are filling up and require decommissioning in the present, and the not too distant future. This problem would be easier to deal with if there existed infinite potential dam sites, which unfortunately is not the case. Therefore, it is becoming more and more important that the longevity of reservoirs is ensured so that the next generation can be provided with water resources. Many studies have been completed to investigate the sustainability of reservoirs regarding the control of sediments (Siyam, Yeoh & Loveless, 2001), the flushing of reservoirs by draw-down (Lai & Shen, 1997), the socio-economic impacts (Hotchkiss & Bollman, 1997), and the assessment of sedimentation patterns (Zhide & Xiaoqing, 1997).

Extending this theory to include estuaries and estuarine barrages, it is imperative that through the development of estuarine areas, no irreparable damage is being done. As a result it is important to ensure that the long-term viability of these structures is guaranteed. It is therefore necessary to continue monitoring after impoundment (HR Wallingford, 1999) to understand fully the long-term affects of barrages and to predict the long-term effects on the hydraulic and sediment regime in the estuary as accurately as possible. For example, a cumulative impact study on the Humber Estuary (Conlan & Rudd, 2000) was completed before construction could be started on four large schemes in the estuary: a sewage treatment works, a power station, a ferry terminal and reclamation and flood defence works were all proposed for sites on the River Humber. The investigation was completed to ensure the sustainability of the estuary during, and after, all the construction was completed, and resulted in the development being phased to minimise the impact on the local environment. Such investigations uncover issues which should be taken into account for future research. The main points, which are relevant to this body of research that arose were;

- establishing a pre-construction benchmark is important so an assessment of the future sustainability can be made;
- monitoring of the long-term effects after the construction phase is complete is also necessary as a way of checking the predictions made;

- recognising that the predictions made rely heavily on the use of mathematical and computational models, although the study mentions the problems that exist when interpolating short-term estimates into the long-term.

The use of mathematical models to investigate these situations is discussed in section 2.4

Consequently, if the sustainability of an estuarine barrage is to be assessed it is important to make detailed long-term predictions on the future regime post impoundment. While water quality issues are a large factor that must be evaluated for sustainability, this research concentrates on the sustainability issues related to sediment regime only. For these to be considered not only must the new sediment regime be assessed using the present climate conditions but some account must be made of the issue of possible climate change. It is essential to assess the effect of climate change on water resource planning. This will require the possible impacts and detailed predictions from climate models before it can be accounted for (Crookall & Bradford, 2000). This is discussed further in section 2.3. Thus, to assess the sustainability of the River Tees impoundment and its sediment regime, following the construction of the total exclusion, it is necessary to estimate the long-term regime under present and future climate scenarios. One of the most comprehensive methods of investigating this is by using computer models.

2.3 Climate Change

In recent years there has been increased emphasis on estimating the effect of climate change on river flows and water resources. Many bodies of work have investigated the possible effects of climate change on water resources (Wood, Lettenmaier & Palmer, 1997; Price, 1998; Arnell, 1998, 1999; Werrity, 2002) and river flows (Arnell, 1992, 2003; Arnell & Reynard, 1996; Limbrick, Whitehead, Butterfield & Reynard, 2000; Reynard, Prudhomme & Crooks, 2001; Black & Burns, 2002). This section aims to give an overview of possible impacts on the River Tees using the methods and conclusions from the present literature.

2.3.1 Predicted Changes to the Climate as a Result of Global Warming

It is commonly accepted throughout the literature that the climate of the UK is changing (UKCIP (a), 2002). These observed changes are probably, due to a combination of both human and natural causes. The climate would vary naturally, even if there were no human impacts upon it: this occurs as a result of changes in the earth's orbit, fluctuations of energy received from the sun, interactions between the oceans and the atmosphere and volcanic eruptions (UKCIP (a), 2002). However, the natural variability is augmented by that caused by human influence, the biggest contributor of which is thought to be increased greenhouse gases. Carbon dioxide and methane are released into the atmosphere as a result of power production, car emissions and land use changes and these gases then act to trap energy in the lower atmosphere, which in turn results in the effect of global warming. However, the process is further complicated by gases such as sulphur dioxide, which act to cool the planet down when they are changed into smaller particles known as aerosols. Models have been set up to investigate whether human or natural influences could explain the recent changes in climate and the results point to important and increasing human influence. As a result of these findings the Intergovernmental Panel in Climate Change concluded that:

> "... most of the warming observed over the last 50 years is likely to have been due to increasing concentrations of greenhouse gases." UKCIP (a), 2002

All aspects of the climate will be affected by the implications of climate change. The consensus view throughout the literature is that there will be an observed increase in annual, average, global temperature of 0.15-0.3°C per decade, predicted by general circulation models (GCMs), if the concentrations of atmospheric greenhouse gases continue to rise at a rate dictated by differing emissions scenarios (Arnell & Reynard, 1996; Arnell, 1998; Limbrick et al., 2000;). The global value translates into a UK prediction, using different emissions scenarios, of between a 0.1-0.3°C rise per decade depending on the location through the country, with a greater warming in the south east compared to the north west (UKCIP (a), 2002). This could lead to significant impacts on local and regional climatic systems (Arnell & Reynard, 1996). Not only will the temperature be affected but, in addition, there will be implications on the precipitation throughout the country. Winter precipitation is predicted to increase in all scenarios by 2080. This rise in precipitation is thought to be between 10-35%, again depending on the scenario or area of the UK (UKCIP (a), 2002). The smallest changes will be experienced in the north west of Britain and the largest in the south, which only serves to strengthen the precipitation gradient that exists over Britain under the existing climate conditions. This may lead to changes in run-off contributions to water systems, although this is further complicated by the issue of land use changes over the same period of time. These changes in temperature and precipitation will definitely impact on river flows and water resources over the next century (Arnell 1999; Reynard et al. 2001;). While every aspect of climate is affected by global warming, temperature and precipitation are the most important aspects for investigating the effect on water resources.

Extreme weather will also be affected. Some of the UKCIP 2002 predictions indicate that rain events that have a 50% chance of occurring under the present climate may increase that chance by up to 20% by 2080. The changes to extreme temperature events means that the chance of the Scottish Highlands experiencing a maximum temperature of 23 °C on any given day may increase from 1% to 15% by the 2080's. However, there is lower confidence in these extreme predictions as low-frequency events are not simulated as well by the GCMs and are harder to validate (UKCIP (a), 2002)

2.3.2 Impact of Climate Change on Rivers and Water Resources

Each catchment is sensitive to climate change, but the degree to which it reacts is partly due to the catchment characteristics (Arnell, 1992; Reynard et al. 2001). This means that not only does the effect of climate change depend on where in the UK a particular catchment is situated but it also depends on the type of catchment. For example, an urban catchment would be more sensitive to an increase in predicted rainfall as most of the precipitation would reach the river in the form of runoff, whereas an upland forested catchment would be less sensitive as there is a greater chance of the water being stored before reaching the river.

Many studies have been completed to investigate the effect of climate change on particular catchments (for example Roberts, 1998; Pilling & Jones, 1999, 2002) and the methods employed are described later. These investigations have applied the most recent predictions of climate change parameters like temperature, precipitation and potential evapotranspiration, to catchment models. The generally accepted practice is to simulate the catchment's response to several of the climate scenarios, which are based on differing greenhouse gas emission predictions. This then gives an upper and lower limit of predictions between which lies the estimate for the effect of climate change on the catchment.

Studies such as those by Arnell, 1992 and Arnell and Reynard, 1996 have investigated several different catchments throughout Britain. The conclusions of these studies state that the largest change in average annual runoff is in the south and east of Britain, which coincides with the predicted exaggeration of the precipitation gradient across Britain. The drier areas of the south and east of Britain show the greatest sensitivity to climate change, whereas the predicted annual changes in the humid north west are much smaller (Arnell & Reynard, 1996). Shorter scale variations, for example on a monthly or seasonal basis rather than annual changes, show a much larger transformation. The studies completed on 21 different types of catchment across Great Britain showed that generally there is a greater concentration of runoff in the winter, and under the drier climate scenarios the summer runoff amounts would be substantially reduced. Low flows were generally found to be reduced under most of the climate scenarios. If these results are coupled with the prediction that snowfall will be distributed different and significantly reduced due to the temperature rise, then this has implications on the timing of flows specifically in the winter and impacts on water resource planning.

While Arnell & Reynard, (1996) investigated catchments all across Britain, they only investigated four in Scotland. Werritty, (2002) continued their investigation by analysing the effects of climate change on the flow duration curves of the four catchments. For the anticipated climate conditions of 2050, Werritty (2002) reports that the annual runoff is predicted to increase by 8.9-11.6% for the four catchments. This agrees with the predicted rise in the Q_{95} value, (flows exceeded 95% of the time), of 5%. In addition, the flow duration curves predict a rise in the Q_5 values, which represent the highest flows in the catchments. The reported increases are: 10% on the River Don, 16% on the River Almond, 24% on the Lyne Water and 11% for the River Nith. These predictions point to a considerable increase in high flows, with the possibility of flooding, and appear to be much higher than those predicted for the English catchments (Werritty, 2002). This may be of interest in a study of the Tees.

Reynard et al. 2001 investigated the effects of climate change on two of the United Kingdoms largest catchments, the Thames and the Severn. For both catchments a general prediction of increased winter runoff was found, which led to an increase in predicted flood magnitude and frequency. This predicted increase was almost certainly a direct result of an increased winter precipitation in all of the climate scenarios. A given return period of a flow in the river could be increased by up to 20% by 2050 according to the predictions, which leads to high flows occurring more frequently.

The study also investigated the effect of land use changes throughout the catchments. It was found that with a large increase in forested areas the impact of climate change was less severe as the runoff into the rivers was reduced. This shows that the management of catchments can help to alleviate flooding problems created by climate change.

While these studies have been completed on individual catchments, it has been recognised that, to date, the most comprehensive current estimates of climate change impacts on water balances and runoff regimes has been completed by Arnell, 1996 (Werritty, 2002). An investigation undertaken by Pilling & Jones in 1999, attempts to improve Arnell's predictions by improving the spatial resolution. The results confirm the pattern of seasonality and the exaggeration of the precipitation gradient from the wetter north west to the drier south east reported by Arnell, (1992; 1996) and Arnell & Reynard (1996). From the predictions in this paper it is possible to interpolate possible values of increase for runoff for the River Tees. Under the 2050 predictions from the Hadley Centre high resolution GCM, the estimated change in the mean effective winter runoff for the Tees is an increase of between 0-15%, while the summer change is between ±15%.

Moving on from the catchment changes, an important focus of climate change is the potential change to sea level, in particular the extreme sea level rises that are experienced as storm surges causing extensive coastal damage. The change in the sea level will not be the same everywhere as the north part of Britain is rising and the southern part sinking due to natural land movements. According to the predictions given in the UKCIP briefing report (a) (2002) the north east of England, where the Tees barrage is situated, is rising at an average of 0.3mm per year, which means a rise of 15cm by 2050. This acts to counter the predicted rise in global sea level of between 6 and 69cm for the low and high emissions scenario in 2050 respectively. Extremes of sea level or storm surge are much more difficult to predict with any confidence (UKCIP (b), 2002). The largest changes to storm surge appear to be predicted for the south east coast of England, where the largest changes in wind speed occur in conjunction with subsiding land. However, the effect on the Tees estuary of any predicted mean sea level rise, and the resulting implications for storm surge, is not obvious at this stage because each estuary behaves differently and the effect is dictated by the estuary's resonance characteristics (HR Wallingford, 2002). In fact, a mean rise in sea level could result in an overall reduction in maximum water levels in some estuaries. However this research has concentrated solely on the effect of climate change to river flows and has not taken into account the possibility of tidal intrusion upstream as a result of climate change effects on the sea.

If a large change to the present hydraulic regime in the River Tees is experienced as a result of climate change then this could have significant implications on the sediment regime in the river. For example if there is an increase in number of large floods, more sediment will be washed into the system, but sediment will also be picked up and washed out of the system resulting in degradation in the impoundment. Conversely, if there is an increased number of low flows on the river during the summer months, more sediment will be trapped as most suspended sediment is dropped out of suspension when the velocities are low. In addition to the change of precipitation and temperature across the catchment, a rise in sea level could prove to be a problem in the Tees estuary area. A rise could change the function of the barrage, under extreme situations, from a total exclusion barrage to a partial exclusion barrage. This change of function could have a resulting impact on the sediment regime of the barrage, as marine sediment may be passed upstream under a partial exclusion barrage regime. However, assessing this is very difficult as it depends on the resonance characteristics of each estuary. Therefore it is very important that the effects of climate change are incorporated into the investigation of the river Tees impoundment.

2.3.3 Methods of Modelling the Impacts of Climate Change on Rivers

Detailed estimations on the change to temperature, precipitation, cloud cover, solar radiation, relative humidity and fog due to climate change for different emission scenarios, exist. These estimations are made from General Circulation Models or GCMs, which are large scale models. It would be difficult to model every one of the complex interactions that occur in the atmosphere, thus the estimates predicted use simplified three-dimensional models, which represent the main aspects that control the interactions between the atmosphere, the land and the oceans. These models are used to predict the present climate predictions for the UK and are called coupled atmosphere-ocean general circulation models, or AOGCMs. The models predict the potential change in climate on a coarse resolution grid, typically >0.5°lat x 0.5°long grid, which covers either the whole planet or an entire continent. The predictions for Europe and Great Britain are mainly completed at the Hadley Centre in England, UK. Due to the coarse resolution of the predictions it is necessary to adapt these results for a smaller area. This is known as downscaling. For example, GCMs predict rainfall spatially averaged across each grid cell, whereas, in reality rainstorms contain pockets of high and low intensities. In addition GCMs do not simulate river flows, hence, there is a need to translate these GCM predictions into scenarios that can be readily used by practising engineers.

There are two main types of downscaling, namely dynamical and statistical. Dynamical downscaling uses a set of hierarchical models, which are nested inside each other. A regional circulation model (RCM) is nested inside the GCM at a much higher resolution and uses the output from the GCM as boundary conditions. These models are able to account for local factors such as the effects of a mountainous region so can such predict more realistic patterns of rainfall than the GCM, however due to their detail have some drawbacks. RCMs can be very computationally intensive due to their complex nature; this has meant that few detailed simulations have been completed, for example Jenkins & Barron, (1997). An added complication comes from the fact that the boundary conditions for an RCM come directly from the GCM which means that any errors or uncertainties from the larger scale model will automatically be handed down to the smaller scale one (Mitchell & Hulme, 1999). Despite these problems the Hadley Centre has used RCMs to predict a more detailed map of potential climate change for the UK on a $50km^2$ grid (UKCIP (b), 2002).

To provide an even more detailed picture of the effect of climate change over an identified area, for example a particular catchment then statistical downscaling is often used. This method has the benefit of using historical, observed weather data for a catchment, which can be built into the model to give extra information. Statistical downscaling takes the output from GCMs and relates it to the surface climate variables using historical data; for example the classification of atmospheric circulation types, of which the simplest kind is Lamb Weather Types (LWT) (Fowler & Kilsby, 2002). These large scale climate predictors are then related to a local scale climate variable, often rainfall statistics in water resource research, via a statistical model. The rainfall statistics most often used are the monthly mean rainfall and the proportion of dry days for each calendar month. A stochastic rainfall generator such as the Neyman-Scott rectangular pulse model or the Bartlett-Lewis model is then utilised to generate hourly rainfall data for the catchment (Wheater & Onof, 1994; 1995; Coppertwait, O'Connell, Metcalfe & Mawdsley, 1996; Fowler, 2000). These stochastic models are first calibrated to the particular catchment using historical data and then used to create hourly rainfall series for arbitrarily long periods by using a Poisson process to simulate storm origins of different intensity throughout the catchment (Lourmas, 2002). The output of the rainfall model can then be used as the input for a hydrological model of the whole catchment such as TOPMODEL (Beven & Kirkby, 1977). Many studies have used this method for example Perrin, Michel & Andreassian (2002). This rainfall-runoff type model must first be calibrated to the catchment in question, using historical data series such as river flows, precipitation and temperature records. An ensemble of combined rainfall and runoff simulations is then used to produce a new flow duration curve or a series of flows for the river under different GCM predictions. This method is a commonly used practice and the overall downscaling procedure is demonstrated in a number of studies, for example (Cameron, Beven & Tawn, 2001; Prudhomme, Reynard, & Crooks, 2002; Fowler, 2000).

Statistical downscaling, then, has been widely used as a method for predicting the effect of climate change on rivers and water resources, however it is based on the assumption of stationarity. This ineloquent term means that the relationship between the large-scale climate variables and the small-scale variables will remain the same under climate change. But, in reality, there is no guarantee that the relationship will remain the same, which could lead to problems. Another problem with the statistical downscaling method is that it is extremely time consuming and site specific. It is rather unreasonable to expect practising engineers to employ this technique as it can take several months for a person to complete for one catchment alone, and as a result, in practice, climate change is often accounted for in design by means of a safety factor. Despite this, this procedure is now being conducted in many research institutions and as a result information on how flow duration curves change with respect to climate for particular catchments is becoming increasingly available. Some quicker method than either statistical or dynamical downscaling is required for engineers to account for climate change.

2.4 Sediment Processes

For the purposes of this thesis it is necessary to include a short section on the basic theory of sediment processes within fluvial environments. This section is designed to explain and define the terms used for each process within this thesis.

As water flows over the bed of a river it applies a shear force to the particles on the bed. As the velocity of the river increases so does the shear force. Each particle on the bed is held in place by gravity until the shear force of the river becomes large enough to counteract the particle force. At this point, the threshold of movement, particles start to move.

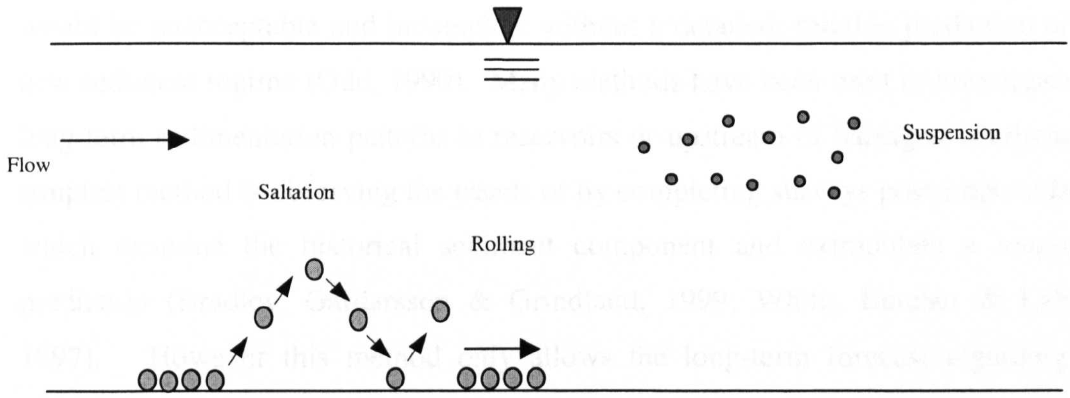


Fig 2. 2 Sediment transport processes

Sediment movement within a river can be characterised in three main ways. Firstly there are the particles, which are rolled or dragged along the riverbed by the force of the water. This movement generally involves coarser grain fractions moved from the bed. Secondly, the process of saltation can be described as grains bouncing along the bed striking other grains, which in turn are caused to move. Both of these first two processes are termed near bed processes and for the purposes of this thesis are termed bedload transport. Thirdly, particles may be transported in suspension within the water. These particles tend to be finer and are often not sourced directly from the bed but enter the river as wash load. For the purposes of this thesis, this third type of transport will be termed suspended sediment or load.

2.5 Numerical Modelling of Sediment Processes

The literature review has concentrated on examining the studies investigating the effects of barrages, sustainability issues, climate change and basic sedimentation processes. In this section attention is drawn to the literature related to the benefits and details of the numerical modelling of similar environments to the Tees impoundment.

To investigate the impacts of barrages on the original estuarine impoundments it is necessary to make a long-term prediction of the behaviour of the sediments. In fact, any environmental impact assessment for a large-scale scheme within an estuary would be unacceptable and incomplete without a detailed, reliable prediction of the new sediment regime (Odd, 1990). Many methods have been used to investigate the long-term sedimentation patterns in reservoirs or upstream of barrages. Perhaps the simplest method is observing the trends or by completing surveys post-impoundment which examine the historical sediment component and extrapolate a long-term prediction (Bradley, Gardarsson & Grindland, 1999; White, Butcher & Labadz, 1997). However this method only allows the long-term forecast regarding the sediment regime to be made after the construction of the works. With the advent of computers and computational hydraulics, it is now possible to model these long-term effects numerically in a more detailed fashion. This type of modelling is recommended for investigating the effect of constructing a barrage in an estuary (HR Wallingford, 1999).

Numerical modelling of a body of water can be completed in different degrees of detail. Numerical models can be:

- one-dimensional, area- averaged models,
- two dimensional, either:
  - width-averaged or
  - depth-averaged models,
- pseudo three dimensional, a prediction created from a layered two-dimensional model with a hydrostatic assumption,
- or fully three dimensional.

While the degree of detail increases with the dimension of the model, so does the number of equations to be solved thus the computer intensity required increases. Therefore some models can predict more detail but are really only suitable for short-term modelling while others forecast fewer details but are useful for long-term investigations.

This overview will investigate the different types of model used to investigate sedimentation patterns in reservoirs and estuarine impoundments, and provide examples of where different dimensional models have been utilised in similar projects. It will discuss the relative benefits and disadvantages of using different types of models. Additionally it will provide a small review of the previous type of numerical modelling that has been completed for the Tees impoundment as regards the barrage.

2.5.1 One-Dimensional Numerical Modelling

One-dimensional or area averaged numerical modelling is one of the simplest type of modelling and was first developed in the 1950's in the USA. From 1960 onwards one-dimensional hydraulic modelling had a wide commercial application and remains the workhorse of civil engineers today due to its simple and non-intensive computational nature. Generally, 1-D models solve the simplified shallow water, St Venant equations and rely on a number of assumptions; the flow is predominantly one-dimensional, the average bed slope is small, the effects of boundary friction and turbulence are small and can be accounted for through resistance laws and the streamline curvature is small with negligible vertical accelerations (for a more detailed description of one-dimensional modelling please refer to section 5.2). Attached to these hydraulic packages often comes a sediment transport package which calculates the erosion and deposition through the model (Otto, 1999; Walker, 2001), alternatively a regime analysis tool can be coupled to one-dimensional models (Odd, 1990; Dennis, Spearman & Dearnley, 2000). Either of these methods will provide a prediction of sedimentation through the model.

Many studies have been completed using one-dimensional numerical models. For example, Walker (2001) completed a study on the River Eden in Cumbria, UK to investigate the effect of a weir on sedimentation. The software ISIS-Sediment was utilised to determine the sediment movement predicted through the gravel-bed river. Continuous runs were completed for one year determining whether the river behaved differently with and without the weir. From these predictions some extrapolation was used to determine the long-term impact of the weir. Another example of a one-dimensional model study was completed by Otto (1999), where the Salzach river, on the border between Germany and Austria, was modelled using the morphological model SEDICOUP. This model was run continuously for 45 years to investigate the long-term effects of different methods of rehabilitation for the degraded areas of the river where too much erosion was observed. These two studies are part of a large collection of investigations completed using one-dimensional models (Copeland, 1989; Odd, 1990; Annadale, 1992; Dennis et al. 2000)

The main advantage of using a one-dimensional numerical model for investigating the effect of sedimentation in rivers or estuaries is that it requires relatively low computing power, meaning that it is feasible to complete long-term continuous runs. These type of models are also very flexible; many packages come with built-in modules which allows the modelling of weirs, bridges and tributaries easily (Halcrow, 1997). However these types of models lack the detail that can be obtained when using higher dimensional models. For example, because the models assume a constant velocity through each cross-section the sediment package must also assume constant deposition or erosion across a cross-section. This is obviously a simplifying assumption but it does give a reasonable overview of where areas of erosion and deposition will occur throughout the modelled reach. While a two or three-dimensional model may be best suited for modelling thermal stratification or saline intrusion, one dimensional models are very useful for long-term studies and widely used in river studies (HR Wallingford, 1999; Lin, Kashefipuor, Harris & Falconer, 2001; Kashefipuor, Lin, Harris & Falconer 2002).

A technique which compromises the lack of detail involved in a one-dimensional model with short-term predictions from a higher dimension model is to produce a hybrid modelling system. This is where a suite of models can be used to predict different aspects of sedimentation in a reach. For example a one-dimensional model could be utilised to compute a long-term forecast while the higher dimensional model is used to give a detailed picture of the areas where sedimentation is predicted to occur through the river. This type of modelling is described by Lin et al. (2001) and Kashipour et al. 2002, where dynamically linked one and two-dimensional models were used to model the Ribble estuary in the UK. The depth averaged two-dimensional model was mainly used to investigate water quality in the estuary as the flow forms are predominantly two or three-dimensional. It was claimed that this approach improved the overall accuracy of model predictions, as it has linked the simpler one-dimensional model and the more complex two-dimensional model, which are used to predict different things. Paquier (2001) employed a similar method for modelling a dam-break situation. Here the one-dimensional model was used to calculate the propagation of the dam break wave through the valley while the two-dimensional model provides detailed pictures of velocity fields at particular points throughout the valley. A dam-break situation is not a long-term modelling problem rather it is a short-term, detailed phenomenon, however this study does highlight the effectiveness of using a suite of models, rather than one in isolation.

2.5.2 Two-Dimensional, Depth-averaged and Width-averaged Numerical Modelling

There are two different kinds of two-dimensional models; namely depth-averaged and width averaged models. Width averaged models are an extension of one-dimensional models (HR Wallingford, 1999), but model several layers through the vertical where velocity, salinity and sediment concentration are allowed to vary. While these types of models permit more detail on salinity currents, sediment concentration mapping and water quality issues by modelling the effect of turbulence, they do not distribute velocities within a layer. Thus, they have a particular application to modelling estuaries, where it is important to understand the effect of the saline wedge. Conversely, the depth-averaged or depth integrated models represent flows and velocity fields in plan and can take account of differing velocity fields throughout the cross section. However, depth-averaged models can be used to predict the impact close to a structure in an estuary or river, and investigate the resulting salinity and sediment distributions. This type of model is generally used where the water is acting largely two-dimensionally and vertical velocities are negligible, for example a lake. Both of these models add information and detail to the situation studied, but with this extra information from turbulence modelling comes an increase in computational time and possible numerical instability. Two-dimensional models have more equations to solve, increasing the computing time and resulting in long-term runs becoming less feasible without extrapolation.

Two-dimensional models are based on the shallow water Navier Stokes equations but are either averaged over the depth or the width. The underlying assumptions for these models are that the flow is two dimensional, either the velocity is uniform over the depth or the width depending on the type of model utilised. The pressure distribution is hydrostatic, and the effects of boundary friction can be accounted for through a resistance law, such as Manning's equation, similar to the one-dimensional models. The depth-averaged models use a method of grids to help the solution of the problem. These grids are often called meshes and can either be structured or unstructured and must permit a good representation of the underlying geometry. This grid then becomes the base from which the solution will be calculated, as often the program will solve for the unknowns at the grid nodes. To ensure the model is solving the problem as accurately as possible it is necessary to discretise the underlying geometry in the best possible manner using the grid. However, if the mesh becomes too complicated from this discretisation it results in an increase in computation time for the solution. Therefore, a balance must be struck with this type of modelling, between accuracy and computational time. This is often known as verifying the model as it is necessary to identify and quantify the computational error inherent in the model (AIAA, 1998).

2.5.2.1 Width-Averaged Models

Many studies have been completed using both types of two-dimensional model, although depth-averaged, two-dimensional models are more commonly used. Firstly investigating width averaged models, which have the widest application in estuaries, the most relevant study using these type of models was completed on the river Tees itself. The study was undertaken by HR Wallingford in 1992 to investigate the long-term effect on the Tees after the construction of the proposed barrage. The study used in-house models called the 2DV modelling suite, which calculate the movement of salinity, mud and water through the estuary. The suite of models are width-averaged with vertical layering. The height of the layers was fixed at 1.5m in the Tees model (Jones, personal communication, 2001) and the water level can move up and down through the model mesh. The cross-sections were taken every 500m along the length of the estuary. The model solves the equations of horizontal momentum, vertical momentum (with a hydrostatic pressure assumption) and the conservation of mass. To represent turbulence a Prandtl mixing length model was used (Jones, private communication, 2001). Several runs were completed using the models, with and without the barrage involved. Individual runs using particular hydrographs were computed. The runs were each of 55 hours long and investigated the 1:10 year flood, 1:1 year flood and a $100m^3/s$ flood. In addition, a 15 day period of $32m^3/s$ was modelled to represent the effect of low flows during the winter period. The long-term effects were then extrapolated from these short-term results. Due to the computationally intensive nature of these types of models, short-term investigations are most often completed. However, these investigations were carried out in the early nineties and, with the increased computing power that is now available it is possible that width-averaged models are now suitable for long-term simulations.

2.5.2.2 Depth-Averaged Models

Depth-averaged models are widely used in the area of lake modelling due to the predominantly two-dimensional flow structure that exists there. However these types of models have been frequently used to model estuaries as well (Betty, Turner, Tyler, Falconer & Millward, 1996; Franks & Falconer, 1999; Malcherek, 2000; Kashefipour et al. 2002). Betty et al. used a two-dimensional depth integrated hydrodynamic and sediment model, capable of modelling water quality, of the Humber estuary to make predictions on the contaminant geochemistry of the water. The estuary is well mixed which allows a 2D layer-averaged model to be used. The model was calibrated against field measurements of salinity and water quality parameters and then used to predict contaminant cycling within the estuary.

Malcherek (2000) used TELEMAC 2D, a depth-averaged two-dimensional code to represent a narrow estuarine tributary in the Wesser estuary. The investigation was interested in the effect on the tidal influence in the tributary after some changes to the river's bathymetry have been implemented. The mesh that was constructed to complete the investigation consisted of 35000 nodes and the computations were completed at a 1s timestep for stability reasons. Therefore, for one spring to neap cycle to be modelled (approximately 14 days) it took 19 CPU-days on a CRAY-YMP machine (Malcherek, 2000). The results, while considered to be reasonable (Malcherek, 2000), took longer to model than they would to observe. This means that although a short-term investigation would take a long time to model it is still feasible. However, for long-term continuous modelling this type of model would not be a reasonable choice.

Many studies have been completed using depth-averaged models to simulate processes in lakes or reservoirs (Zeigler & Nisbet, 1995; Zhou, Chen & Song, 1997; Paquier, Massart, Krzyk & Cetina, 1999; Walker, 2001). Walker (2001) used a hydrodynamic model linked with a sediment transport solver to investigate the use of wetlands in removing the sediments from stormwaters and to investigate the long-term sedimentation patterns. To do this, short events were again utilised as the method for analysis, which kept the computing time down. In contrast, Zeigler & Nisbet (1995) used a two-dimensional model to simulate a 30-year period. This study was aimed at investigating the long-term simulation of fine grained sediment transport in a reservoir. This study proves that, although some two-dimensional models appear to be too computer intensive to be useful for long-term investigations, some are capable and in the future the use of these types of models may become more widespread.

2.5.3 Pseudo-Three Dimensional and Fully Three Dimensional Models

There are two distinct types of three-dimensional hydrodynamic models; namely pseudo and fully three-dimensional. In the case of a pseudo or quasi three-dimensional models, the model solves a series of inter-related two-dimensional simulations in the plan view, and is based on the assumption that a hydrostatic pressure distribution exists. The water depth and the velocity components in the x and y directions are solved using the two-dimensional shallow water equations and then the vertical velocity is calculated through the closure of the mass-conservation equation. These types of models are predominantly used for coastal applications and estuaries where it is necessary to ascertain the different currents through the depth, or to investigate sediment transport.

Many studies have been completed using quasi three-dimensional packages such as TELEMAC 3D (Falconer & Lin, 1997; Le Normant, 2000; Kopmann & Markofsky, 2000; Corti & Pennati, 2000) and others (Lin & Falconer, 1997, 2001; Wu, Falconer & Uncles, 1998; Franks & Falconer, 1999; Wu & Falconer, 2000). Le Normant (2000), used the finite element package TELEMAC 3D to model cohesive sediment transport in the Loire Estuary. After the model was validated, several runs were completed of 72 hours duration, due to the inherent computing cost. The computer intensity is not reserved for TELEMAC 3D; other modelling packages are similar, for example CH3D (Gessler, Hall, Sposojevic, Holly, Pourttaheri & Raphelt, 1999; Holly & Spasojevic, 1999). This model was applied to the Mississippi River, to represent the hydrodynamics and sediment transport over an 84km stretch (Gessler et al., 1999). The vertical discretisation was set at 10 layers, and the resulting mesh had 69000 nodes. Using this mesh the daily sediment deposition at particular flow discharges was determined using two-day simulations, then these results interpolated to produce an 8-year deposition volume. Both of these investigations shows that short-term detailed studies can be completed with success on high dimensional models, however a long-term continuous run for the purposes of long-term prediction is presently not practical.

A three-dimensional, layer-integrated model was refined by Wu et al. (1998) to include cohesive sediment transport. It was then used to model the Humber estuary with success. Eight layers were implemented in the model, each 3m thick and the model was then run over a tidal cycle to compare the predictions with collected field data to assess the models accuracy. Lin & Falconer (2001) used a similar model which incorporated a solute transport equation to model the Bristol Channel with regard to water quality issues. After the model was calibrated to field data, it was then used to investigate the bacteria concentrations in Swansea Bay. These types of models are very useful for identifying the cause and position of high contaminant concentrations and can be used to investigate the effect of different types of treatment. Research such as this can often require only short-term, detailed modelling (for example over one or two tidal cycles). Therefore, the computationally intensive, but detailed three-dimensional layer-averaged models are ideal.

Fully three-dimensional models, are required when the assumption of hydrostatic pressure is no longer applicable. These type of models were developed by the Mechanical and Aeronautical industry to calculate air flows around objects and to design jet engines. Fully three-dimensional codes require the solution of many more equations than the simpler quasi-three dimensional packages, and tend to be labelled under the banner Computational Fluid Dynamics or CFD. CFD has only been applied to civil engineering problems relatively recently, with river like channels only being modelled in the 1990's (HR Wallingford, 1996; Sinha, Sotiropoulos & Odgaard, 1998; Morvan, Pender, Wright, & Ervine, 2000; 2001;). However, despite being very computer intensive and requiring a large amount of input data for model construction, verification and validation, studies have shown that river conditions that are clearly non-hydrostatic are represented better by fully three-dimensional flows, particularly at river confluences (Lane, Biron, Bradbrook, Chandler, El-Hames, Richards & Roy, 1998; 1999). Applications are still research orientated in the Civil, Geomorpological and Environmental field so far, but in the future a fully three-dimensional model will be a powerful tool for investigating small-scale short term effects on velocity field patterns round proposed structures.

2.5.4 Previous Modelling Completed on the Tees Impoundment

Several studies have been completed on the Tees barrage at the design stage (HR Wallingford, 1988, 1992 (a), 1992 (b)), however apart from this piece of work there have been some recent investigations conducted for the Teesmouth, the area downstream of the barrage (HR Wallingford, 2002). The investigations completed at the design stage used; one-dimensional continuous long-term modelling (HR Wallingford, 1988, described in more detail in section 2.6.1.5 and 4.2), physical model studies (HR Wallingford, 1992 (a)), and more detailed two-dimensional modelling (HR Wallingford, 1992 (a), described in detail in section 2.5.2.1). The short-term results from the detailed modelling were then extrapolated to create long-term sedimentation predictions.

The recent study completed for the Teesmouth area, regarding sedimentation, was commissioned by English Nature to investigate the perceived loss of bird feeding capacity to Seal Sands, downstream from the barrage in the Tees Estuary. One of the concerns was that since the barrage was constructed an increased amount of sediment was becoming trapped upstream, which in turn was leading to a decrease of fine sediment downstream. However, computer models set up in 1991 predicted that marine sediments dominated the sediment movement in the estuary and the river contributed a relatively small amount to this process. No new sediment modelling was completed upstream or downstream of the barrage, so the study relied on evaluating the previous work completed by HR Wallingford at the design stage and other studies. The outcome of the study stated that the estuary was unlikely to be in "regime" due to the on going maintenance and relatively recent construction of the barrage, identified the major controls on the change in sediment regime and investigated mitigation methods.

2.5.5 Discussion on Numerical Modelling for Long-term Sedimentation Studies

When investigating the long-term effects of a barrage on the overall sustainability of the created impoundment with regards to sedimentation, it is necessary to simulate many years into the future to realistically represent the possible change to the sediment regime. Due to the fact that long continuous runs give realistic predictions when investigating sedimentation, it is important that non-computer intensive models are utilised. This unfortunately means that some of the detail afforded by the higher dimensional models must be compromised. Thus, higher dimensional models must be discarded as a possible tool if the intention is to model long-term situations continuously rather than extrapolating long-term results from short-term predictions, which can be notoriously difficult (Odd, 1990). This leaves one-dimensional models as the tool of choice for such situations, but it does mean that some of the detail has been compromised. However, perhaps the solution to this is to create hybrid-modelling schemes, which aim to investigate the long-term changes using the one-dimensional model and employ higher dimensional models to investigate some of the detailed velocity patterns. This research is primarily aimed at investigating the long-term change to the sediment regime in the Tees impoundment and as such from the literature it is clear that the most useful type of model for this is a one-dimensional hydrodynamic model with a sediment transport module attached.

2.6 Long-term Sedimentation Studies: Methods of Extending Flow Records

Sediment regimes take many years to establish and as such morphological or sedimentation studies in rivers must be considered long-term investigations. While there exists many historical datasets of river flows for particular rivers, it is impossible to know exactly what the flow in the river will be one day ahead never mind 50 years. Therefore, through the years many different methods have been developed and utilised to solve the problem of extending flow series. These methods have generally fallen into two different categories; those which have been employed by hydraulic modellers assessing the effect of sedimentation, and those which have been used by stochastic modellers for the express purpose of extending existing hydrological time series. A review of some of the current literature regarding these methods is presented. It aims to discuss and criticise some of the more widely used techniques.

2.6.1 Methods Employed by Hydraulic Modellers

Within the literature there have been several different methods employed by hydraulic modellers, which aim to combat the problem of extending existing hydrological time series for the purpose of testing the long-term effects of different hydraulic designs. The methods tend to simplify the process in order to make the long-term simulations more conducive to computer modelling purposes, or use empirical methods to help predict sedimentation without extending these records. However, in terms of extending flow series, for synthetic or simulated series to be useful, when they are used as the upstream boundaries for these long-term models, they must bear a resemblance to the historical series, which they are trying to mimic in terms of statistical properties that reasonably describe the historical data. These properties are often defined as the sequence statistics such as the mean, standard deviation, skew and autocorrelation.

2.6.1.1 Recycling

One of the simplest methods employed involves merely recycling the historically recorded time series (Havis, Alonso & King, 1996; Zeigler & Nisbet, 1996; Otto, 1999; Wright, Holly, Bradley & Krajewski, 1999). In these studies, a historical daily flow series, recorded at a gauging station over a period of around 50 years, was implemented as the upstream boundary of a hydraulic model. These flows were then used to simulate long-term effects in waterways. This method has the benefit of preserving the flow series statistics perfectly, thereby creating a realistic situation for modelling. However, river discharge is driven by weather conditions and is therefore an inherently stochastic process. In recycling historic data the random element of the stochastic process is being ignored, since the historic flow series is unlikely to be repeated again and therefore is not representative of the future response of the system

(Matalas, 1967). A long flow record is a further requirement for this method, which may pose problems, as extensive, continuous flow records are not commonplace.

2.6.1.2 Individual Flood Hydrographs with Long-term Interpolation

Another method, which appears to be widely used to predict long-term changes, uses particular representative flood hydrographs for the watercourse being modelled (HR Wallingford, 1992 (a); Annandale, 1992). The hydrographs are modelled deterministically using one or multi-dimensional hydraulic models, depending on the degree of detail required, to show flow and sedimentation patterns during these floods. It is then possible to extrapolate from these particular hydrograph predictions, either by stochastic means or deterministically, to give an overall prediction for sedimentation or flooding problems for the future. This method has some serious problems, especially when considering long-term sedimentation patterns. If each hydrograph is simulated separately then this method takes no account of the erosive force of the flood acting on previously deposited material. For example, each "typical" hydrograph is modelled only once and then the results are interpolated to give a long-term prediction. Simulating a few hydrographs and not a continuous series of flows does not take account of how the river reacts to smaller floods between these larger events. Perhaps smaller floods do not have an erosive effect, thus leading to more deposition. Then, if the bed has been raised the effect of the "typical" hydrograph will be modified the next time it occurs on the river and less deposition will occur. This will result in different prediction of long-term sedimentation amounts and consequently the different water heights during floods. Modelling of "typical" hydrographs also gives no information to the modeller regarding how long it will take the river to reach regime. This type of modelling that uses cumulative short-term predictions to explain long-term effects in watercourses tends to over predict sedimentation results (HR Wallingford, 1992(a)) and is notoriously difficult (Odd, 1990). This over-prediction stems from the fact they neglect to take into account the cumulative, stochastic nature of flow series.

2.6.1.3 Regime Theory

To depart from these deterministic methods, a functional method is proposed by Spearman et al. 1996 and Dennis et al. 2000. This hybrid model uses a one-dimensional flow model for the flow dynamics coupled to a morphological algorithm to model sediment movement. The morphological algorithm was based on a relationship between tidal flow and estuary cross-section, which effectively uses the hydraulic parameters as an input to predict the evolution of the estuary. This process is an iterative one, which assumes the estuary is in some regime state at the beginning of the investigation. The civil engineering works are then added to the model and the new hydraulic parameters are calculated, which act as the input to the morphological algorithm for the purpose of predicting the evolution of the estuary. The geometry of the estuary is updated after each new prediction. This process is repeated until the change in successive estuary geometries has fallen to 5% of the original value. The number of iterations the process required can then be used to predict the time which it will take to return the estuary back to regime by matching the volume of accretion predicted by one tidal cycle with that predicted by one iteration. This method has been successfully used for the Thames estuary to predict the long-term effect of the barrage (Spearman et al. 1996) and the Lune estuary to investigate the effect of a training wall (Dennis et al. 2000). In addition the same general principle was implemented to investigate the long-term effects of a barrage in the Severn estuary (O'Connor, 1990 cited in Spearman et al. 1996).

However one of the main problems with this technique is the need for detailed pre and post construction field surveys, which are often unavailable. Certainly, for the case of the Tees barrage a pre-impoundment survey was not available despite attempts by the author to obtain one. This method offers a potentially powerful tool for assessing the long-term impacts of civil engineering schemes, despite this; it requires a large amount of information to begin with, which is not always readily available. In addition, the method predicts the evolution of the estuary, but may not do this in sufficient detail for all studies.

2.6.1.4 Prediction of Trapping Efficiency

Reservoir sedimentation is a large area of research with many studies investigating the prediction of sedimentation in these bodies of water. The Tees barrage study could be considered as a reservoir sedimentation study due to the fact that the barrage is a total exclusion type, which permits no saline intrusion upstream. Therefore the barrage can be treated the same way as a dam. The barrage creates a long, narrow impoundment, which acts in the same way as a reservoir and traps sediment. A very popular method for predicting sedimentation in reservoirs is by applying an empirical relationship, which predicts trap efficiency, for example Brune's Curves. Brune's curves have been criticised for their generality and often their use is inappropriate because of the local hydrodynamic conditions, which exist within the reservoir. The curves describe the dynamics of sedimentation using the capacity of inflow only, which takes no account of the source or type of sediment arriving into the reservoir. These basic curves have been used extensively and over the years researchers have developed these curves to create new and simpler trap efficiency relationships (White, 1990; Reeve, 1992; Carvalho, 1999; Siyam, Yeoh & Loveless, 2001). However, these models have the disadvantage of not providing the user with any estimation of the distribution pattern of the sedimentation, rather they provide the user with an overall trap efficiency of the reservoir, which in turn can provide the information required to predict the useful lifetime of the reservoir. These curves tended to be popular before the widespread use of computers and nowadays methods exist to predict more detailed estimates of trapping efficiency and distribution patterns together. For the Tees barrage project the prediction of sedimentation patterns was an essential part of the research, thus the use of Brune's curves, or other empirical relationships were disregarded as a possible method.

2.6.1.5 Flow Exceedence Curve Method

Meadowcroft, Bettess and Reeve, 1992, presented a different method for predicting reservoir sedimentation, which calculated both trap efficiency and the sediment distribution throughout the system. The method uses numerical models to provide a more detailed assessment of the sedimentation than is provided by Brune's curves and avoids using recycled flow data. A one-dimensional model is utilised despite the fact that is will not model the local effects such as scour round outlets because this type of numerical model can be used for long-term modelling due to its non-computer intensive nature. The model is a time stepping model which uses flow conditions calculated at a particular time step to compute sediment transport predictions. For this method it is necessary to make the assumption that because changes in flow conditions take place on a much shorter time scale than sedimentation changes, the flow can be regarded as steady for each time step. By this it is meant that flows can be split into a series of steady flows and the calculation reduces to a series of backwater calculations. Then the sedimentation can be predicted for each steady flow state. The series of steady flows can be estimated from the flow exceedence curve calculated for the river (HR Wallingford, 1988; Copeland, 1989; Randle, 1989; Bettess, personal communication, 2001). The flow exceedence curve holds some of the statistical information of the flow series, and can be translated into a series of steady flow durations for the year. For example, a flow that is exceeded for 1% of the time would be modelled for 3.65 days for every year into the future the model was required to predict. The flow structure for this model is entirely based on the flow exceedence curve, which means that the flows are fed into the model in decreasing order of magnitude. Therefore the short, intense flows are modelled first; followed by the longer, lower flows, which is then looped annually for the desired length of flow series. This method is based on the assumptions:

- the data is independent,
- the ordering of the flows does not matter, and
- seasonality is not accounted for.

Physically, this means that the method does not allow for the random nature of flow series, rather it requires the flows to be fed into the model in increasing order of occurrence. This imposes a structure on the flow regime, which bears no resemblance to the historic data, preserving none of the stochastic nature of the flow. Yet, on the positive side it does continuously model long-term effects in the system, which avoids attempting to add short-term predictions to produce long-term recommendations. Additionally, this method does maintain some of the statistical properties of the time series, like the mean, but it has the disadvantage of not reproducing the autocorrelation of the series at all. A detailed investigation into the effect of using this method rather than a truly stochastic flow series for long-term prediction is described further in section 4.2.

2.6.2 Methods Employed by Stochastic Modellers

For many years a branch of hydrology has been interested in forecasting or extending existing recorded time series using different methods of an overall branch of analysis known as time series analysis. This branch of research is particularly interested in reproducing the statistics of the hydrological events as accurately as possible. Hydrological events, similar to other meteorological or geophysical processes such as wind speeds, precipitation and earthquakes, are considered to involve a large amount of irregularity and uncertainty. To interpret the phenomena into ways in which they can be understood it is necessary to break them down. Stochastic processes can be described in terms of two components, one deterministic and one probabilistic or random (Chow, 1978). The deterministic part can be thought of as a trend while the random component is often referred to as noise. Thus a stochastic series can be determined by finding the deterministic trend and using the probabilistic noise to represent the errors around this trend (Chow, 1978). To identify these properties in a time series, it is necessary to have a record of considerable length, which can be problematic when extending river flow series, as long records can be difficult to find. Obviously, if there is a long record at a site then there is more data on which to base the analysis meaning that the analysis can be considered more robust (Lawrance & Kottegoda, 1977).

If a sequence of measurements is denoted:

$$\{x_t\} \text{ for } t=1,2,\ldots,n$$

Equation 2. 1

and is termed a time series, then the probability model for the time series can be denoted as:

$$\{X_t\} \text{ for integer } t$$

Equation 2. 2

Often these series are seasonal and to analyse these accurately the seasonal trends must be removed. It is necessary to check this time series for stationarity. A random process is stationary in the mean if the mean doesn't change over time (Metcalfe, 1997).

$$E[X_t] = \mu$$

Equation 2. 3

A recorded time series can either be stationary or non-stationary therefore before a model is chosen the stationarity of the series must be determined.

2.6.2.1 ARMA Models

ARMA models are general linear stochastic models and are made up of two different types of model; the auto-regressive (AR) type model and the moving average (MA) type model, both of which are termed 'short memory' models (Lawrance & Kottegoda, 1977). This term derives from the fact that the model is based on the short-term memory or autocorrelation function of the series being analysed. Each part of the ARMA model will be explained separately as each can be used independently or collectively.

Firstly, the auto-regressive (AR) type of model is very useful for practically occurring time series. The current value of the process can be determined from a finite linear aggregate of the previous value of the series and a random component or shock (Box, Jenkins & Reisnel, 1994).

$$X_t = \alpha X_{t-1} + E_t$$

Equation 2. 4

Where E_t are the errors or residuals around the relationship, which make up the shock or noise component. A process { X_t } is auto-regressive of order p (AR (p)) if:

$$(X_t - \mu) = \alpha_1 (X_{t-1} - \mu) + \cdots + \alpha_p (X_{t-p} - \mu) + E_t$$

Equation 2. 5

If the process is of order one (AR(1)), then this is known as a Markov process as it has the Markov property (equation 4.1). However, these models can also be of higher order, which implies that more of the short-term history of the series is used to create the stochastic series. The model has always got p+2 unknown parameters $\mu, \alpha_1, \alpha_2, \cdots, \alpha_p, \sigma_E^2$ which have to be estimated from the data. σ_E^2 is known as the variance of the noise or residuals E_t, which are left after the Markov part of the model has been fitted. However, to fit the model, an assumption must be made beforehand on the distribution of these residuals. There has been widespread debate over the starting assumption for this distribution (Lawrance & Kottegoda, 1976;

Peagram, 1989; Boxet al., 1994). No clear consensus has emerged; consequently a trial and error method is commonly used

The moving average (MA) model is similar, however this time the current value of a process is linearly dependent on a finite number q of previous random shocks E_t. A moving average process (MA) of order q defines a process by;

$$X_t = \mu + E_t + \beta_1 E_{t-1} + \cdots + \beta_q E_{t-q}$$

Equation 2. 6

Again this model has q+2 unknown variables; $\mu, \beta_1, \beta_2, \cdots \beta_q, \sigma_E^2$ which must be estimated from the original series. Unfortunately, the same problem exists regarding making an assumption *a priori* for the distribution of the residuals, thus a trial and error method must be employed.

An ARMA or autoregressive moving average model combines the two separate models described above. These models are often combined for the reasons of parsimony, as it may be possible to model a process using fewer parameters than using either an AR or a MA model singularly. An ARMA model of order (p,q) defines a process as;

$$X_t = \alpha_1 X_{t-1} + \cdots + \alpha_p X_{t-p} + E_t + \beta_1 E_{t-1} + \cdots \_ \beta_q E_{t-q}$$

Equation 2. 7

This model can be simplified by introducing the backward shift operator *B*,

$$BX_t = X_{t-1}$$

Equation 2. 8

Which can be written more generally as,

$$B^n X_t = X_{t-n}$$

Equation 2. 9

Thus, the ARMA model can be written:

$$\phi(B)X_t = \psi(B)E_t$$

Equation 2. 10

where $\phi(B)$ is a polynomial in B of the order p, and $\psi(B)$ is a polynomial in B of the order q.

These models are simple approximations of the rather more complicated process that occurs naturally. Determining the order of the model, affects the accuracy of the outcome however, there is no one correct answer but the simplest model is usually the best, using the principle of parsimony (Metcalfe, 1997). The correlogram of the series and the partial correlation function (*pacf*) can be used to determine the order required for a model. More guidance on fitting these models can be found in, Box & Jenkins, 1976, Box et al. 1994, or Metcalfe, 1997.

AR, MA or ARMA models have been utilised extensively in hydrology, to forecast time series (Peagram, 1980; Wright et al. 1999; Salas & Sin, 1999; Abrahart & See, 2000). They have often been used to model monthly or annually averaged flows with some success however it may prove difficult to simulate high flows with this method (Matalas, 1967; Lawrance & Kottegoda, 1977). Historically, hydrologists have tackled this problem by separating out the high flows and applying some type of extreme distribution to accurately model them, yet this is not possible with the autoregressive models. Additionally, some criticism has been levelled regarding the generation of daily streamflows (Xu, Schumann, Brass, Li & Ito, 2001), where the prominent features of shorter flows have not been accounted for using ARMA methods.

2.6.2.2 ARIMA Models

If the recorded series is known to be non-stationary, as many series are in hydrology, then a different type of model is required. For example series that are not deseasonalised are non-stationary. One of the important properties of this type of model is that, not only can it model both stationary and non-stationary processes; it can possess autocorrelation structures, which do not damp over long lags. Thus this model can be termed a long memory model (Chow, 1978). An ARIMA (autoregressive integrated moving average model) uses some of the theoretical basis from the ARMA model as it is made up from autoregressive as well as moving average parameters, however it explicitly includes differencing in the model formulation. An ARIMA (p, d, q) model is constructed from (p) autoregressive parameters, (d) number of differencing passes and (q) moving average parameters. If the theory of the model starts with the basic equation for the ARMA model (Equation 2. 10) where $\phi(B)$ is the stationary autoregressive operator, the model can be written as;

$$\phi(B)\nabla^{d} X_t = \theta(B)E_t$$

Equation 2. 11

where ∇^{d} is a differencing operator of the power d which is defined by;

$$\nabla = 1 - B$$

Equation 2. 12

Therefore the model corresponds to the assumption that the d^{th} difference of the series can be represented as a stationary ARMA (p, q) process (Box et al. 1994).

The basic type of model has been used and developed throughout literature (Schreider, Jakeman, Dyer & Francis, 1997; Montanari, Longoni & Rosso, 1999). However, again the same problems remain as for the simpler ARMA models, thus the extreme flows may not be modelled accurately, especially in terms of daily stream flow generation, which in turn affects the reproduction of the skew of the series.

2.6.3 Discussion on Methods of Extending Flow Records

This overview of methods utilised for extending flow records is not an exhaustive review, nor is it meant to be. The aim was to review some of the more popular methods that have been employed in recent studies. What is clear from this review is that there is still no generally accepted method for extending flow records, and some of those that exist involve complicated techniques or tend to over-simplify long-term trends. Therefore, it would be desirable to develop a method of extending flow records which is simple and easily utilised by engineers for long-term modelling studies. In addition to this it would be ideal if the proposed method could take into account the possible effects of climate change on river flows.

2.7 Summary of Key Aspects

The aim of this chapter was to review current literature which is relevant to long-term barrages sedimentation studies. Firstly a concise overview was presented regarding the impact barrages have on their environment and how this can relate to sustainability issues. To ensure sustainability of present structures it is necessary to carry out long-term investigations to understand their impacts under existing and future climate situations. A review was then presented of the numerical methods that have been utilised in the past for such studies, with a discussion on the most suitable method. Then, finally the current methods utilised to extend flow records which provide the boundary condition for the numerical methods and are an important component of the predictive models, were discussed and criticised. This overview aimed to highlight the most important and relevant research relating to the subject of long-term sedimentation studies.

Most investigations and modelling for barrage impact assessment tends to be completed at the design stage, and as such it is essential that long-term predictions and monitoring are part of the research priorities for the future (HR Wallingford, 1999). Any construction erected in a waterway will have an impact on the hydraulic and sediment regime of the channel, changing the sediment transport capacity of the channel and forcing a new depositional pattern which can impact on flooding levels and the useful life of the impoundment. The hydraulic regime will be instantly changed while the sediment regime will take many years to adjust. An added complication arises when the impact of climate change is considered, as this may have a large effect on river flows and water resources. Therefore, in today's society, with the increased emphasis on sustainability and environmental issues, it is imperative that the behaviour of this new regime is assessed and understood by taking into account all possible factors.

Numerical models have proved to be a useful and important tool for predicting impacts of construction in waterways. The dimensionality of the mathematical model affects the detail of the prediction and the run time of the model. Thus a compromise must be made when long-term continuous investigations are required. Some detail must be sacrificed if continuous runs are used as a method of analysis as higher dimensional models can prove too time-consuming to be a viable option at present, although this could change in the future. Continuous runs are the preferred method as extrapolation of long-term forecasts from short-term predictions can be notoriously difficult and conservative.

If continuous runs are chosen as the best method, it is necessary to extend the flow records for the river into the future so that they provide an upstream boundary condition for the numerical model. This problem has been addressed in many different ways by hydraulic and stochastic modellers alike. Many methods used by hydraulic modellers tend to oversimplify the problem in an attempt to make the modelling straightforward, however it can mean that the results are over predicted, or the position of the deposition is different, as they do not take into account the inherently stochastic nature of flow series. Alternatively, stochastic modellers have developed more complicated methods, which reproduce yearly and monthly flows well but still do not predict daily flows to the same degree. Therefore there is a need for a simple method for extending flow series, which is easily utilised by engineers and has the capability to incorporate climate change scenarios into its forecasts.

As a consequence, the purpose of this thesis is to carry out a long-term sedimentation study on the River Tees, post impoundment, with the aim of assessing the impoundment's sustainability, using numerical modelling that accounts for climate change and develops a method for extending flow records.

Chapter 3: Data Collection

3.0 Introduction

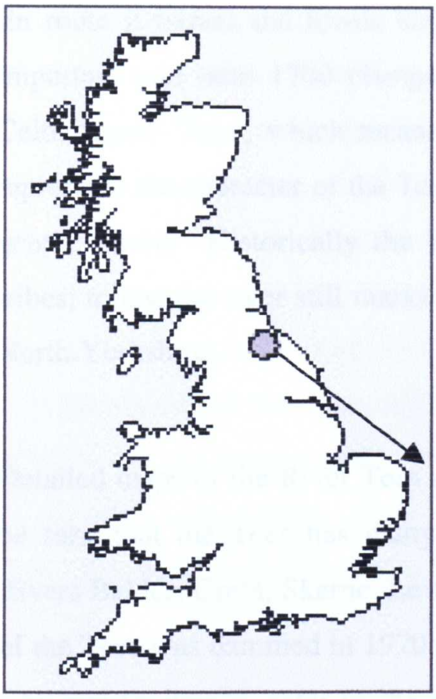
This chapter aims to describe the catchment and the history of the River Tees. It will describe the ongoing monitoring on the River Tees, explain the data collection that was completed in the summer of 2000, and detail the interpretation of the fieldwork.

Computational modelling of flow and sedimentation in rivers requires a large amount of topographic and hydrological data. This includes measured flow and sediment inputs at the boundaries of the model, and detailed topographical data of the river basin and its surrounding floodplains. Due to the absence of a pre- or post-impoundment topographical survey data, a field data collection campaign on the river was required to gather the necessary information.

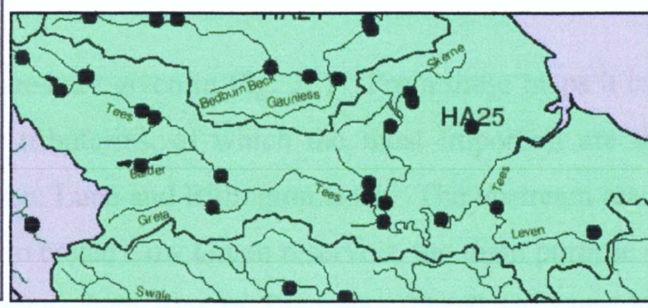
3.1 River Tees Catchment

The Tees River basin has a catchment area of 1906 km^2 (Hudson-Edwards et al. 1997) and is located in the North East of England, UK (Figure 3.1). The source of the Tees is in the Pennine hills at an altitude of about 600m O.D. on the eastern slopes of Crossfell. From there the river flows through a valley for approximately160km to the sea at Middlesbrough.

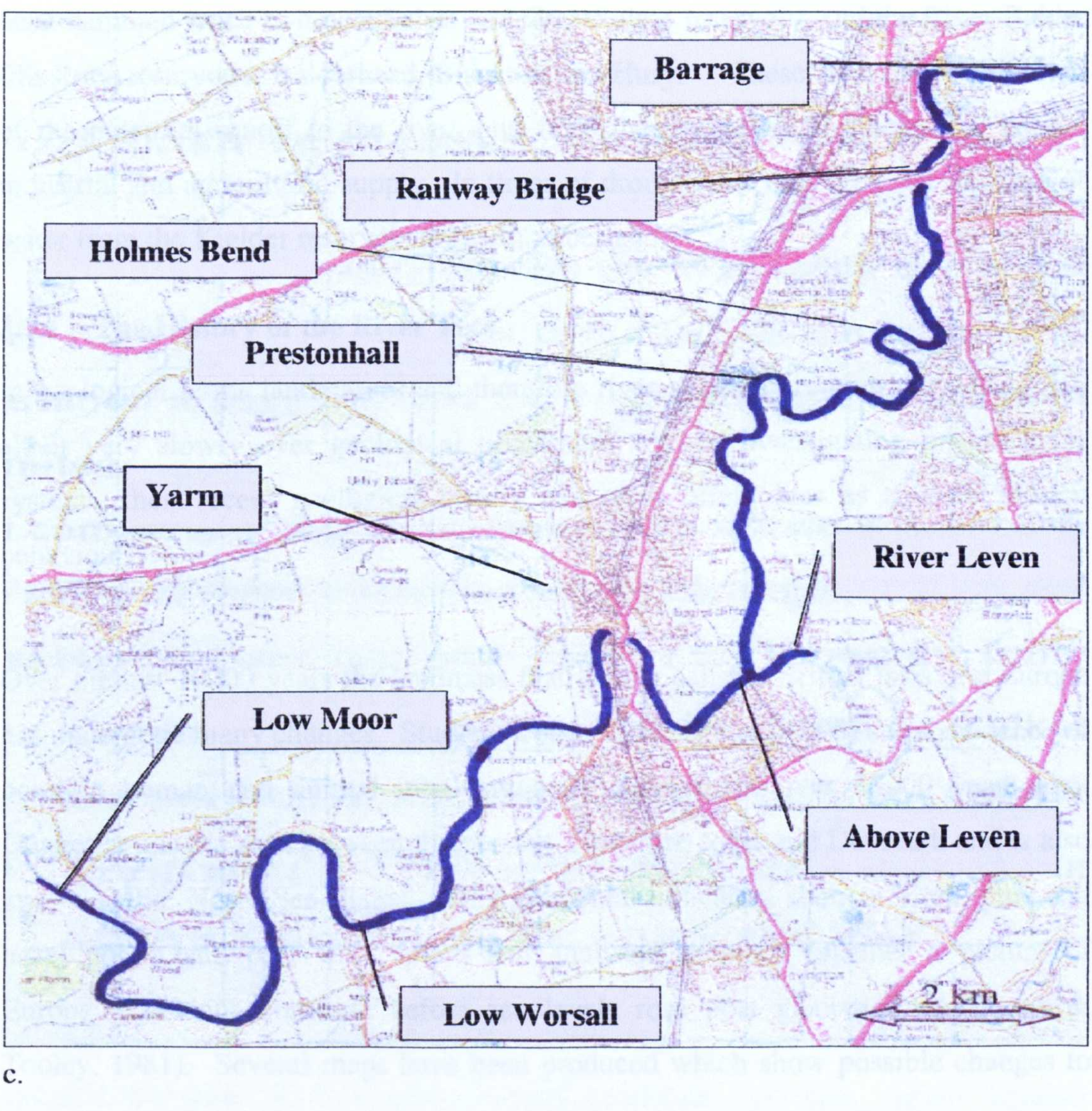
Fig. 3. 1 Maps showing: a. the situation of the River Tees in Northern England, b. detail of the whole catchment (a & b from NRA webbsite), and c. map showing the lower section of the River Tees, upstream from the barrage.



a



b



c.

En route it passes the towns of Darlington and Yarm. Yarm was the Tees most important port until 1700 (Simpson, 2002). The name Tees was derived from the Celtic name 'Teis', which means 'boiling, surging water'. This phrase accurately represents the character of the Tees during a flood, when it is changed from its usual gentle nature. Historically the Tees has marked the border between regions and tribes; today, the river still marks the boundary between the counties of Durham and North Yorkshire.

Detailed maps of the River Tees area are given in Fig. 3. 1. From these maps it can be seen that the Tees has many tributaries, of which the most important are the Rivers Balder, Greta, Skerne, Leven, Lune and Billington Beck. The upstream reach of the Tees was dammed in 1970 to create Cow Green reservoir, the main purpose of which is to supply water to the many industries in Teesside. The River Lune has been dammed twice to create Selset and Grassholme reservoirs and the River Balder fills three reservoirs; Balderhead, Blackton and Hury. These reservoirs store some of the potential runoff to the river, and from them water is abstracted for public, industrial and agricultural supply. In times of drought the Tees recieves transfers of water from the Kielder reservoir in Northumberland.

3.1.1 The History of the River Tees

In geological terms landmasses and therefore river systems are constantly changing albeit very slowly over geological timescales. When investigating present river systems, their recent geological history can often offer clues as to their present behaviour.

Over the last 10000 years the landmass that is now call the British Isles and Europe has undergone many changes. Studies (Coles, 1998; Brejck, 1995) show evidence of possible human and animal inhabitation in Doggerland over 10000 years ago. Doggerland is the area between the present Yorkshire coast and Denmark and is also known as the North Sea Plains. Environmental indicators such as birch, pine and hazel pollen and peat were found and analysed to piece together a picture of Europe's previous coastline before sea levels rose post glaciation (Simmons & Tooley, 1981). Several maps have been produced which show possible changes to the landmass around the Tees estuary, indicating a rise in sea levels since the period of glaciation. Maps devised by Coles and Roulliard (Coles, 1998) indicate that Europe was once one landmass connected via Doggerland. River basins such as the Elbe may once have stretched out into what is now the North Sea. This is interesting when investigating the River Tees itself because it is sensible to assume that as the sea level rose, the tidal limit of the Tees River encroached further inland. It would appear that the tidal limit of the Tees estuary has fluctuated over the last 10000 years very slowly due to these possible changes to the coastline. Consequently, this might indicate that the estuary itself may be relatively robust and able to deal with change as regards sedimentation. The new tidal limit as created by the barrage may be closer to where the historical tidal limit has been in the geological past.

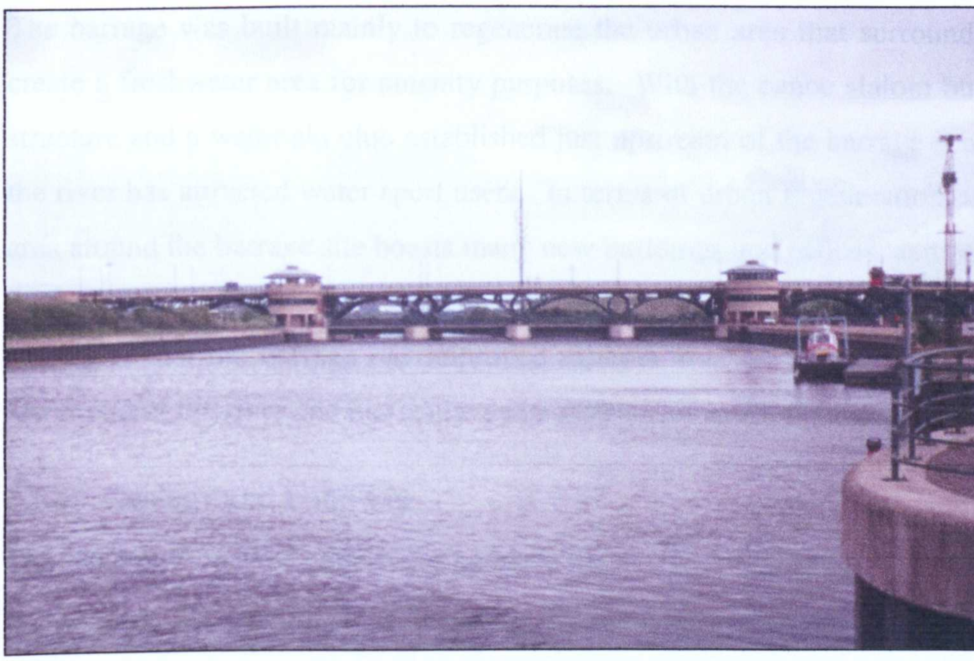
Looking at more recent historical trends within estuaries can also aid the understanding of a particular river especially with regards to sediments and the contaminants held within these.

With the arrival of the Stockton to Darlington Railway in 1825 came a period of industrialisation for the River Tees and the first chemical works were established on its banks in Egglescliffe in 1833. Alongside these chemical factories sat steel and iron works which, despite helping to make the lower Tees valley a major industrial centre, caused problems for the river itself. In the 1920s the Tees was considered the third most important salmon fishery in England, but concerns about the impact of reservoirs and industrial pollution on the aquatic life were identified (Sheail, 2000). In particular effluents from the coke ovens, necessary in the production of steel, were identified as having a toxic effect on fish. During the inter-war years a Standing Committee on Rivers Pollution (SCORP) was created nationally, which was the driving force behind several surveys carried out on the river. Their surveys discovered that not only did the effluent from the coke ovens impact on the aquatic life but also the eight large sewers that discharged untreated sewage into the river also affected the state of the water.

By 1926 ICI (Imperial Chemical Industries) had invested heavily to create a chemical complex at Billingham, which produced fertilisers, heavy organic chemicals and chlorine (Nelson, 1999). Slowly, chemical and petro-chemical companies began to replace the more traditional steel and iron industries on the Tees attracting big companies such as Monsanto, Rohm, Shell Oil and Phillips Petroleum to the area. Nowadays the oil refineries in Teesside make up 10% of the total UK capacity and with discharged waste products ending up in the river, industrial pollution remains a problem. By 1970, the Tees was considered to be one of the most polluted estuaries in the UK, with the water in the estuary almost completely depleted of oxygen.

In the 1980s a major pollution control initiative cut the amount of domestic sewage that was discharged into the river. This lead to an increase in the amount of oxygen in the river and the first steps towards the regeneration of the estuary. In 1987, a barrage on the Tees was proposed, partly in an effort to regenerate the waterside area and attract more businesses, and partly to improve the water quality in the estuary (Nelson, 1999). Years of pollution from heavy industry had affected not only the water in the Tees but the sediments too. The proposed barrage site was to be Blue House Point, which was just upstream of most of the major polluters in the estuary. This way the proposed total exclusion barrage would protect the upper river from the tide spreading the polluted water upstream. In 1992 work began on the Tees barrage, and by January 1995 the barrage was operational.

The barrage was designed to be a total exclusion barrage; it incorporates a navigation lock on the right bank and on the left bank a purpose built canoe slalom and a fishpass. It is 70m long, with four separate gates; each gate is 13.5m long, 8.1m deep and has a mass of 50 tonnes. The barrage is managed to keep the upstream impounded water to a level between +2.35m and +2.85m above ordnance datum (HR Wallingford, 1992). This is similar to the high tide level of the river before the barrage was built, and creates a freshwater lake. Fig. 3. 2 a. shows the barrage from upstream looking downstream with the navigation lock on the right hand side, while Fig. 3. 2 b. shows the canoe slalom that is built into the structure.



a.

b.

Fig. 3. 2 a. Tees Barrage, taken upstream looking downstream and b. Canoe Slalom (courtesy of free.foto.com)

The barrage was built mainly to regenerate the urban area that surrounds it and to create a freshwater area for amenity purposes. With the canoe slalom built into the structure and a water-ski club established just upstream of the barrage it is clear that the river has attracted water sport users. In terms of urban regeneration, the riparian area around the barrage site boasts many new buildings and offices, and has attracted the University of Durham to build its new Stockton Campus on its banks. Therefore, it is clear that the barrage has improved riparian area for amenity purposes at the lower end of the river and has achieved its purpose of urban regeneration.

3.1.2 Geology and Land Use

The different types of underlying bedrock for the Tees catchment are wide ranging. In the East the catchment is underlaid by Jurassic sediments, while in the west sediments are more predominantly Carboniferous (Novis, 1999). In the upper parts of the River Tees and its tributaries the river flows over bedrock and bouldery channels, whereas further down the catchment the underlying geology is harder to ascertain, as it remains hidden under construction and vegetation.

The tributaries of the River Tees drain different land areas, from the Pennines (River Tees headlands) to moorland. The River Leven drains from the south (North York Moors) to the north through one of the more geologically varied areas, passing over Mudstone, Lias and Quaternary tills, and has a tendency to carry very high sediment loads during high flows (White, 2001). In comparison, the River Skerne drains from north to south over predominantly magnesian limestone and through towns such as Darlington and Newton Aycliffe. Built up areas can impede mud reaching rivers by covering up the sediment sources; however, run-off from these areas can be larger and quicker due to the impermeability of the land.

The geology of the catchment can be an important factor in explaining the land-use around the river. For example, the North West of the catchment has history of heavy metal mining and the abundance of lead in the geology has meant that there is evidence of mining as far back as 1279 (Simpson, 2002), although archaeological evidence implies it may have commenced in Roman times (Macklin, Hudson-Edwards & Dawson, 1997). In the west of the catchment, the Tees descends from the Pennines into Upper Teesdale. The land use in this area is predominantly for rough grazing although there are sections of moorland.

Fig. 3. 3 Land use in the Tees catchment – arable land (farmland and water meadows)

Fig. 3. 4 Land use in the Tees catchment – industrial (business parks)

Further down the catchment towards Barnard Castle in lower Teesdale, land use is mainly rural and used for grazing, with some small villages. Then the river flows on towards the larger towns in the lower catchment, such as Darlington and Newton Aycliffe on the River Skerne. The Tees itself passes through more arable land (Fig. 3. 3) until just before the Leven confluence (Fig. 3. 1), where the river flows between Egglescliffe and Yarm. After Yarm, the river flows through intensively farmed agricultural land, until it reaches the built up areas of Stockton on Tees (Fig. 3. 4), just upstream of the barrage. This area has benefited most from the barrage construction with new businesses and offices moving to a riverside position.

Land use is an important issue when investigating sedimentation in rivers and reservoirs. Many studies have been produced which consider the effect of vegetation and land use changes on the sediment load observed in streams (Mitchell, 1990; Singh, 1998; Rompaey, Govers & Puttemans, 2002). Deforestation can be one of the main contributors to increased suspended sediment reaching watercourses, but from the land use description above it is clear that this is not a major problem for the River Tees catchment.

Agricultural and intensively cultivated areas are among the main land uses on the banks of the River Tees and its tributaries. This type of land use can cause an increase in sediment supply to rivers, especially in areas where the soil is compacted as this decreases infiltration and therefore increases surface runoff and sediment supply (Mitchell, 1990). Another form of farming practice, animal grazing, can also increase sediment supply. If animals are allowed unrestricted access to the riverbanks this can result in the banks becoming unstable and suffering severe erosion (Bowie, 1999). Certainly bank collapse has been observed on the River Tees (White, 2000), however whether this is directly related to grazing is difficult to ascertain.

In urban areas, while runoff is increased due to little or no infiltration, sediment supply is reduced as tarmac covers most sources. This kind of decrease in sediment supply in conjunction with increased flow can lead to and overall erosion of the bed;

however, during the period of urban construction it is a different story, with sediment supply being increased as much as 200 times (Thorne, Hey & Newson, 1997).

3.1.3 Previous Studies

Several recent studies have investigated the Tees catchment; for example the LOIS (Land-Ocean Interaction Study) project investigated the effects of heavy metal pollution from historical mining activities in the rivers of the North East of England, UK. In particular, they studied the dispersal processes, deposition, storage on floodplains and the re-mobilisation of these polluted sediments. (Macklin et al. 1997; Hudson-Edwards, 1997).

Perhaps the most important work, which has been completed on the Tees catchment in terms of this project are the pre-impoundment studies conducted at HR Wallingford Ltd in 1992 (HR Wallingford, 1992). This report used pre-impoundment topographical data of the Tees basin; unfortunately, despite concerted enquiries, the author was unable to locate this information. As a result the Tees impoundment was re-surveyed in the year 2000 and consequently the topographical information used for this work is from 6 years after the river was impounded (discussed later in section 3.3). In the HR Wallingford Ltd report the pre-impoundment data was used to create several computer models using the: TIDEFLOW-2DV, SALTFLOW-2DV and MUDFLOW-2DV software packages. These models were calibrated and used to predict upstream sedimentation after the construction of the Tees Barrage (method discussed in section 2.5.2.1 and 2.6.1.2). This report investigated the effect of representative floods, the 1:1 year flood (350 m^3/s); 1:10 year flood (550m^3/s); a 100 m^3/s flood and a period of 15 days at 32 m^3/s. These were modelled using design hydrographs and sediment information for flows up 65m^3/s (collected between 1985-89) provided by Northumbrian Water. Additional observations for suspended sediment concentrations over this threshold were made by the National Rivers Authority (NRA) at Low Worsall in 1990. However, very few observations at high discharges were made, which led to uncertainty in the accuracy in the rating curve for high flows. No information on how this suspended sediment data was collected was included in the report.

In addition to the above, the HR Wallingford Ltd report calculated estimates of the annual suspended sediment yield for the years 1986-1990. From these calculations it is clear that the annual sediment yield from the Tees and the Leven varies widely; the report quotes values of total annual yield in the region of 10,000-60,000 tonnes depending on the magnitude and frequency of the fluvial flood events and the value of the daily mean flow.

Previous to this study in 1992, some one-dimensional modelling was completed on the Tees at the design stage for the barrage. This was completed to investigate the long-term effects on the sedimentation in the impoundment following the closing of the barrage (HR Wallingford, 1988). A flow exceedence curve method was used for this research, which is described in more detail in section 2.6.1.5.

Now that the barrage has been operational for eight years, new data had to be collected to make this project viable. Topographical data had to be collated in the absence of any available pre-impoundment data, and in addition, flow and suspended sediment information at the top end of the modelled reach was necessary.

3.2 Monitoring

To create an accurate, effective and useful computer model of any river it is necessary to obtain detailed information on the flow and sediment inputs for the modelled reach. The Tees has several operational monitoring stations along its length, details of which are given below.

3.2.1 Environment Agency

The Environment Agency (EA) has, in total, eighteen monitoring stations on the River Tees and its tributaries. These stations hold long-term records of flow magnitudes from as far back as 1956. The lowest station on the River Tees itself is situated at Low Moor (Fig. 3. 1), which is just upstream of the old tidal limit of the river and has been operational since 1970. The station at Low Moor monitors the flow from upstream through this section and as Low Moor marks the upstream extent of the computer model it provides valuable historical flow information for this work.

The station itself is a velocity-area station and has good calibration, which has been confirmed even at high flows (NRFA, 2002). The National River Flow Archive (NRFA) has allowed access to flow data from this particular gauging station from as far back as 1975, although there have been some interruptions to this data due to problems with the equipment. The flow data that has been made available is in either 24 hour averaged or 1 hour averaged form, depending on the year it was recorded. Where the data is in 24 hour averaged form it has been calculated over the water day, which is 9am to 9am the next morning. The water day is calculated such, because 9am is the time that manual rain gauges were emptied every morning, and to remain consistent with historical data it has remained as a standard.

3.2.2 Flow and Suspended Sediment Monitoring by Durham University

Continuous flow and suspended sediment modelling commenced at the beginning of this project in 1999, although the design and calibration of these stations occupied most of the summer of 1999 (White, 2000). Low Moor gauging station was considered to be the best place to install the equipment as the Environment Agency (EA) already had an established flow gauging station at the same place (Fig. 3. 5). In addition to this, the position of Low Moor is just upstream of the old tidal limit of the river. After an initial visit to the river it was decided to take Low Moor as an upstream boundary for the computational model for several reasons;

1. This point marks the old tidal limit of the river and the highest point at which the barrage affects the river.
2. The lowest Environment Agency gauging station on the Tees is situated at Low Moor therefore a long flow record from 1970-2000 was available.
3. As part of the SIMBa project suspended sediment was monitored at Low Moor over the period of a year by Durham University. This provided essential input information for the model.
4. There is a weir at Low Moor, which mostly prevents bedload sediments from progressing downstream and leaves the measured suspended sediment as the major component for sedimentation.

While it is understood that bedload sediments will be able to progress downstream some years after the weir has been completed, and in periods of large fluvial flood, this investigation has concentrated solely on the impact of suspended sediments.

The suspended sediment monitoring equipment was established and maintained by Durham University with whom this project is linked through an EPSRC grant. The instrumentation included a self-cleaning nephelometric turbidity sensor, which continuously monitors the turbidity of the water. At the same time a pressure transducer monitors the river level, and the information was logged every fifteen minutes (White, 2000). Water samples were taken using an automatic sampler, which was programmed to sample according to increments of flow. For example when the flows increased or decreased by the programmed amount, samples were taken, as it was hoped this would ensure a more uniform testing of the flow distribution (following Wass and Leeks, 1999). The station became operational in November 1999, and resulting flow and suspended sediment data was made available for modelling purposes. Data collection was disrupted by the outbreak of Foot and Mouth disease in February 2001 (White, 2001).

Fig. 3. 5 Low Moor Gauging Station

From the turbidity measurements the 15-minute suspended sediment concentration data was derived. The water samples, which were taken mainly during high runoff events, were then filtered and the suspended sediment concentration was determined in order to compare it with the turbidity data and construct a sediment rating curve.

The rating relationship derived was:

$$Q_s = 2.1123T^{0.769}$$
$$R^2 = 0.88$$

Equation 3. 1

Where Q_s is the suspended sediment concentration (mgl^{-1}), T is turbidity (NTU) and R^2 value is the coefficient of determination, which lies in the range $0 \leq R^2 \leq 1$. The closer the value is to 1 means the more variability in the data which can be explained by the regression equation, therefore the closer the R^2 value is to 1 the more accurate the equation.

Preliminary results from the station showed that the peak suspended sediment concentrations lagged behind the peak flow for storm events. The Tees has a large catchment and this is characteristic as the principal sediment sources are usually in the headwaters (Thorne et al. 1997). For these river systems the flood peak usually travels down the river faster than the sediment can be transported by the flow and leads to a predominantly anticlockwise hysteresis in plots of discharge versus sediment concentration.

Following the unusually high rainfall that the Tees catchment experienced through the early autumn and winter of 2000/2001 a change in sediment supply was evident from the data (White, 2001). Data recorded suggested that the series of extreme runoff events, which occurred in November 2000 caused a significant change to the previous sediment transport response to such events. Sediment concentrations were much higher, and in contrast with previous behaviour the sedigraph peak began to precede the hydrograph peak. In addition, variability not related to the flow became much more evident. At the time, the suggestion was that this was caused by the mobilisation of new sediment sources, which were predominantly closer to Low Moor than before. Observations of bank collapse following the autumn 2000 floods were observed during a walking survey and confirm the explanation for the observed change in behaviour (White, 2002).

A comparison of sediment yield for the Tees catchment was compiled by Durham University using the calculated sediment yield for the year February 2000 to January 2001 (Table 3. 1). As can be seen this calculated value is over twice the average estimate quoted in the design report for the Tees Barrage (HR Wallingford, 1992). To put this into context it is necessary to look at the total annual flow for the same period, which reflects the extreme hydrological conditions experienced over the winter 2000-2001, and shows an annual flow of almost double that estimated for Low Moor (1970-1990) in the HR Wallingford report. So, in terms of sediment yield per unit flow, the data for 2000/2001 while still higher than estimated in the design report is not as extreme as comparison of sediment yield alone would suggest (White, 2002).

	Calculated for year Feb 2000 to Jan 2001	Annual average estimates from HR Wallingford (1992)
Sediment Yield (tonnes)	85598	35630[1]
Sediment Yield per unit area (t km^{-2})	67.7	28.1
Total flow (mm)	771	453[2]
Yield per unit flow (t mm^{-1})	111	78

Table 3. 1 Comparison of calculated annual sediment yield for 2000-2001 with annual average estimates from (HR Wallingford, 1992) (from White, 2002)

Notes:

1. From Table 1, HR Wallingford (1992)
2. Average total flow at Low Moor from 1970-1990 (except 1973 and 1974, based on Table 3, (HR Wallingford, 1992)

While it is probably not unusual for rivers like the Tees to change sediment transport regime over a timescale of years in response to extreme events (White, 2002), long-term monitoring would be required to further understand this characteristic. What does seem clear is that over the monitored period the Tees has changed regime in response to extreme runoff conditions. With on-going climate change, it may transpire that in the future, extreme flows, and the resulting increase in sediment yield, will become more common.

From this data, it is possible to derive a relationship between flow and suspended sediment known as a sediment rating curve, which is an important input parameter for modelling the Tees. The relationship is described in more detail in section 3.4

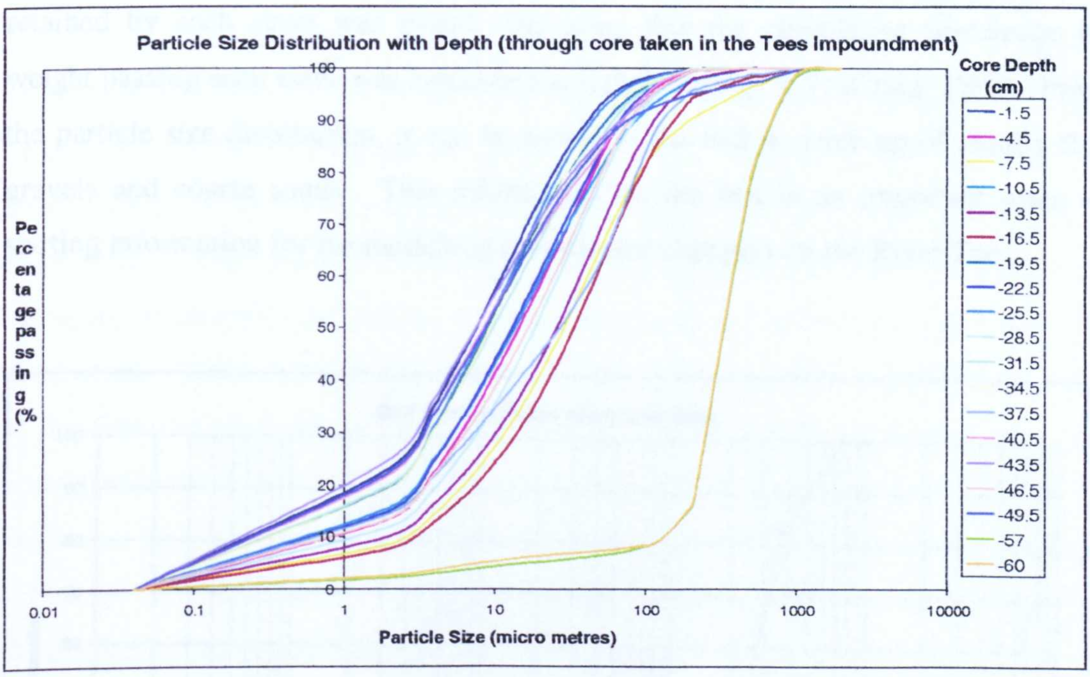


Fig. 3. 6 Graph showing change in particle size distribution through the core taken upstream of the Tees Barrage, interpreted as the boundary between pre and post impoundment

3.2.3 Sediment Cores and Bed Samples

Durham University collected and analysed sediment cores directly upstream of the barrage. A particle size analysis was completed at several cross sections at different depths through the cores on a Coulter system laser granulometer. This piece of equipment accurately measures silt size fractions but is less accurate for sand and clay. A distinct change from sand and silt to clay was identified in the cores at a depth of 50 and 55 cm down through the core. This change was interpreted as the marker for the boundary between the pre and post impounded river (Fig. 3. 6), and can be used to validate the sediment transport in the modelling section. Although the depth of sediment post impoundment can be measured physically in the cores, the rate of sedimentation is much harder to assess. What is not clear from the core is when and how much sediment was deposited at any particular time. This phenomenon is discussed further in section 5.5.3

Bed samples were taken upstream of Low Moor to give a representative particle size distribution for the bed of the river. The samples were taken using a grab sampler extended from the boat in the centre of the river, and then analysed at Glasgow University. The analysis was completed by passing the soil through a series of standard test sieves with successively smaller mesh sizes. The weight of the soil retained by each sieve was found, and using this the cumulative percentage by weight passing each sieve was calculated and plotted (Fig. 3. 7) (Craig, 1992). From the particle size distribution, it can be seen that the bed is made up of mainly fine gravels and coarse sands. This information on the bed is an important piece of starting information for the modelling of sediment transport on the River Tees.

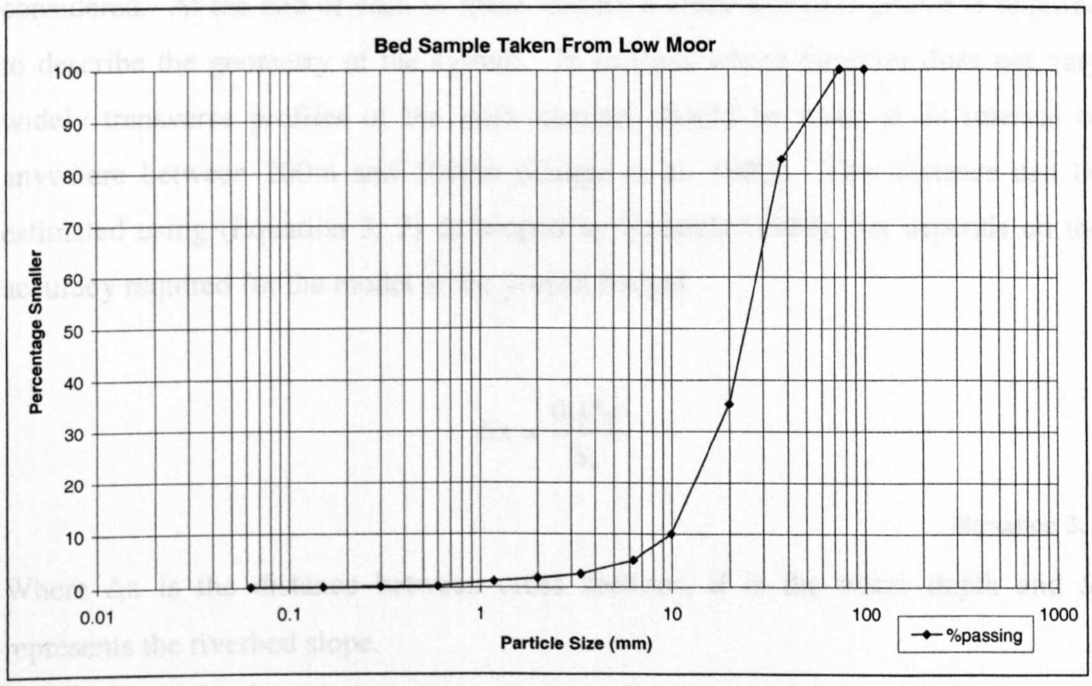


Fig. 3. 7 Particle size distribution of bed sample taken at Low Moor

3.3 River Tees Field Survey

Due to the lack of availability of pre-impoundment topographical data for the River Tees a survey, aimed at gathering detailed information of the riverbed and surrounding banks, was initiated in the summer of 2000. Topographical data, in cross-sectional form, was required for the entire 25km length of the impounded section of the River Tees from Low Moor at the upstream end to the Barrage at the downstream end.

The topographical data required to set up a one dimensional mathematical river model stems from the hypotheses on which the shallow water flow equations are based, and must describe the geometry of the simulated system. When designing or completing a survey it is necessary to break up the river or watercourse into a series of imaginary reaches. These reaches should not include rapid changes in cross-section or singular head losses or control structures; in fact each reach should be small enough to remain hydraulically similar throughout its length. In a river where there exists a high density of hydraulic structures (e.g. bridges, weirs) or a rapidly changing cross-sectional shape, a greater amount of short reaches should be considered. At the end of each of these reaches a cross-sectional profile is required to describe the geometry of the system. In sections where the river does not vary widely transverse profiles of the main channel should be taken at an interval of anywhere between 200m and 5000m (Cunge et al. 1980). This distance can be estimated using (Equation 3. 2) developed by Samuels (1989), but depends on the accuracy required for the model or the project budget.

$$\Delta x = \frac{0.15d}{S_0}$$

Equation 3. 2

Where Δx is the distance between cross sections, d is the water depth and S_0 represents the riverbed slope.

Samuels (1989) provides some guidance on locating cross sections on rivers where the hydraulic conditions are not interrupted by hydraulic structures. The information required at each cross section should supply the elements necessary to define channel width, cross-sectional areas, special features of the riverbed (pools, riffles etc.) and the definition of the banks and floodplains outwith the normal bank-full system. The distance between each of these cross sections is required to determine the overall bed slope and the whole survey must be tied into a common level datum. The two extremes of the surveyed reach act as the boundaries for the model; if there are any tributaries through the modelled length these too must be surveyed for they are considered to be external boundaries to the model.

3.3.1 Surveying Method

The survey was completed in two two-week periods during the summer of 2000. The author designed the survey and it was completed with the extensive help of Durham University as regards equipment hire and personnel. Surveys are designed either by undertaking a walking tour of the river ahead of time or from detailed, large-scale maps of the area. The latter method was used for the position of cross-sections on the River Tees, using previous centreline survey maps from the Teesside Development Corporation. These were modified on site as the survey progressed if the maps had not been sufficiently detailed, or if the situation of one particular transect was not physically possible.

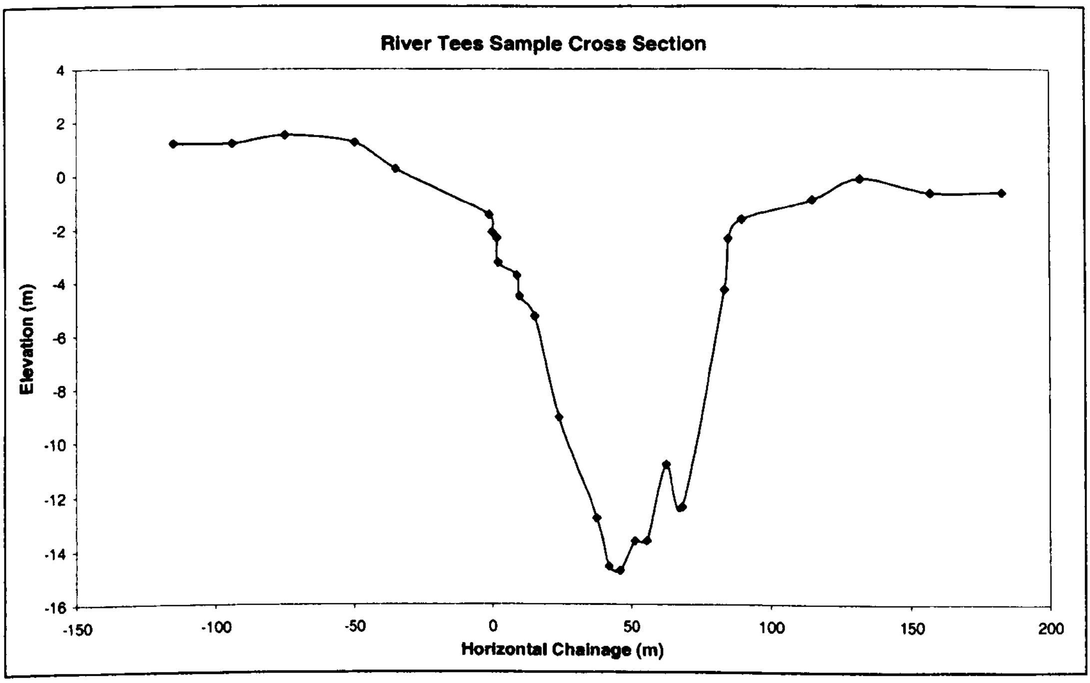


Fig. 3. 8 Example of a surveyed cross section translated into 3D co-ords from the River Tees

Fig. 3. 9 Total Station, Survey on the River Tees

Initially it was proposed that the survey would be completed using a logging Global Positioning System (GPS) in conjunction with a logging echo sounder. After one day of using this on site in conjunction with a total station the data from the GPS was downloaded and plotted to reveal that the accuracy in the x and y co-ordinates was insufficient for the purpose. The precision z-coordinate was found to be very variable and since it is very important that the z-co-ordinate for a hydrographic survey is accurate to within 10mm, the use of the GPS was abandoned. This discovery was a set back to the project, as GPS systems are very quick and easy to use; had a more recent, advanced model been available the survey time would have been, at least, halved.

To complete the survey an open traverse method was employed, using a Sokkia Total Station. The Total Station (Fig. 3. 9) was positioned on one bank at what was termed a station and recorded the bank height and water level on each side of the river for each transect/cross-section. The first position of the Total Station was chosen to be at a Temporary Benchmark (TBM) by the barrage, which gave a useful reference point for tying in the survey to ordnance datum. The Total Station was moved from station to station along the river by boat, which was bought by Durham University for the SIMBA project. One person manned the Total Station at all times and one person with a target on a staff walked each bank. The targets were placed at points on the bank and by the water for each designed cross-section as mentioned earlier.

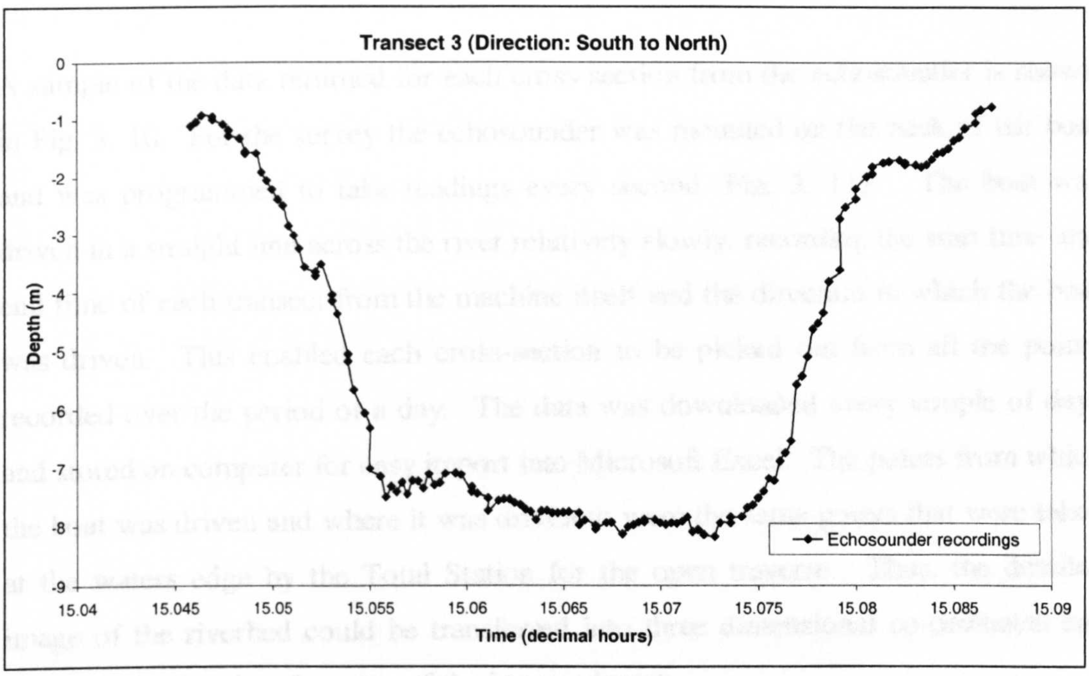


Fig. 3. 10 Sample output from the echosounder

In hydrographic studies it is very important to gather a large amount of information about the shape of the riverbed. This is impossible to do by using an extension of the open traverse method through the riverbed, as the Tees is, at points, a very deep, fast-flowing river. Keeping a target on a staff, perpendicular to the bed in the middle of a large river is impossible, so another method had to be found. Echosounding is a common method used in such circumstances. This is a piece of equipment that uses transducers to transmit and receive acoustic signals. The depth of the water is measured by timing the interval between the transmission of a pulse of sound energy from the boat and its reception after reflection at the riverbed. The accuracy of measurement depends on matching the recorder's time scale with the velocity of the acoustic pulse, which can be calibrated using a known depth of river. Calibration was completed on the river and the accuracy of the echosounder used was found to be within ±10mm. Problems can arise with an echosounder due to the fact that the beam of sound is not always transmitted back cleanly and as a result, the machine can occasionally give false readings. Indeed small potholes can be missed and when operating over steeply sloping beds the machine can record what is termed as false depths; for example it may give a randomly deep value at a particular point, which does not fit the rest of the data. Hence, care should be exercised when interpreting the results recorded.

A sample of the data returned for each cross-section from the echosounder is shown in Fig. 3. 10. For the survey the echosounder was mounted on the back of the boat and was programmed to take readings every second (Fig. 3. 11). The boat was driven in a straight line across the river relatively slowly, recording the start time and end time of each transect from the machine itself and the direction in which the boat was driven. This enabled each cross-section to be picked out from all the points recorded over the period of a day. The data was downloaded every couple of days and stored on computer for easy import into Microsoft Excel. The points from which the boat was driven and where it was driven to were the same points that were taken at the waters edge by the Total Station for the open traverse. Thus, the detailed image of the riverbed could be transferred into three dimensional co-ordinates and produce a comprehensive map of the impoundment.

Fig. 3. 11 Boat used for survey of the Tees, containing 2 Technicians from Durham University

This process of using an open traverse linked to an echosounder, which recorded the make up of the bed, was completed for a 25km stretch of the Tees (from the barrage to Low Moor Gauging Station). Fig. 3. 12 shows graphically the design of the survey. Cross sections were recorded approximately every 200m (smallest distance

75m; largest distance 350m) taking care to reflect all the special features of the riverbed shown by the echosounder (Cunge et al. 1980). The survey included 105 measured profiles along the River Tees and two profiles on the River Leven, which is a major tributary about 12km upstream from the barrage. At the upstream end the survey was tied into another benchmark at Low Moor, which meant it was possible to assess the error in the process over the vertical dimension. Comparing the difference between the predicted heights of the benchmark from the survey and the actual value according to ordnance datum gave an error of ±200mm over the vertical dimension over the full 25km of the survey.

Through the course of the survey, several problems were encountered. One of the main obstacles to the survey was gaining permission from the riparian landowners who were not always happy about lending their banks for the survey. Indeed this held up the survey for a couple of days until permission was given for one section of land bordering the river. Their problem, which they felt had not been taken into account, was that they believed the barrage had caused increased bank collapse and erosion of their land.

Another set back to the survey arose when the equipment failed. The total station was tested most mornings to check that it was working properly. One morning a fault was noticed, so it was taken to the closest repair centre, which happened to be in Sunderland. Although this was relatively near in terms of distance, it lost the survey a couple of days while the equipment was repaired.

On a practical level, some problems were encountered while on the river itself. Deciding to complete the survey in the summer had advantages and disadvantages. On the positive side, the weather was warm and, theoretically at least, drier; however, on the other hand, the foliage was thick and this made sighting of the targets and orientating cross-sections more difficult. As a solution to this problem, a handsaw was kept in the boat in case it was possible to remove some of the offending branches. One other practical problem came with the echosounder, which recorded a minimum depth of 0.42m. This only became a problem towards the upper end of the Tees and was solved in places by taking extra points using the Total Station.

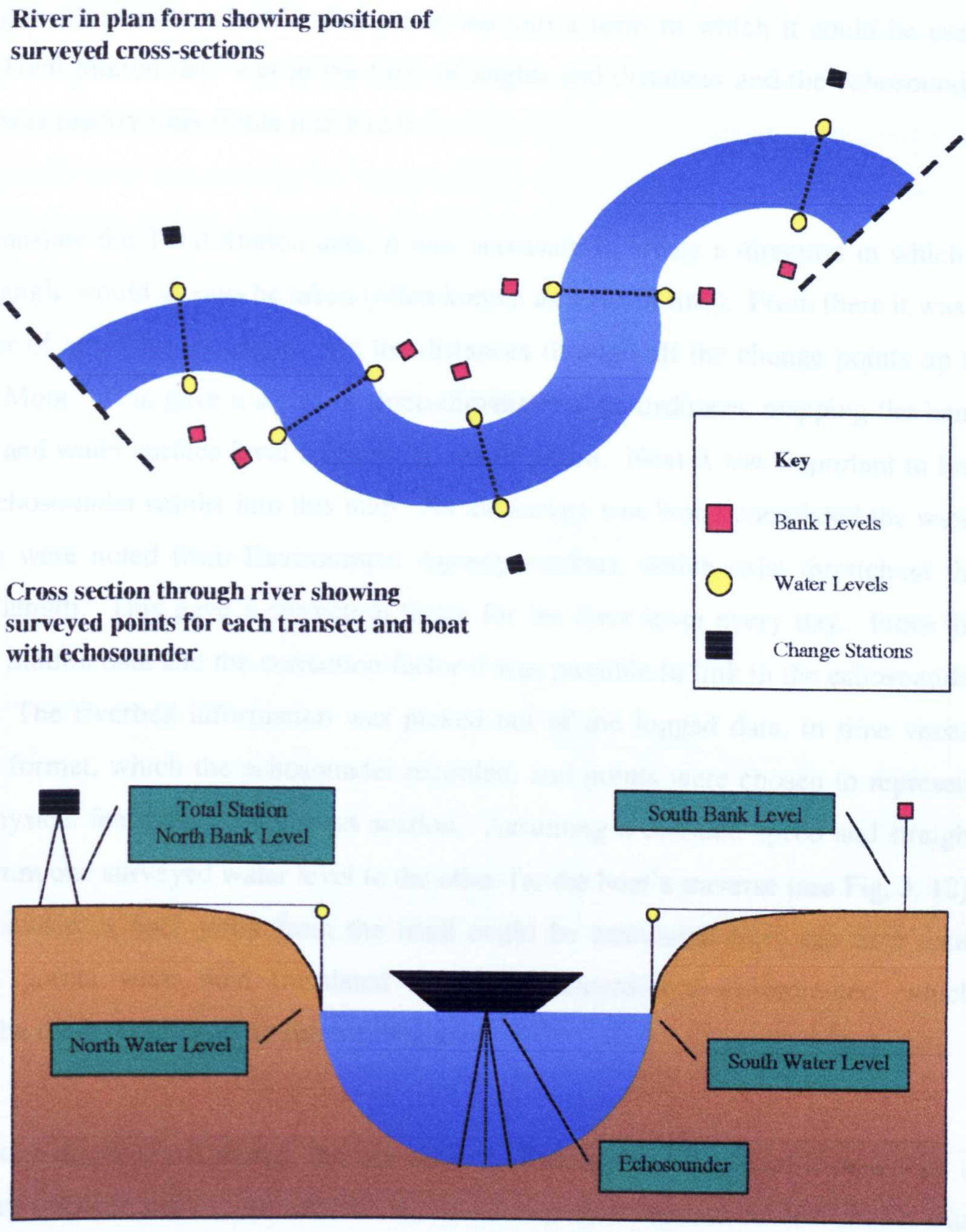


Fig. 3. 12 Diagram showing the design and layout of survey method for the River Tees.

3.3.2 Data Processing

Once the raw data had been collected on the river itself, the information was sent to Glasgow University where it was processed into a form in which it could be used. The Total Station data was in the form of angles and distances and the echosounder data was readily importable into Excel.

To translate the Total Station data, it was necessary to create a direction in which a zero angle would always be taken (often known as a North line). From there it was a matter of applying the angles and the distances through all the change points up to Low Moor. This gave a series of three-dimensional co-ordinates mapping the bank lines and water surface level through the whole 25km. Next it was important to link the echosounder results into this map. As the survey was being completed the water levels were noted from Environment Agency markers, which exist throughout the Tees length. This gave a correction factor for the river level every day. From the Total Station data and the correction factor it was possible to link in the echosounder data. The riverbed information was picked out of the logged data, in time versus depth format, which the echosounder recorded, and points were chosen to represent the physical features of each cross section. Assuming a constant speed and straight line from one surveyed water level to the other for the boat's traverse (see Fig. 3. 12), the distance of each point from the bank could be calculated from the time data. These points were then translated into three-dimensional co-ordinates, which describe the riverbed and its surrounding area.

For a one-dimensional model, the raw data must be in cross-sectional format with a distance between each cross section. So, from three-dimensional co-ordinates it was necessary to change this information into coherent two-dimensional plots of each transect (see Fig. 3. 8). Once this had been completed a distance between each transect was required. Finally, with all the data in this format, the information could be used to build a one-dimensional ISIS model.

3.3.3 Survey Results

From this survey a map of the Tees impoundment was created which stretches from the barrage at the downstream end to Low Moor gauging station at the upstream end. Comparing the survey results in the vertical direction to ordnance datum through Ordnance survey results showed an error of ±200mm, which can be considered as an acceptable error considering the length of the surveyed area. A two-dimensional map of the impoundment can be seen in (Fig. 3. 13).

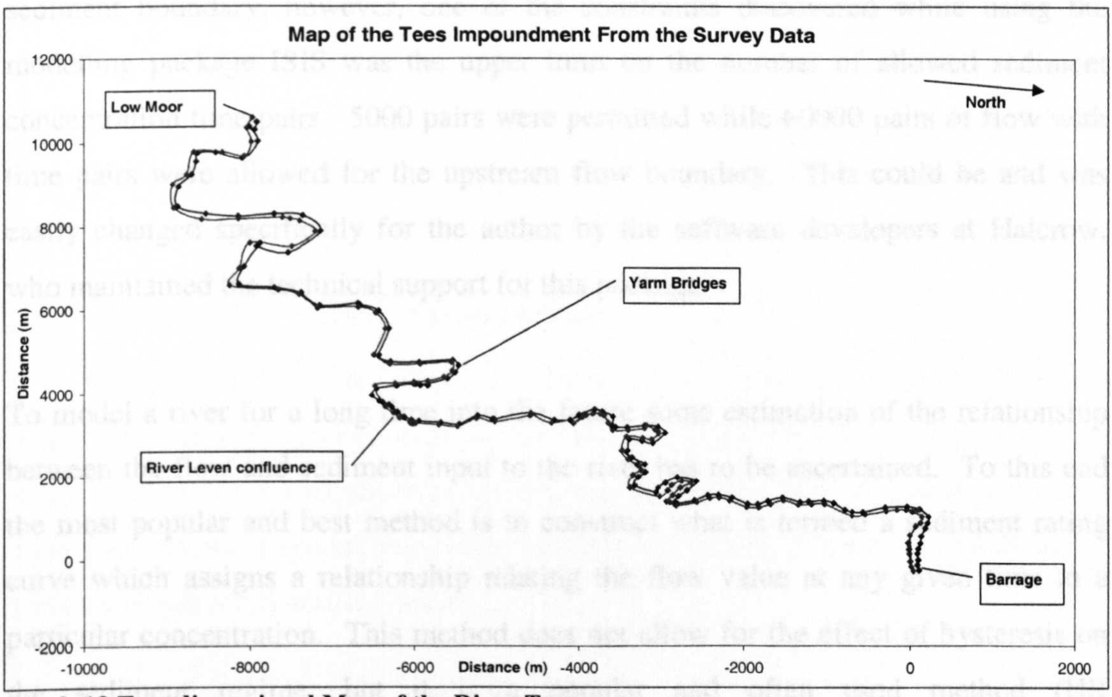


Fig. 3. 13 Two-dimensional Map of the River Tees

3.4 Interpretation of Suspended Sediment Data

A one-dimensional computer model, which simulates both flow and sediment, requires an upstream boundary condition for each component. For sediment, this upstream boundary condition can take several forms; for example, sediment transport rate with time, sediment concentration (as measured) with time or a sediment rating curve which gives sediment concentration with flow. Using the data collected, in the form of sediment concentrations over the period of a year, by Durham University, it was necessary to construct an upstream boundary condition for the long-term Tees model.

If a sediment concentration with time boundary condition is utilised, this affords more accuracy over the sediment input rather than using a rating curve. The concentration-time boundary can assign different concentrations of sediment for each time period, therefore different flows may have different concentrations associated with them, and this is more realistic than expecting each flow to have an unchanging concentration attached to it. If the concentration input has been measured for a long period of time this would perhaps be the better method of defining the upstream sediment boundary; however, one of the constraints discovered while using the modelling package ISIS was the upper limit on the number of allowed sediment concentration time pairs. 5000 pairs were permitted while 60000 pairs of flow with time pairs were allowed for the upstream flow boundary. This could be and was easily changed specifically for the author by the software developers at Halcrow, who maintained the technical support for this package.

To model a river for a long time into the future some estimation of the relationship between the flow and sediment input to the river has to be ascertained. To this end the most popular and best method is to construct what is termed a sediment rating curve which assigns a relationship relating the flow value at any given time to a particular concentration. This method does not allow for the effect of hysteresis on the sediment regime, but it is a popular and often used method (HR Wallingford,1992 (a); Janssen & Erlingsson, 2000; Holz & Feist, 1989). The mathematical equation most often fitted for a sediment rating curve takes the form:

$$Q_s = aQ^b$$

Equation 3. 3

Where Q_s is the sediment concentration in mg/L, a and b are constants fitted according to the data, and Q is the flow in m^3/s.

The raw sediment data was received from Durham University in flow against suspended sediment concentration format. The nature of the flow regime has been discussed in some detail in section 3.2.2, which highlighted a significant change in sediment supply over the period of time sediment monitoring occurred at Low Moor.

Extreme events during the winter of 2000 seem to have modified the sediment behaviour of the Tees from a river that gained most of its sediment from distant sources to one, which records a predominantly clockwise hysteresis. This change in sediment regime over the monitored period provided better understanding of the sediment regime of the Tees, which in turn could be incorporated into the model to give a more robust relationship between flow and sediment. Discussions with the partners at both Durham and Cranfield Universities led to investigations of the relationship before and after the regime changed. The sediment and flow data was split first into summer and winter data, and then re-split into pre and post October 2000 data to investigate which method better modelled the extremes of the information. The pre- and post-October 2000 split proved more useful at modelling the extreme and as such the following analysis is completed on this data.

3.4.1 Methods For Sediment Interpretation

It is important to find as robust a relationship as possible between flow and suspended sediment concentration, so that the inputs for the model can be considered to be reliable. Two methods were investigated to find the best relationship between these two factors; stepwise regression analysis and fitting a sediment rating curve. These methods are described below.

3.4.1.1 Stepwise Regression Analysis

The purpose of this method is to investigate the relationship between a dependent variable, in this case predicted sediment concentration (Q_s), and several independent or predictor variables. This method is based on the theory of multiple regressions, in which a comprehensive model, with many variables is tested, which generally takes the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_kX_k$$

Equation 3. 4

Where k is the number of predictors, $b_{1\text{-}k}$ are the regression coefficients, $X_{1\text{-}k}$ are the independent variables and Y is the predicted variable. From this complex model, each of the components of the original model are tested progressively to identify less comprehensive sub models that adequately account for the phenomenon under investigation. Finally, from all these sub-models, the simplest is picked to be the best explanation of the phenomenon. Simpler models are preferred for a number of reasons; they are easier to test in replication and cross validation studies and are more efficient to put into practice.

For this case the dependent variable Q_s was investigated along with the independent variables, flow at time t (Q_t), and both sediment concentration and flow at lag periods of time *t-1*, *t-2* (Q_{t-1}, $Q_{s,t-1}$, Q_{t-2}, $Q_{s,t-2}$). These independent variables were taken because the behaviour of suspended sediment concentration can be described partially by the conditions of the flow at the same timestep but also by the conditions of the flow and sediment previous to this. For example, if the timestep is preceded by elements describing the rising limb of a sedigraph, usually in conjunction with the rising limb of a hydrograph, a higher suspended sediment concentration than at the previous timestep should be predicted, but if these predictors map a falling limb then the concentration should be lower.

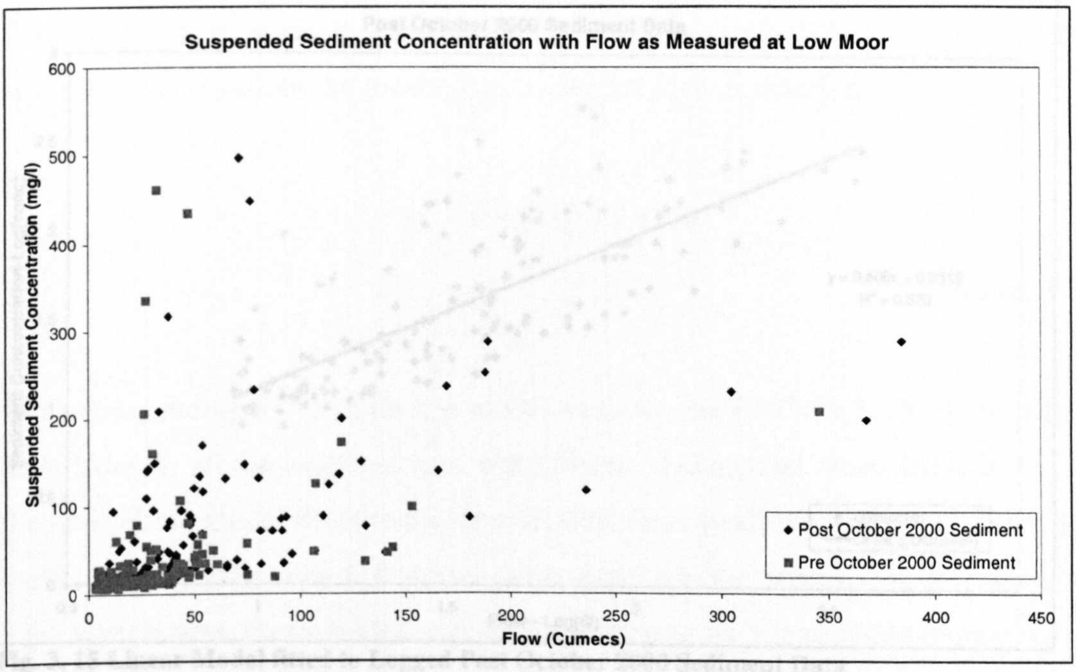


Fig. 3. 14 Flow and Suspended Sediment Concentration data measured at Low Moor split into Pre and Post October 2000 data

The base 10 logarithms of the variables and the predictor were taken, and then the data was checked for normal distribution. Taking logarithms of the data is a common statistical method for ensuring a more normal distribution of the data. A stepwise analysis was completed using the statistical package MINITAB. To find the 'best' sub model the R^2 value was maximised (as close to 1 as possible) and the c-p value was minimised (the lowest value is equal to the amount of variables being tested + 1). The most accurate model found using this method used just two variables (Q_t and $Q_{s,t-1}$) and gave an R^2 value of 0.998 and a c-p value of 3. This sounds very accurate, but when the predicted values of sediment concentration were calculated and compared to the measured data, the precision was found to be less than desirable. So, in an attempt to improve this model, an Excel spreadsheet was utilised to optimise the efficiency. The errors between the predicted and real series were calculated and squared (to remove negative values); next these errors were summed and the optimise function was used. This function allows the value in a particular cell to be minimised or maximised by changing variables in different cells, using the Generalised Reduced Gradient (GRG2) non-linear optimisation code. Despite this final calculation, the comparison between real and calculated data remained large and so another model was proposed (see Fig. 3. 18).

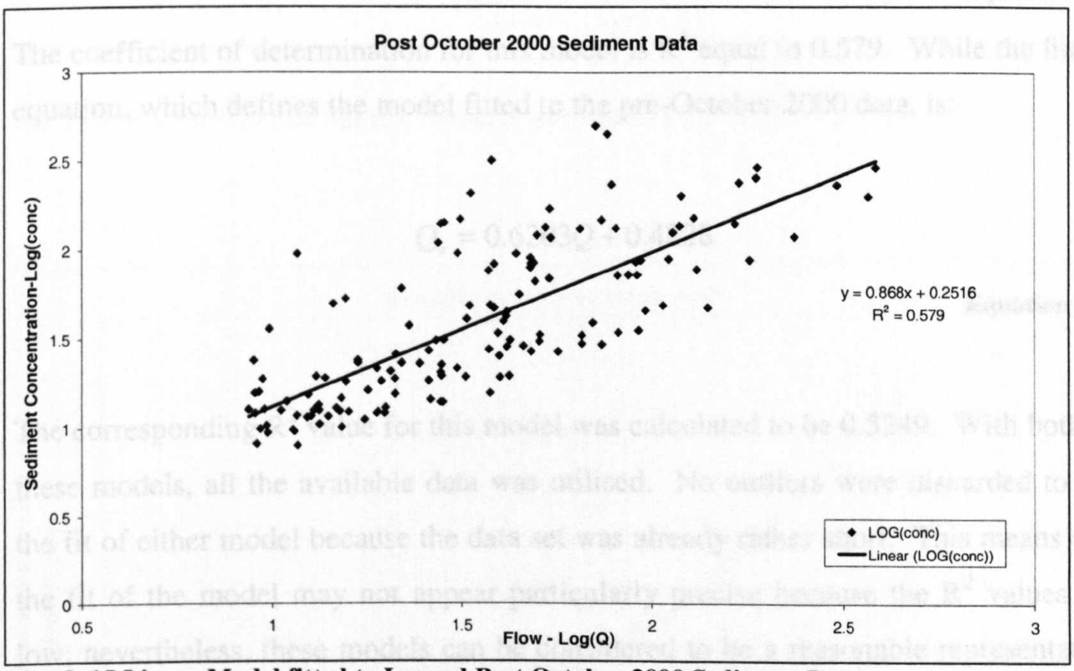


Fig. 3. 15 Linear Model fitted to Logged Post October 2000 Sediment Data

3.4.1.2 Rating Curve Method

Assigning a sediment rating curve to relate suspended sediment concentration and flow for a particular river is a very common method, in fact the HR Wallingford study on the Tees pre-impoundment used this type of relationship for their modelling work. For this method, the data was split into winter/summer data, analysed and then divided into pre- and post-October data. All details given here refer to the pre- and post-October split because this was discovered, after discussions with Sue White at Cranfield University, to give the best representation of the extremes of the data.

The first step in this procedure, after the division of data, was to calculate the base 10 logarithms of the data and then plot them on a graph. This enables a straight line or linear regression model to be fitted to the data, which can be re-arranged to give a relationship of the form $Q_s = aQ^b$. This relationship is then in the same form as a sediment rating relationship. An example of a linear model being fitted to the post-October 2000 sediment data is illustrated in Fig 3.15.

The linear equation, which defines this model for the post-October 2000 data, is:

$$Q_s = 0.868Q + 0.251$$

Equation 3. 5

The coefficient of determination for this model is R^2 equal to 0.579. While the linear equation, which defines the model fitted to the pre-October 2000 data, is:

$$Q_s = 0.6203Q + 0.4828$$

Equation 3. 6

The corresponding R^2 value for this model was calculated to be 0.5249. With both of these models, all the available data was utilised. No outliers were discarded to aid the fit of either model because the data set was already rather short. This means that the fit of the model may not appear particularly precise because the R^2 values are low; nevertheless, these models can be considered to be a reasonable representation of the data. After fitting these linear models it is important to analyse the residuals, which act as a check on the model's adequacy. A residual is the difference between a measured value of Q_s and the value predicted for it by the model; in linear regression this can be thought of as the 'vertical' distance between these two points. These residuals can either be positive, if the measured of Q_s is above the line, or negative if it is below the line, and describe the variance not explained by the model.

The main assumptions when fitting a simple linear regression model are that the residuals are independent and normally distributed, but these assumptions must be checked (Metcalfe, 1997).

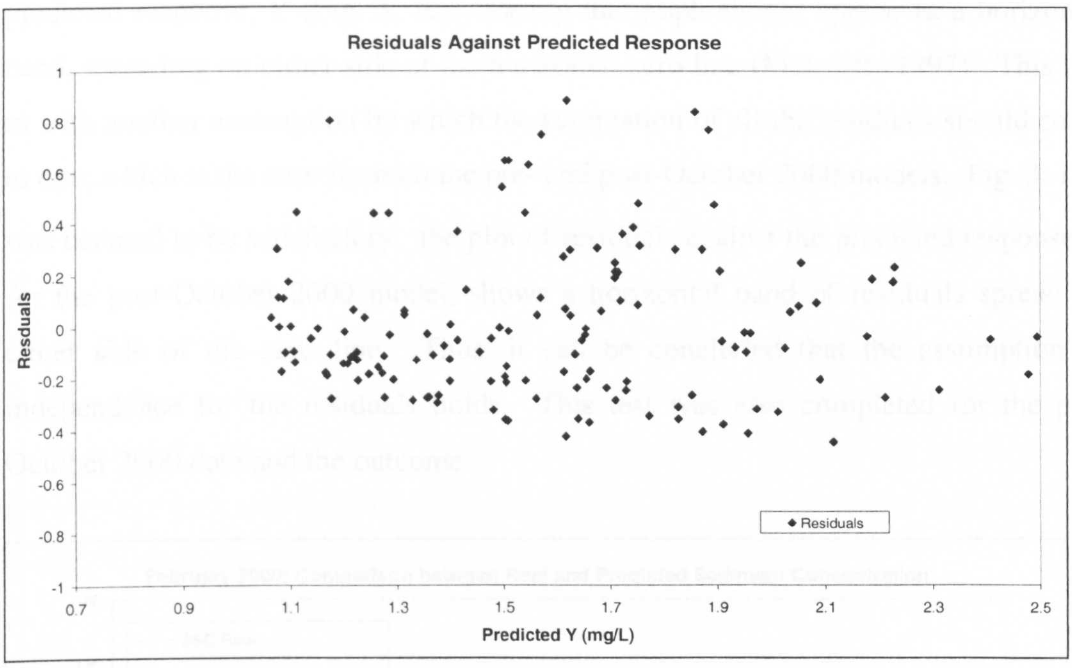


Fig. 3. 16 Plot of Residuals against Predicted Response – Post October 2000 data

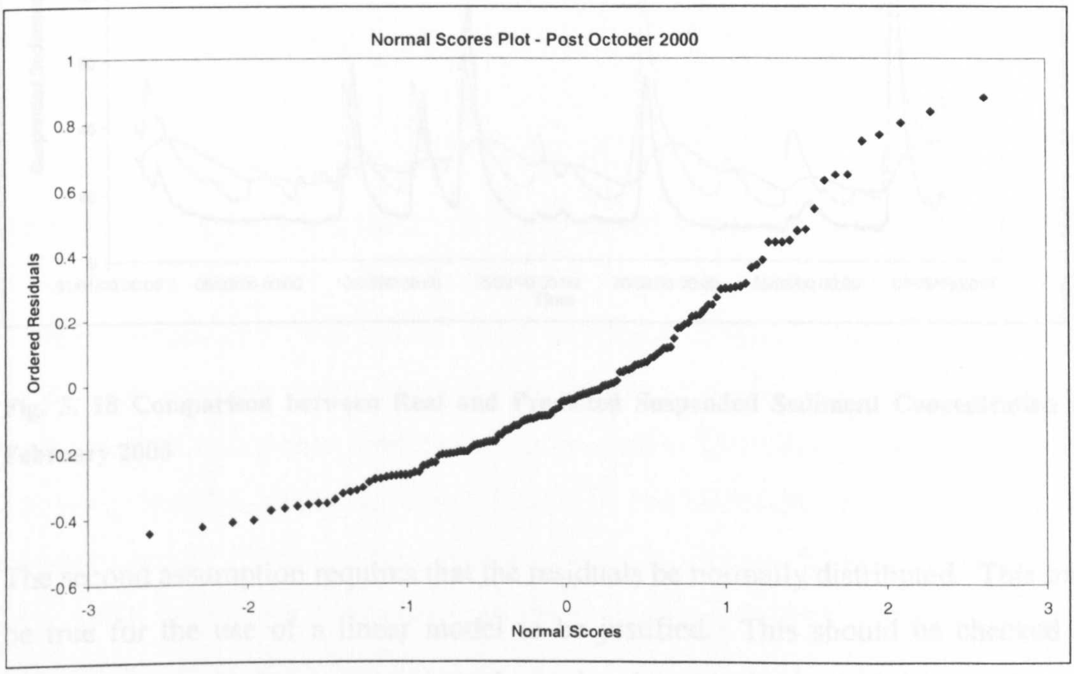


Fig. 3. 17 Normal Scores Plot – Post October 2000

The independence of residuals means that the knowledge of the error (residual) associated with one particular observation does not give any information as to how to relate this to another error attached to a different observation. In order to check that the residuals are indeed independent it is necessary to plot the residuals against the predicted response, Y (Fig. 3. 16). Ideally the graph should appear as a horizontal band, spreading on either side of the horizontal zero line (Metcalfe, 1997). This ties in with another assumption by which the summation of all the residuals should come to one, which is the case for both the pre- and post-October 2000 models. Fig. 3. 16, was deemed to be satisfactory. the plot of residuals against the predicted response Y for the post-October 2000 model, shows a horizontal band of residuals spread on either side of the zero line. Thus, it can be concluded that the assumption of independence for the residuals holds. This test was also completed for the pre-October 2000 data and the outcome

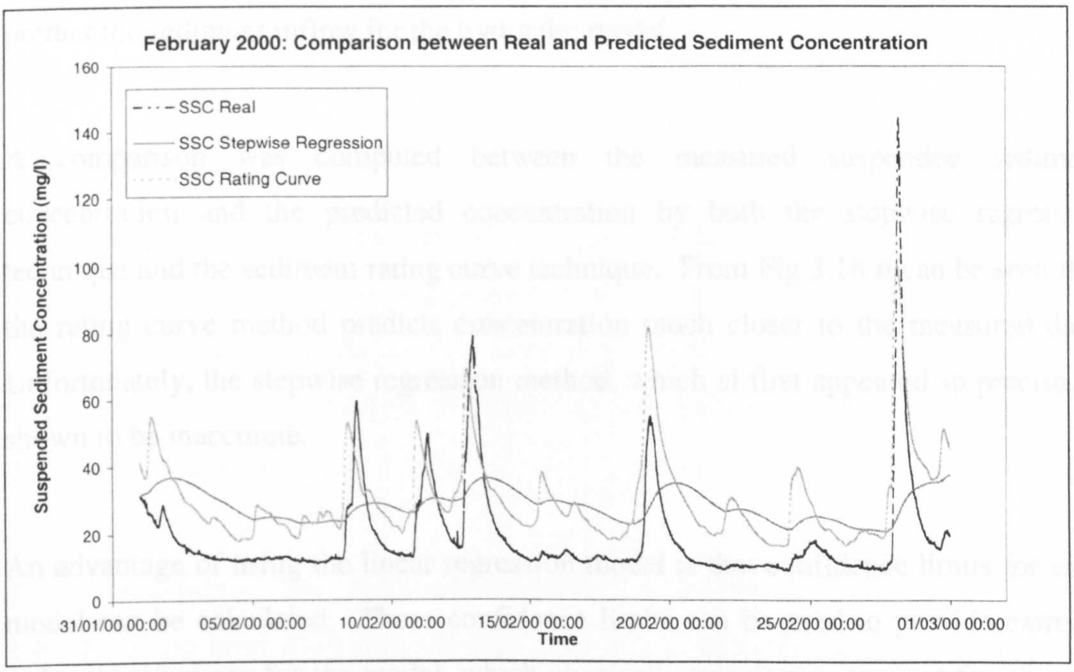


Fig. 3. 18 Comparison between Real and Predicted Suspended Sediment Concentration for February 2000

The second assumption requires that the residuals be normally distributed. This must be true for the use of a linear model to be justified. This should be checked by plotting the normal scores against the ordered residuals, and if this produces a straight line in the plot then the residuals can be considered normally distributed

(Metcalfe, 1994). A plot of normal scores against the ordered residuals for the post-October 2000 data, which were calculated in MINITAB, shows a reasonably straight line (Fig. 3. 17). The outliers in the original data have been included in the analysis and as a result the upper end of the plot becomes non-linear. However, this can be explained by the nature of suspended sediment in the Tees. At high flows suspended sediment concentration becomes less correlated with the flow as occasions of bank collapse increase the sediment concentration quickly, while the flow increases steadily. The physical explanation of this phenomenon can be seen in the hysteresis plots created and analysed by Durham University (White, 2001). The inclusion of these outliers means that the normal scores appear to deviate from normal at the upper end, but the use of a linear model can be considered justifiable despite this. Due to the nature of the suspended sediment concentration in the Tees, at the extremes of the data, the linear model is not as good at predicting the concentration, but because the main body of data is well described by the model it was chosen to predict the sediment inflow for the hydraulic model

A comparison was computed between the measured suspended sediment concentration and the predicted concentration by both the stepwise regression technique and the sediment rating curve technique. From Fig 3.18 it can be seen that the rating curve method predicts concentration much closer to the measured data. Unfortunately, the stepwise regression method, which at first appeared so precise, is shown to be inaccurate.

An advantage of using the linear regression model is that confidence limits for each model can be calculated. These confidence limits can be used to provide extreme sediment situations for the model, which physically translate to account for changes in sediment sourcing during the period the hydraulic model is run for. For example the upper 95% confidence limit model can be used to simulate high sediment input to the river, thereby giving an upper bound to the sediment predictions from the hydraulic model. This will be discussed further in sections 5.5 and chapter 6. The upper 95% confidence limits for both linear models (pre- and post-October 2000) were calculated and they take the form:

$$Q_s = 3.6939Q^{0.6936} \quad \text{pre-October 2000 – Low Sediment Scenario}$$

$$Q_s = 2.7844Q^{0.9908} \quad \text{post-October 2000 – High Sediment Scenario}$$

Equation 3. 7

The original equation, when translated back in normal form after the calculation of linear regression, was completed on the natural logarithms giving the equations:

$$Q_s = 3.0393Q^{0.6203} \quad \text{pre-October 2000}$$

$$Q_s = 1.7849Q^{0.8680} \quad \text{post-October 2000 – Medium Sediment Scenario}$$

Equation 3. 8

These sediment equations were then used to predict the upstream sediment boundary condition for the ISIS model. Having four curves to predict this boundary is perhaps too many and as a result a calibration of these curves was completed. This helped to narrow down the curves used to three. A more detailed explanation of the sediment calibration process for the ISIS model can be found in section 5.5.3.

3.5 Summary

In this chapter the River Tees has been described in terms of its catchment, geology and land use, which allows this project to be set into context. In addition, it has discussed the previous studies that have been completed on the Tees Catchment, which highlights that analysis described in the following sections has not been undertaken previously.

More importantly, the on-going suspended sediment monitoring by Durham University has been explained, the results of which have been analysed and detailed in the chapter. The interpretation of these results is an important finding, as they will form the basis for the upstream sediment boundary condition of the one-dimensional hydraulic model.

A four-week survey of the river was completed in the summer of 2000. The data recorded was reduced at the University of Glasgow and three- dimensional co-ordinates of the river environment were created. This information formed the basis of the geometric data input for the one –dimensional ISIS model.

This background, measured data from the River Tees, itself, can now be used to construct the ISIS model, which is the main tool being used to assess the long-term sustainability of the barrage impoundment.

Chapter 4: Statistical Modelling of Boundary Conditions

4.0 Introduction

To assess the overall sustainability of the Tees impoundment it is necessary to show how it will behave in the future, with regard to sediment. Consequently, flow and sediment boundary conditions for the hydrodynamic model ISIS were required for a long period of time (50 years). Fifty-year simulations gave a sensible period of time to investigate the sedimentation patterns while considering a reasonable design life for the structure. Upstream boundary conditions for the sediment boundary have been described in Chapter 3. This chapter explains the method developed to derive the upstream flow conditions, for input to the model.

4.1 Markov Chain Method for Extending Flow Records

The literature review provides an examination of many of the previously employed methods, utilised to assess the effects of civil engineering structures in watercourses. These methods have generally fallen into two different categories; those which have been employed by hydraulic modellers assessing the effect of sedimentation, and those which have been used by stochastic modellers for the express purpose of extending existing hydrological time series. Several criticisms were levelled at these models during the course of the discussion and as a result a different method for extending flow records was developed. This method is based on the Markov Chain process and aims to present a relatively fast approach for extending flow records while still maintaining the overall statistics of the recorded time series. The method has then been developed further to take account of climate change within the model, thus creating an alternative method for predicting the effect of climate change on flow records, for the specific use in water resources management. Markov Chains have been used historically in the fields of hydrology, wind speed modelling and geology

4.1.1 Markov Chain Modelling Theory

Markov chains are a generic modelling technique that can be use to forward predict existing data sets based on their statistical properties. They are named after the Russian mathematician, Andrei Markov (1856-1922), and are a stochastic process based on the Markov property of which there is a continuous-time version and discrete-time version. For the discrete-time version, a series consists of $X_t = \{X_1, X_2, X_3, \cdots, X_n\}$of random variables, where$\{X_t\}$is the state of the system at time *t*. Therefore the Markov property states that the condition distribution for the future $X_t = \{X_{t+1}, X_{t+2}, X_{t+3} \cdots X_{t+n}\}$ given the past, or historical sequence $X_t = \{X_1, X_2, X_3, \cdots, X_n\}$ depends only on the past through $\{X_t\}$. In other words, the future distribution of the series is dependent only on the present state of the system and not on the earlier history of the system.

$$
\begin{aligned}
&P[X_t = s_n | X_{t-1} = s_{n-1}, X_{t-2} = s_{n-2}, \cdots, X_1 = s_1] \\
&= P[X_{t+1} = s_n | X_{t-1} = s_{n-1}]
\end{aligned}
$$

Equation 4. 1

Equation 4. 1 is known as the Markov property, where $s_1, s_2, s_3, \cdots, s_n$ are a series of states.

This method is a short-term memory method is that it uses the short-term memory of the series as a starting point for forecasting future data. The technique uses limited historical data to establish Markov transition probabilities. These are the probabilities of moving from one state (*i*) at time *t*, to another state (*j*) at time *t+1*. Once these have been calculated they act as a guide to producing synthesised data series.

A discrete time Markov Chain has two basic ingredients, namely a transition matrix **P** and an initial series of states $s_n = \{1,2,3,\cdots,n\}$. The initial series of mutually exclusive states is constructed from the original historical series, $X_t = \{1,2,3,\cdots,t\}$. To define the transition matrix it is necessary to assign to each pair of states a transition probability, defined by the real number p_{ij} such that the properties:

$$p_{ij} \geq 0$$
$$\sum_{j=0}^{\infty} p_{ij} = 1$$

Equation 4. 2

are satisfied. Therefore the transition matrix **P** is defined by

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1k} \\ p_{21} & p_{22} & \cdots & p_{2k} \\ \vdots & & \ddots & \vdots \\ p_{k1} & p_{k2} & \cdots & p_{kk} \end{bmatrix}$$

Equation 4. 3

For example if the series *s* consisted of only state 1 and 2, the transition probability p_{ij} of moving from state 1 to 2 could be defined as α and p_{ij} of moving from state 2 to state 1 could be defined as β. This would give the matrix **P** such that,

$$\mathbf{P} = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix}$$

Equation 4. 4

The discrete time Markov Property defines the 'memory', or order, of the chain. Thus the details given above would be classed as an order one Markov Chain as the future of the process is only dependent on the state of the present. However if the process were such that the future depended not only on the present but the recent past (i.e X_{t+1} depended on X_t, X_{t-1}) then the Markov Chain would be termed second order. This can be extended to incorporate as much of the recent history as is required but has the disadvantage of creating a large, complicated transition matrix.

Markov Chain modelling has been utilised heavily in the field of hydrology, specifically for precipitation modelling and forecasting (Metcalfe, 1997; Chapman.1997; Jimoh & Webster 1996, 1999). The Markov chain in this case is most often used to predict the occurrence of wet and dry days, which can be considered as the first part of modelling rainfall. Once the wet days have been forecast, then a distribution is chosen to describe the amount of precipitation occurring on those wet days. The shape of the distribution is estimated from the historical series. Markov chains have also been used in the field of geology where they can be applied to estimate lithologies (Davis, 1986; Rosenbaum, Rosen & Gustafson, 1997). The chains in this case are used spatially to predict a sequence of rock types based on an original borehole investigation.

In addition, Markov chains have been employed in the field of wind speed modelling (Castino, Festa & Ratto, 1998; Sahin & Sen, 2001). Here Markov chains were employed to model short duration wind speeds (averaged either 3 hourly or hourly). In Castino et al. 1998, the Markov chain was used to predict pulses of calm or windy states and then an autoregressive model was applied to create the wind speeds during the windy states. However, Sahin & Sen, 2001, divided the historical record of wind speeds up into several states and created a large transition matrix. This matrix was then utilised to create a series of pulses of different heights, with the actual wind speed being assigned using a uniform probability distribution function, apart from the extreme states where a shifted exponential distribution was used. Both these methods gave good comparisons with the statistical properties of the original series, which is imperative when creating a stochastic series. Similar methods have been used in the field of stream flow prediction, however the research has mainly concentrated on streams with intermittent flow where the Markov chain is used to predict the occurrence of a wet day and the height of the pulse (Aksoy & Bayazit, 2000; Xu et al. 2001). Once a pulse has been predicted different distributions have been fitted to the historical data which are then used to predict the amount of flow on the wet days, depending on whether a rising limb or recession limb of a hydrograph is predicted. Both studies reproduce daily stream flows adequately but suggest ways of improvement for the methods.

Markov chains have been employed to synthesise many different types of series with success and seem to preserve many of the statistical parameters of series well (Sahin & Sen, 2001; Aksoy & Bayazit, 2000). Thus a Markov chain method has been developed to extend the duration of the upstream inflow boundary condition for the River Tees.

4.1.2 Markov Chain Modelling Method

Firstly, it was necessary to gather as much historic flow data as was possible from the Low Moor gauging station. For the duration of the SIMBA project, approximately two years, 15 minute flows were recorded at the station. However, to increase the accuracy of the extended data, a longer flow record was required. Consequently, flow data dating back to 1969 was obtained from the National River Flow Archive, which holds historical flow records from most Environment Agency gauging stations. The flow data was recorded as daily and hourly flows, although the hourly flows were only available for five years. Due to the fact it was important to use as much historical data as possible to construct the synthetic data set, daily flow data was used. A sensitivity test was completed to investigate the effect of using daily flows, requiring a time increment of 24 hours in the computer model, instead of hourly flows, and an increment of 1 hour, on the predicted sedimentation patterns, the results of which can be found in Chapter 5 section 5.6. The conclusions of the sensitivity test show that by using daily flow data, the model will tend to over-predict the amount of sedimentation occurring in the impoundment. Therefore the results of this study will be a conservative estimate.

The flow data recorded at Low Moor dated back to 1969 and contained one interruption of 9 months during the period 1974-1975. For model validation purposes it was necessary to omit part of the record when creating the model to predict the synthetic series. Thus, the section of the series recorded through the period 1970-1980 was not used in the generation of the Markov Chain transition matrix. The recorded flows from 1981 to 2000 were used as the basic information required to create the Markov chain model.

Once the flow data had been collected the first step was to divide the flow record into a series of states. Some advice on dividing the data into states is given in Sahin &

Sen, 2001, where the divisions were determined using the mean and standard deviations of the series. However, the flow record for the Tees was such that categorisation in this manner was unsuitable. The standard deviation of the series was prohibitively large which would have resulted in the lower flows being lumped into one state. This would have resulted in a less accurate portrayal of the statistics of the data due to the fact that a large proportion of the flow record is comprised of low flows. Therefore a different method was employed to categorise the flows.

State	Lower Flow Value (cumecs)	Upper Flow Value (cumecs)	% Overall Record	Cummulative Prob. Distrib.
1	0	6	30	30
2	7	15	30	60
3	16	30	20	80
4	31	60	10	90
5	61	90	5	95
6	91	129	4	99
7	130	upwards	1	100

Table 4. 1 State divisions for the flow record for the Markov chain method

Firstly the 'peaks over threshold' POT value was obtained from the information appended to the Flood Estimation Handbook (Robson & Reeve, 1999) for the River Tees. This was found to be $130m^3/s$. As this value has been pre-defined as a lower boundary for the 'high' flows on the Tees by the Institute of Hydrology, this then became the threshold for the highest state. Separating out the higher flows by putting them into one state allows them to be treated differently when assigning flow, which is one of the advantages of the technique. With the upper state being defined as a flow of $130m^3/s$ and over, it was then necessary to divide all flows lower than $129m^3/s$ into a set of states. Ideally, dividing the flow record should have been completed using a linear scale of thresholds, however this would have resulted in too few data points in some bands and too many in others. Therefore a method using the cumulative probability distribution of the series was utilised. Ordering the series starting with the lowest flow, the record was divided up as shown in Table 4.1 using the cumulative probability distribution. The position of each flow value was calculated as a percentage of the overall series and then, depending on the position, a cut off for each category was decided. Most of the flows are concentrated around the lower end, with 60% of the series having a flow value of 16 m^3/s or less. The lower end of the flow scale was divided into two categories, each containing 30% of the overall record: the upper 40% was then divided into 5 categories. The upper state had already been defined and contained 1% of the record, and the other 4 classes were classified by taking 20%, 10%, 5%, and 4% of the flow record respectively.

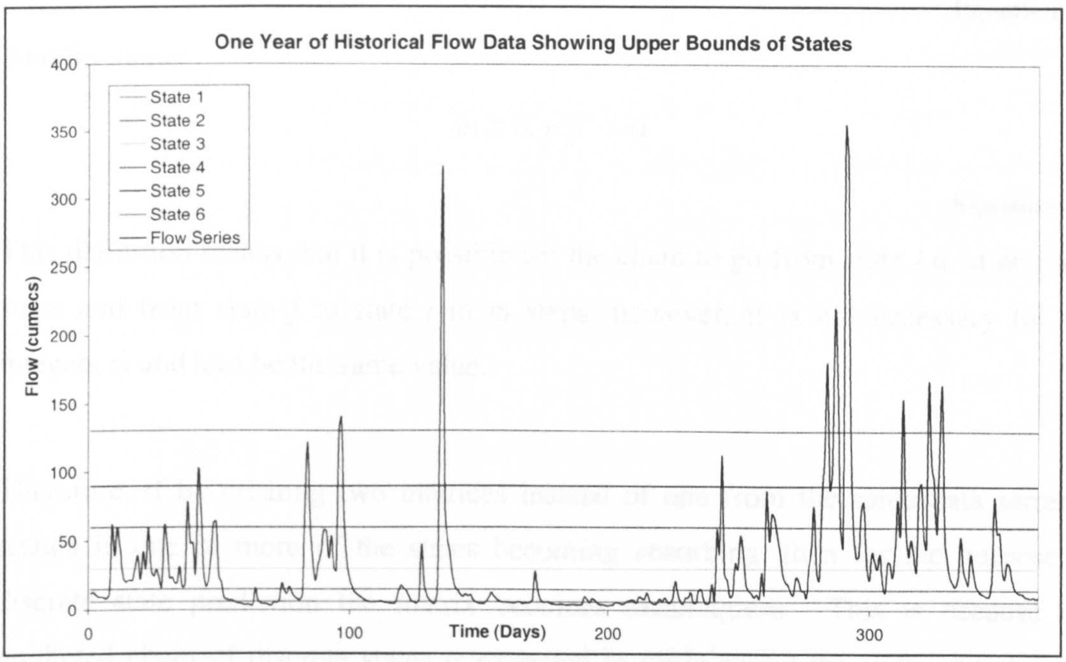


Fig. 4. 1 Graphical portrayal of the spread of states

This gave 7 states with boundaries at 6m^3/s, 15m^3/s, 30m^3/s, 60m^3/s, 90m^3/s and 130m^3/s. The graphical spread of states can be seen in Figure 4.1. This shows that there are only a few times every year where the flow enters the most extreme state; conversely, the flow spends most time in the lowest two states.

The series of states were then divided into two different series to take account of seasonality. River discharges vary widely, and a specific trend in Great Britain can be observed during the winter months where higher flows are usually observed. This means that more transitions between the higher states will be observed. Therefore, to preserve these transitions accurately in the synthetic series, it is necessary to calculate two transition matrices. Treating the seasons differently prevents information getting "lost" through dilution. When splitting the data into seasons, however, care should be taken to ensure enough transitions remain to keep the matrix ergodic. For the matrix to be ergodic, there must be a chance for each state to recur. This means that there must be one irreducible closed subset of persistent states. A Markov chain is said to be irreducible if, and only if, all sets of states intercommunicate (Issacson & Madsen, 1976). For a pair of states, *i* and *j*, to intercommunicate then:

$$n \geq 0, p_{ij}^{(n)} > 0$$

Equation 4. 5

And for some:

$$m \geq 0, p_{ji}^{(m)} > 0$$

Equation 4. 6

This definition means that it is possible for the chain to go from state *i* to state *j* in *n* steps and from state *j* to state *i* in *m* steps; however, it is not necessary for the integers *m* and *n* to be the same value.

Therefore, if by creating two matrices instead of one from the same data series it results in one or more of the states becoming absorbing, then for the purpose of discrete state prediction the matrix becomes meaningless. This is because the predicted chain of discrete states is expected to cycle round the states maintaining similar statistical properties to the historical series. If the predicted series becomes 'stuck' in one state then the matrix is no longer accurately portraying the historical statistics. Thus when dividing the historical series into seasons, care must be taken to ensure that all the states intercommunicate in the transition matrix. So while dividing the series into seasons and creating more than one matrix for the data should improve the statistical reproduction of the predicted series, this is limited by the possibility of any state becoming absorbing. The choice of the number of matrices utilised then becomes and issue of judgement. For the River Tees model the historic data was divided into two seasons only; it is anticipated that if the data set had been longer then four seasons could have been considered. The two seasons were defined as winter (October – March) and summer (April – September).

Once the historical record, which is being used for the model generation, has been turned into a series of states and divided into seasons it is possible to calculate the transition probabilities. The transition probabilities are calculated directly from the data by summing all the times a particular transition occurs between two states and dividing it by the overall number of times that the starting state has occurred in the historical sequence. The calculation of transition probabilities p_{ij} is given by:

$$p_{ij} = \frac{\sum tr_{ij}}{\sum s_i}$$

Equation 4. 7

Where tr_{ij} is a transition between state i and state j and s_i is state i. These probabilities make up the transition matrix **P** as described in Equation 4. 3, which have the properties defined in Equation 4. 2. These properties state that each transition probability must be equal to or greater than zero and that the sum of the elements of each row of the transition matrix must equal one.

$$\mathbf{P} = \begin{bmatrix} 0.8838 & 0.0886 & 0.0189 & 0.0063 & 0.0019 & 0 & 0.0005 \\ 0.2566 & 0.6140 & 0.0899 & 0.0307 & 0.0055 & 0.0022 & 0.0011 \\ 0.0167 & 0.4444 & 0.4056 & 0.1056 & 0.0139 & 0.0111 & 0.0028 \\ 0 & 0.0459 & 0.4337 & 0.4388 & 0.0561 & 0.0102 & 0.0153 \\ 0 & 0 & 0.2162 & 0.5135 & 0.1622 & 0.1081 & 0 \\ 0 & 0 & 0 & 0.6 & 0.2 & 0.2 & 0 \\ 0 & 0 & 0 & 0.375 & 0.375 & 0 & 0.25 \end{bmatrix}$$

Equation 4. 8 Summer First Order Matrix

$$\mathbf{P} = \begin{bmatrix} 0.8014 & 0.1307 & 0.0509 & 0.0085 & 0.0068 & 0.0017 & 0 \\ 0.1162 & 0.6775 & 0.1372 & 0.0534 & 0.0084 & 0.0063 & 0.001 \\ 0.0044 & 0.2332 & 0.5182 & 0.1859 & 0.0418 & 0.0121 & 0.0044 \\ 0.0027 & 0.0246 & 0.3629 & 0.4407 & 0.0928 & 0.0437 & 0.0327 \\ 0 & 0 & 0.0615 & 0.6089 & 0.1844 & 0.0726 & 0.0726 \\ 0 & 0 & 0.011 & 0.5385 & 0.1758 & 0.1868 & 0.0879 \\ 0 & 0.0152 & 0 & 0.3939 & 0.1667 & 0.1818 & 0.2424 \end{bmatrix}$$

Equation 4. 9 Winter First Order Matrix

The transition matrix **P** holds the transition probabilities and can be of any order. As explained, the order of the Markov chain describes the amount of history used to create the transition matrix, which in turn is used to predict the value of flow in the synthetic series. Both first order and second order seasonal transition matrices were calculated for the River Tees so that the effect of incorporating more history into the

P =

	1	2	3	4	5	6	7
1.1	0.9	0.07	0.02	0.01	0	0	0
1.2	0.37	0.48	0.11	0.04	0	0	0
1.3	0.05	0.53	0.3	0.1	0.03	0	0
1.4	0	0.08	0.46	0.23	0.15	0	0.08
1.5	0	0	0	0.5	0.5	0	0
1.6	0	0	0	0	0	0	0
1.7	0	0	0	0	1	0	0
2.1	0.78	0.2	0.01	0.01	0	0	0
2.2	0.24	0.65	0.06	0.03	0	0	0
2.3	0.02	0.43	0.4	0.09	0.04	0.02	0
2.4	0	0.11	0.54	0.25	0.07	0.04	0
2.5	0	0	0.2	0.8	0	0	0
2.6	0	0	0	0	1	0	0
2.7	0	0	0	0	1	0	0
3.1	0.83	0.17	0	0	0	0	0
3.2	0.18	0.63	0.14	0.02	0.02	0.01	0
3.3	0.01	0.49	0.39	0.1	0.01	0	0.01
3.4	0	0.03	0.39	0.5	0.05	0	0.03
3.5	0	0	0.4	0.6	0	0	0
3.6	0	0	0	0.5	0	0.5	0
3.7	0	0	0	0	1	0	0
4.1	0	0	0	0	0	0	0
4.2	0.22	0.56	0.22	0	0	0	0
4.3	0	0.33	0.49	0.15	0	0.02	0
4.4	0	0.05	0.38	0.5	0.05	0.01	0.01
4.5	0	0	0.27	0.36	0.27	0.09	0
4.6	0	0	0	1	0	0	0
4.7	0	0	0	0.33	0	0	0.67
5.1	0	0	0	0	0	0	0
5.2	0	0	0	0	0	0	0
5.3	0	0.75	0.25	0	0	0	0
5.4	0	0	0.47	0.47	0.05	0	0
5.5	0	0	0.17	0.83	0	0	0
5.6	0	0	0	0.75	0	0.25	0
5.7	0	0	0	0	0	0	0
6.1	0	0	0	0	0	0	0
6.2	0	0	0	0	0	0	0
6.3	0	0	0	0	0	0	0
6.4	0	0	0.67	0.33	0	0	0
6.5	0	0	0.33	0	0.33	0.33	0
6.6	0	0	0	0.67	0.33	0	0
6.7	0	0	0	0	0	0	0
7.1	0	0	0	0	0	0	0
7.2	0	0	0	0	0	0	0
7.3	0	0	0	0	0	0	0
7.4	0	0	0.33	0.67	0	0	0
7.5	0	0	0	0.33	0	0.67	0
7.6	0	0	0	0	0	0	0
7.7	0	0	0	1	0	0	0

Equation 4. 10 Summer Second Order Transition Matrix (Notation outside the matrix: numbers on the vertical indicate the behaviour of the flow series for the previous two time steps, while those on the horizontal indicate the future behaviour

P =

	1	2	3	4	5	6	7
1.1	0.82	0.12	0.05	0.01	0.01	0	0
1.2	0.22	0.53	0.17	0.07	0.01	0	0
1.3	0	0.38	0.25	0.22	0.06	0.06	0.03
1.4	0	0.2	0	0.8	0	0	0
1.5	0	0	0	0.75	0	0	0.25
1.6	0	0	0	1	0	0	0
1.7	0	0	0	0	0	0	0
2.1	0.74	0.18	0.07	0.01	0	0	0
2.2	0.13	0.69	0.12	0.04	0.01	0.01	0
2.3	0.02	0.28	0.39	0.25	0.05	0.01	0
2.4	0	0.04	0.41	0.41	0.12	0.02	0
2.5	0	0	0.38	0.5	0.13	0	0
2.6	0	0	0.17	0.67	0	0.17	0
2.7	0	0	0	0	0	0	0
3.1	0.75	0.25	0	0	0	0	0
3.2	0.04	0.68	0.18	0.08	0	0.01	0
3.3	0	0.26	0.5	0.18	0.04	0.01	0
3.4	0.01	0.04	0.4	0.4	0.09	0.04	0.03
3.5	0	0	0.08	0.55	0.24	0.08	0.05
3.6	0	0	0	0.4	0.3	0.2	0.1
3.7	0	0.25	0	0.25	0.25	0.25	0
4.1	0.5	0.5	0	0	0	0	0
4.2	0.06	0.72	0.11	0.11	0	0	0
4.3	0	0.16	0.63	0.17	0.03	0.01	0.01
4.4	0	0.02	0.35	0.45	0.09	0.05	0.03
4.5	0	0	0.03	0.53	0.25	0.1	0.09
4.6	0	0	0	0.44	0.19	0.22	0.16
4.7	0	0	0	0.33	0.17	0.21	0.29
5.1	0	0	0	0	0	0	0
5.2	0	0	0	0	0	0	0
5.3	0	0.18	0.82	0	0	0	0
5.4	0	0.01	0.37	0.45	0.08	0.05	0.05
5.5	0	0	0.06	0.76	0.09	0	0.09
5.6	0	0	0	0.85	0.15	0	0
5.7	0	0	0	0.38	0.31	0.15	0.15
6.1	0	0	0	0	0	0	0
6.2	0	0	0	0	0	0	0
6.3	0	0	0	0	1	0	0
6.4	0	0.02	0.37	0.41	0.1	0.04	0.06
6.5	0	0	0.06	0.63	0.13	0.13	0.06
6.6	0	0	0	0.41	0.24	0.24	0.12
6.7	0	0	0	0.25	0	0.38	0.38
7.1	0	0	0	0	0	0	0
7.2	0	1	0	0	0	0	0
7.3	0	0	0	0	0	0	0
7.4	0	0.04	0.19	0.65	0.08	0.04	0
7.5	0	0	0	0.82	0.09	0.09	0
7.6	0	0	0	0.67	0.08	0.25	0
7.7	0	0	0	0.56	0.13	0.06	0.25

Equation 4. 11 Winter Second Order Transition Matrix (Notation outside the matrix: numbers on the vertical indicate the behaviour of the flow series for the previous two time steps, while those on the horizontal indicate the future behaviour

prediction process could be evaluated. The summer first order transition matrix is shown in equation 4.8, with the winter first order matrix shown in equation 4.9. They both have dimensions [7x7] as the specified number of states defines the size of the matrix.

Equation 4.10 and 4.11 show the second order matrices constructed for the summer and winter seasons respectively. For the matrix to be second order, it means that more of the short-term history of the original series is used to create the matrix and therefore the predicted series. Thus the transitions calculated are that of not only from t to $t+1$, but from $t-1$, t to $t+1$. The number of transition possibilities that require to be counted are subsequently many more than for the simple first order matrices, which results in large, cumbersome matrices. In this case the second order matrices for the River Tees are [49x7]. If the effect of third order matrices on the predicted series statistics were to be investigated it would make the matrices even larger.

Not only do the matrices become more cumbersome as the order of the matrix increases, but also the chance of the matrix becoming irreducible increases. This is because a higher order of matrix effectively dilutes the data over a larger number of possible transitions. The historical data series does not increase with the order of the matrix, therefore the same amount of data must always fulfil the criteria that all states must intercommunicate (equation 4.5 and 4.6). This becomes increasingly difficult as the order of the matrix increases. For example, if there are x number of states defined, a first order matrix would have x^2 transition probabilities to include all possible historical permutations, a second order matrix would have x^3 transition probabilities, a third order matrix would have x^4, and so on. Therefore the same number of overall transitions from the historical data set must satisfy an increasing number of states, all of which must still intercommunicate. Consequently, when deciding on the optimum order of a matrix it is necessary to consider that this may be limited by the historical series itself.

For the Tees impoundment both first order and second order matrices were constructed from 20 years of historical data. Third order matrices were not considered as the size of the matrix became prohibitively large. In addition, the second order matrices had started to become sparse of data. This meant that some rows were already summing to zero, which means that there are no historical events which performed that particular transition. This situation is not conducive to intercommunication, and as a result a third order or higher matrix was not calculated.

Once the Markov transition matrices were calculated they were used in conjunction with a random number generator to create a series of discrete states. The random number generator was set up to produce a uniformly distributed random number between 0 and 1: for this work the random number generator in Excel was used. Firstly, however, it is necessary to provide a seed vector *w*. The seed vector is simply a way of defining the starting state of the synthetic series. For example, the seed vector used for this project was consistently kept at state 1. This provides the process with a starting vector with which to multiply the matrix **P**. The multiplication picks out the desired row in the matrix, which gives the transition probabilities for that starting state according to the historical series. These probabilities are known as a probability density function, which is effectively a curve such that the area under it between any two values represents the probability that a continuous variable will be between these values (Metcalfe, 1997).

$$pdf = w\mathbf{P}$$

Equation 4. 12

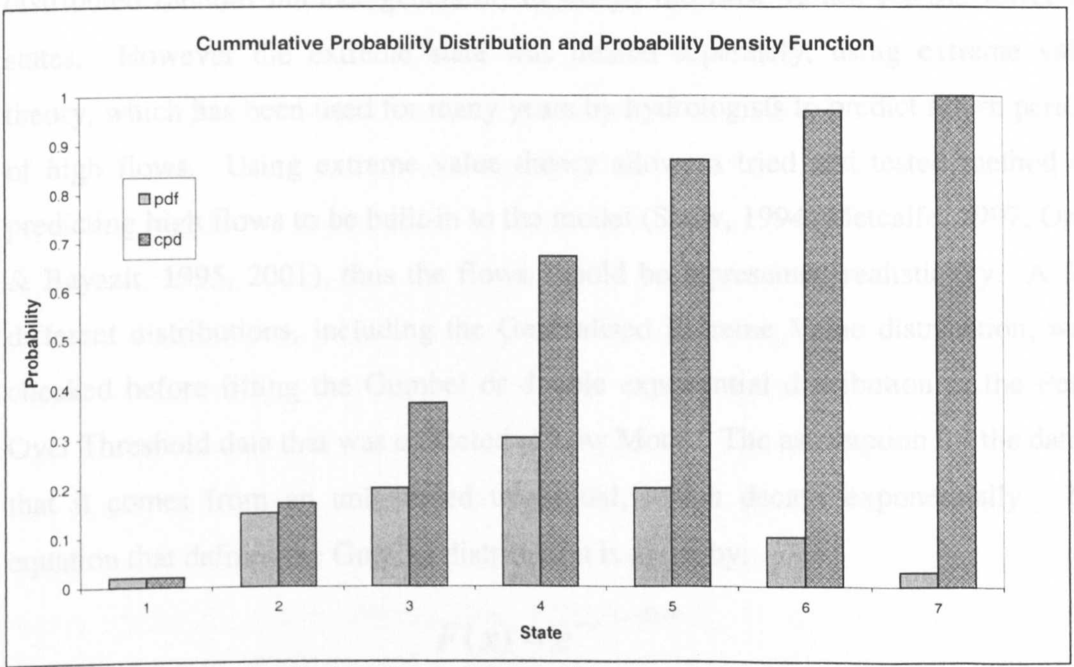


Fig. 4. 2 Probability density function and the resulting cumulative probability distribution.

From the predicted probability density function it is possible to create a cumulative probability distribution by summing each probability consecutively as shown in Figure 4.2. In fact, a probability density function is the derivative of a cumulative probability distribution. Then, depending on where the uniformly distributed random number falls within that cumulative probability function, this determines the next state in the synthetic series. This new state then takes the form of the new vector, which can be multiplied through the matrix again. This process is repeated as many times as is necessary to produce a series of discrete flow states, which create the basis of the synthetic flow series of desired length.

Once the series of discrete states have been created, it is necessary to apply flow values to them to create a full flow series, which can then be used as an upstream boundary for the ISIS model. Applying a flow value to each state is a relatively simple procedure for the lower six states, but because the upper state defines the most extreme flows a different method was employed for assigning flow values. Therefore two different methods were used; the flows were assigned by sampling from:

- an Extreme Value Gumbel distribution for the most extreme state
- a Uniform Probability distribution for states 1-6

A uniform probability distribution function was used, in conjunction with an evenly distributed random number generator, to assign the flow values for the lower six states. However the extreme state was treated separately, using extreme value theory, which has been used for many years by hydrologists to predict return periods of high flows. Using extreme value theory allows a tried and tested method for predicting high flows to be built-in to the model (Shaw, 1994; Metcalfe, 1997; Onoz & Bayazit, 1995, 2001), thus the flows should be represented realistically. A few different distributions, including the Generalised Extreme Value distribution, were checked before fitting the Gumbel or double exponential distribution to the Peaks Over Threshold data that was collected at Low Moor. The assumption for the data is that it comes from an unbounded upper tail, which decays exponentially. The equation that defines the Gumbel distribution is given by:

$$F(x) = e^{-e^{-(x-\xi)/\theta}}$$

Equation 4. 13

where ξ and θ are determined from the historical series and are respectively the mode of the distribution and a scale factor. The latter must be positive. Both of these parameters are related to the moments of the population. These parameters were ascertained from the data attached to the Flood Estimation Handbook (Robson & Reeve, 1999) but they can be calculated from the data by equating the sample mean and standard deviation with the theoretical population values (Metcalfe, 1997). If equation 4.13 is the cumulative distribution function then differentiating it will give the probability density function, which is:

$$f(x) = \frac{1}{\theta} e^{-(x-\xi)/\theta} e^{-e^{-(x-\xi)/\theta}}$$

Equation 4. 14

For the purpose of assigning flow values to the extreme state, it is necessary to transform equation 4.13 into its alternative form:

$$x = \xi - \theta \ln(-\ln(F(x)))$$

Equation 4. 15

A graph was produced to check the fit of the distribution. Figure 4.3 shows the comparison between the Peaks Over Threshold data collected at Low Moor, which has been ordered and plotted as a cumulative probability, and the distribution calculated for this series. From the figure it can be seen that a good fit exists between the distribution and the data; and so this distribution was used to assign the higher flow values for the synthetic series. This part of the method should improve the modelling of the higher flows as a standard method is being employed here to predict high flows. Extreme value distributions are regularly used to predict the peak flows in a river for engineering design and thus incorporating this method into the Markov chain method will have the effect of predicting the high flows reasonably. One of the problems of time series analysis and ARMA models is that it is notoriously difficult to reproduce high flows realistically in the predicted series. Therefore, the Markov Chain method offers a simple, reasonable alternative to time series modelling for extending flow series, which incorporates well-researched methods for the prediction of extreme flows.

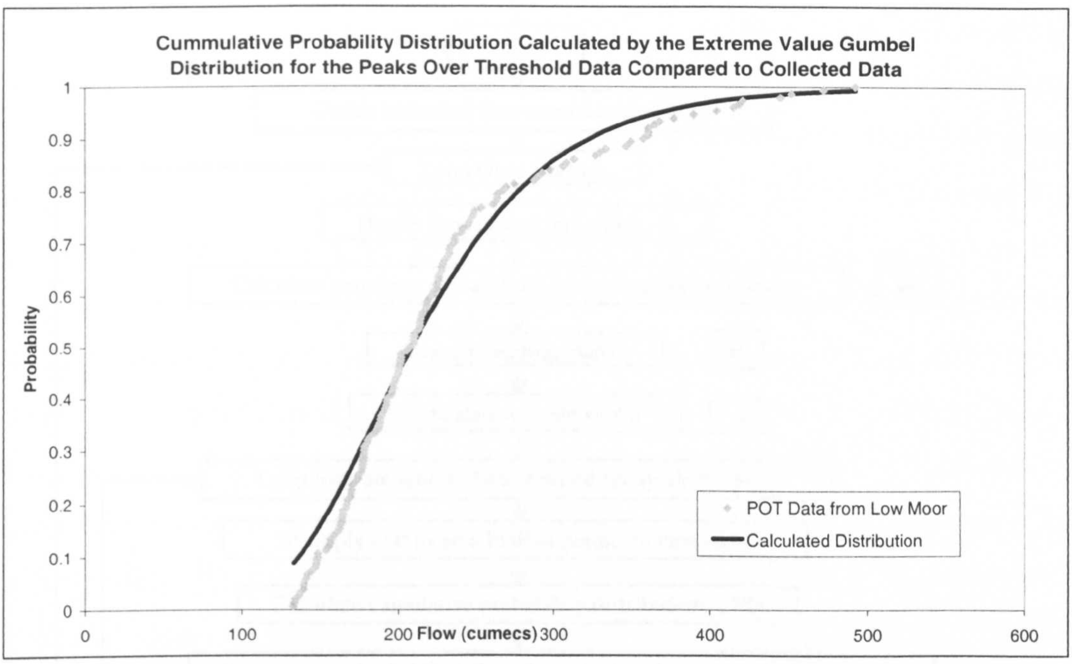


Fig. 4. 3 Cumulative probability distribution for extreme flows calculated by the Gumbel extreme value distribution

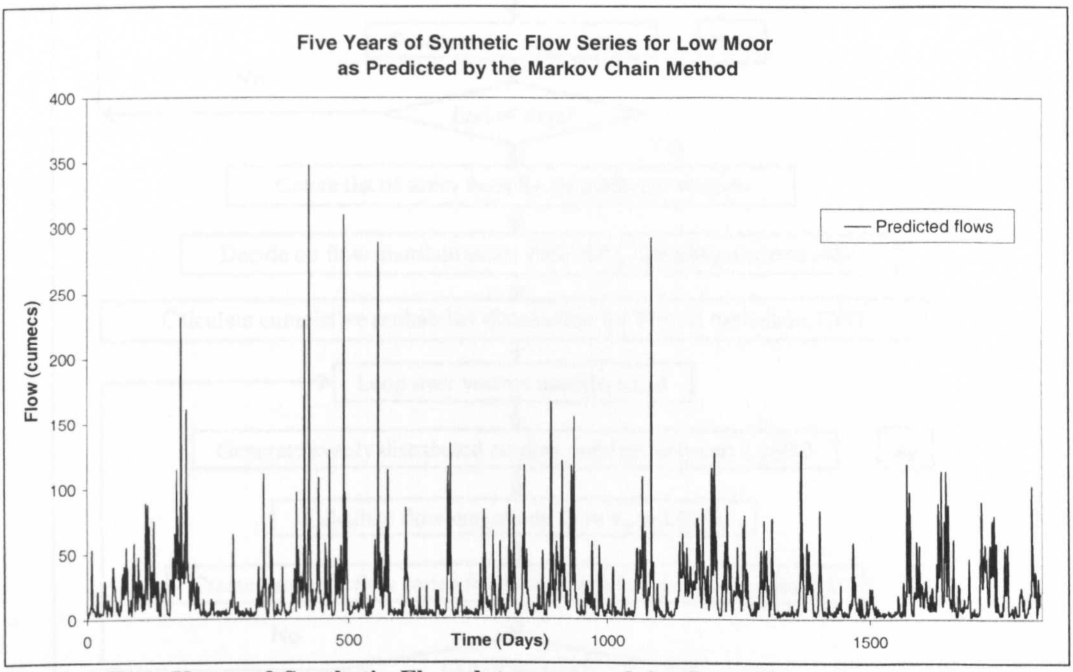


Fig. 4. 4 Five Years of Synthetic Flow data prepared for Low Moor Gauging Station on the River Tees

Once the extreme value distribution was chosen, flow values could be assigned to the state seven discrete states. This was completed by sampling from the distribution using a uniformly distributed random number generator.

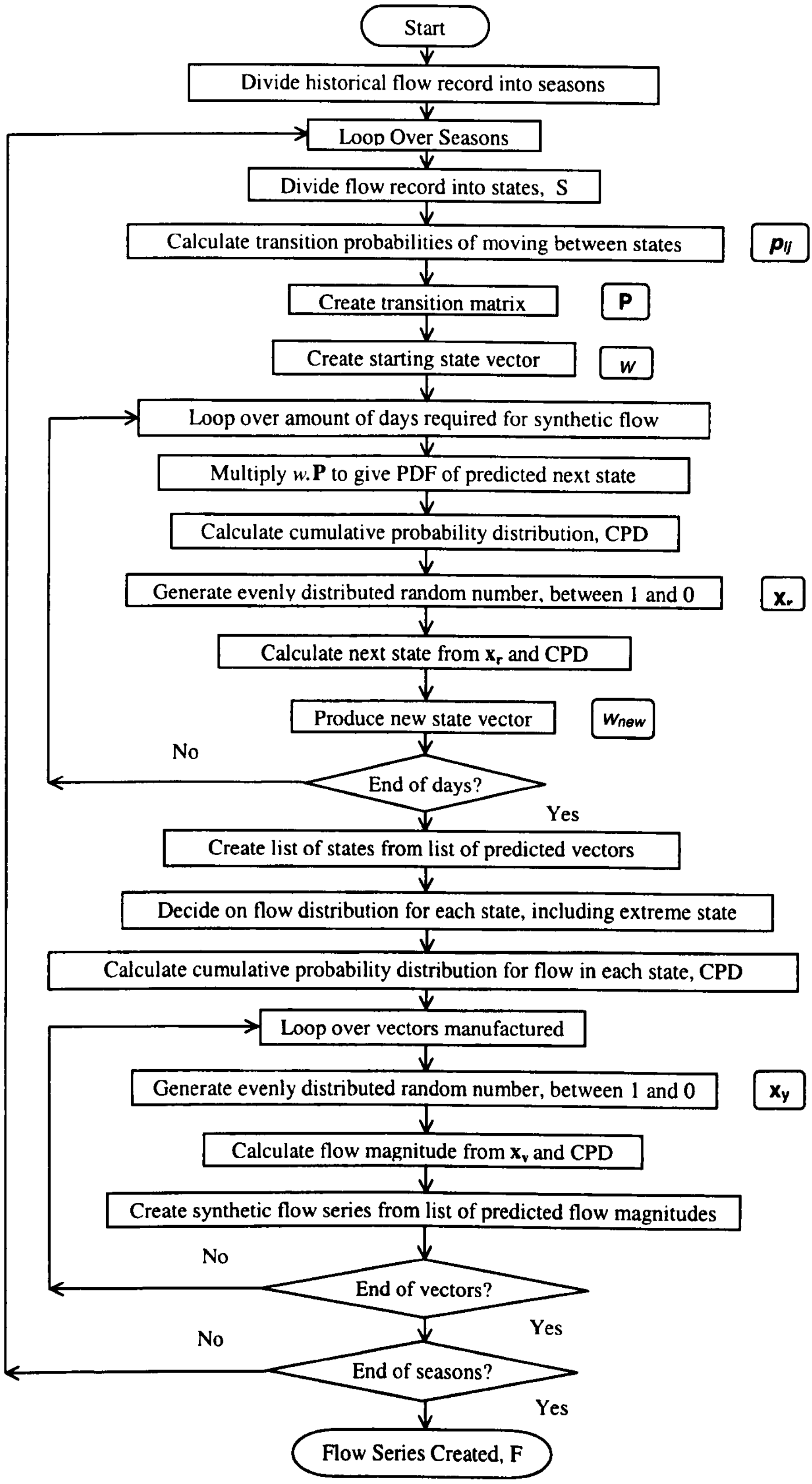


Fig. 4. 5 Flow chart detailing the Markov Chain method for generating flows under existing climate conditions

A comprehensive flow chart for the whole Markov chain method, which has been developed for this particular problem, is shown in Figure 4.5, while Figure 4.4 shows a synthetic flow series that has been constructed for Low Moor. The graph shows a sample of five years from this series; however, a synthetic record of fifty years length was constructed for use as the upstream boundary of the ISIS model. This period of time was chosen as it incorporates a reasonable design limit on the structure while allowing enough time to investigate the effect of the barrage on the sedimentation patterns. As sedimentation changes take place over an extended period of time, it is advisable to extend investigations as long as possible, however it is necessary to balance this with a reasonable estimate on the design life of the structure being investigated. This synthetic flow series is based on statistical properties of the historical data and makes no allowance for climate change; as a result this flow record has been used to predict the effect of sedimentation in the Tees under present flow conditions, the results of which are reported in detail in Chapter 6.

4.1.3 Statistical Analysis of the Markov Chain Method

To ensure that the Markov chain model is a good method for producing synthetic flow series, several checks must be made on the data produced. A statistical test on the models was completed by comparing a predicted ten year synthetic flow series from both a first order and second order Markov chain model, with the recorded flow record from 1970-1980 at Low Moor. In addition, it was necessary to decide which model, either the first order or the second order model, would be used to predict the flows for the upstream end of the ISIS model.

4.1.3.1 Chi-Squared Goodness of Fit Test

This test is used to estimate whether the difference between two series can be described as statistically different (Rowentree, 1981). Here it is used to examine the difference between the modelled and observed flow data at Low Moor. The chi-squared test is non-parametric and based on the assumption that the comparison data set (the measured data in the case) is truly representative of the longer term flow statistics of the river. This means that the distribution of data recorded between 1970-1980 must be truly representative of the distribution of the data.

For the purposes of this test a statistical hypothesis will be set out and then either proved or disproved by the Chi-Squared goodness of fit test. The Chi-Squared test will aid in rejecting or accepting the statistical hypothesis set out. However if the test results in a negative conclusion for the hypothesis, is still scientifically acceptable to state that there is insufficient evidence to categorically dismiss the hypothesis.

The Statistical Hypothesis:

The synthetic series created using the Markov Chain method is statistically similar to the recorded series at Low Moor.

The Test:

The Chi Square test is completed by first dividing the flows into a series of states, which has been done previously. Then a comparison can be made between the frequency of observations predicted in each state and that, which is expected, or observed from the real series. The chi-square (χ^2) statistic measures the agreement between the categorical data and the model that predicts the relative frequency of outcomes in each possible category and is defined by:

$$\chi^2 = \sum \frac{(f_o - f_e)^2}{f_o + f_e}$$

Equation 4. 16

Where f_o is the observed frequency and f_e is the expected frequency. This calculation summarises the discrepancies between the two series and was calculated twice, once for the first order series and again for the second order series.

State	1	2	3	4	5	6	7
Real Series	1759	1141	693	447	114	50	28
First Order	1660	1035	757	530	153	74	23
Second Order	1529	1019	793	618	154	69	50

Table 4. 2 Table showing the frequency of each state for the real and predicted series over the test period from 1970-1980

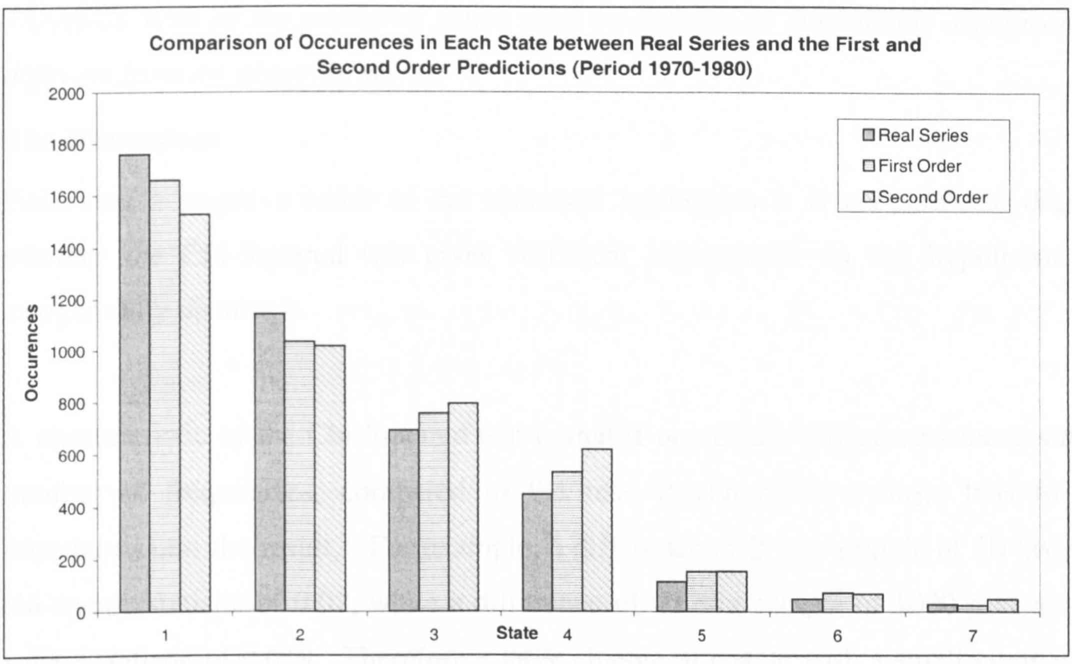


Fig. 4. 6 Histogram showing the occurrences in each state for all three series

To determine whether these models are statistically significant it is necessary to calculate the degrees of freedom and then the associated *p* value for each series. The *p* value will determine whether the series is statistically significant to the 0.1% level. The degrees of freedom for this situation are 6 for each test as the degrees of freedom can be calculated by taking one less than the amount of categories used for the test. From the χ^2 statistic and the degrees of freedom it is possible to find the *p* value as this is found from the distribution of the chi-square statistic, which is a family of curves that change slightly depending on the degrees of freedom.

The Results:

The data in Table 4. 2 shows the frequency of observations in each state for each series and a graphical presentation of this table can be seen in the histogram in Fig. 4. 6. The resulting chi-square statistic values were *28.738* and *72.374* for the first order and second order predictions respectively. Both of these numbers are rather large, although the chi-square statistic for p=0.001 for 6 degrees of freedom is 22.46, which is not much smaller than the value recorded for the first order series. The values of *p* for the first and second order predictions were calculated in MINITAB, and were recorded as *0.00006814* and $1.331x10^{-13}$ respectively.

Therefore both of the predicted series must be defined as statistically significantly different from the observed series.

The Discussion:

Following a negative result to the statistical hypothesis it is necessary to decide whether the Chi-Squared test gives sufficient information on the hypothesis to categorically dismiss it.

A characteristic of the Chi Squared test is that if one of the binned sets has a small number of frequencies, compared to the rest, it can cause a large bias to be introduced into the result. For example, a difference of 2 in a sample of 50 gives a chi-square statistic of 0.02, while a difference of 40 in a sample of 1000 give a chi-square statistic of 0.019. Therefore a large change in a state with a small number of observations will skew the test dramatically. The way the data has been split up for this problem means that fewer observations will be available for the upper few states (state 6 and 7). This is because extreme high flows will be much less frequent than the most flows.

When analysing the results, it must be borne in mind that the comparison data may not be truly representative (it is may not be the defining distribution of the flow series at Low Moor), therefore one of the assumptions on which the test is based is compromised. There is a higher frequency of observations in the upper states from the predicted data due to the fact that historical data from which the matrices were built was considerably wetter. This means that the differences predicted in these high states bias the result of Chi Squared statistic test. The Chi-Square goodness of fit test may give better results if a comparison period of flow series had been hydrologically similar, i.e. if it had not included a drought.

On this basis then, rather than categorically dismissing the hypothesis it is possible to say that; while the chi squared test shows that the synthetic series is statistically significantly different, this test does not yield enough evidence to dismiss the hypothesis. As a result further tests were carried out.

4.1.3.2 Descriptive Statistics

To examine the series more closely in light of the result of the Chi-Squared test some other tests were investigated. Simple comparisons of some of the moments of the observed and modelled flow distributions were completed. This included the first four moments: the mean, standard deviation, skew and kurtosis of the series.

- The mean (μ) is simply as the average value of the sample, and gives a measure of the centrality of the series.
- The standard deviation (σ) is the positive square root of the variance, where the variance is described in equation 4.17. Standard deviation gives a measure of the spread of the series.

$$\sigma^2 = \sum_{i=1}^{n} (x_i - \mu)^2 / N$$

Equation 4. 17

Where x_i is a member of the sample and N is the number of members in the sample. Variance and standard deviation are closely linked and as a result only the standard deviation of the series will be investigated

- The skew is a measure of the asymmetry of the series; it can be calculated from equation 4.18. If the value is close to zero then the series is symmetrical, otherwise large positive values indicate that the distribution has a long tail to the right.

$$\hat{\gamma} = \frac{\sum (x_i - \mu)^3 / (N-1)}{\sigma^3}$$

Equation 4. 18

- The kurtosis is a measure of the weight in the tails of the series and is defined by equation 4.19. Positive values indicate relatively extensive tails compared with a bell shaped distribution.

$$\hat{\kappa} = \frac{\sum (x_i - \mu)^4 (N-1)}{\sigma^4}$$

Equation 4. 19

Comparison of the statistics of the series described above will give a representation of the shape of the distribution of the new synthetic series and how it relates to the shape of the original recorded series, and is one of the recommended ways of assessing the manufactured flows (Lawrance & Kottegoda, 1977; Aksoy & Bayazit, 2000). Table 4. 3 contains a comparison of the mean, standard deviation, skew and kurtosis of each of the three series.

Statistics	Real Series	First Order	Second Order
Mean	17.229	18.475	21.471
St. Deviation	23.976	25.759	30.577
Skew	4.233	4.311	4.557
Kurtosis	28.411	30.945	32.551

Table 4. 3 Comparison of the descriptive statistics of the flow series recorded at Low Moor (1970-1980) with the series predicted by the first order and second order Markov chain method.

Before a comparison is made, it is important to remember that the flows taken over the period from 1970-1980 were recorded during a drier period on the River Tees than from 1980-2000, which are the data used to create the models. From 1974-1976 a period of drought was recorded in the region; this can be investigated by comparing the mean flow recorded over these periods. The mean during 1980-2000 was calculated to be 19.27m^3/s, which is over 2m^3/s higher than for the period 1970-1980. This must be borne in mind during the assessment of the method.

Firstly, by comparing the mean of the series it can be seen that the first order transition matrix predicts a series with a good comparative mean. The values 17.229m^3/s and 18.475m^3/s compare well, whereas the second order matrix predicted a series with a mean of 21.471m^3/s. The mean of this series is slightly high, but could be partly due to the fact that more history of the series is being taken into account and as such is predicting higher flows due to the historical legacy of the construction sample. Looking more closely at the spread of each series the standard deviation compares well for the real series and the first order prediction with a value of 23.976 and 25.759 respectively. However, the second order prediction results in a larger value for the standard deviation, at 30.577. This is due to the fact that the standard deviation is calculated by averaging the deviations from the mean of the whole series. Therefore, if more high flows are predicted by the second order matrix because of the legacy of the construction data, this will be reflected in the standard deviation results. However, overall the statistics that define the centrality and the spread of the series compare well with the real series data, with the first order series showing a better comparison than the second order series.

After comparing the centrality of the series it is important to look at the asymmetry of the series since the majority of flow rates recorded are low and as such the distribution is generally skewed, with the majority of the sample being bunched at the lower values and a long tail to the right signifying the less abundant extreme flows. From examining the skewness coefficient of the three series it can be seen that there exists a very good agreement between all three. The real series records a value of 4.233, while the skewness coefficients of the first order and second order series are 4.311 and 4.557 respectively. This shows that the Markov method has synthesised flow data, which reproduces the skew of the series well. Consequently, each series has a predicted long tail to the right, with both the created series reporting a slightly longer tail than the recorded series, with both created series showing a slightly more evident tail.

To check whether the extreme flows are well represented it is necessary to investigate the kurtosis of the series. Comparing the values it can be seen that the real series reports a value of 28.411, the first order series has a value of 30.945 and the second order series has a value of 32.551. These values again show a reasonable comparison with the real series, but the first order series is more accurate. Similar kurtosis indicates a similar weight in the tails of the distributions. The value of the kurtosis for the manufactured series may be slightly higher than that of the real series due to the fact that the historical data used to create the transition matrices included more periods of high flows. Therefore extreme flows were predicted slightly more frequently in the synthetic series leading to a higher kurtosis value.

From the comparison of the statistics of the two modelled and the observed flow series it is possible to conclude that:

- Both modelled series reproduce the mean, standard deviation, skew and kurtosis of the observed series.

- The first order model performs slightly better than the second.
- Kurtosis values suggest that extreme flows were slightly overestimated by the models.
- However, the bulk of the data is being modelled well.

4.1.3.3 Boxplots

To further investigate the reproduction of the extremes an analysis based on boxplots was conducted. A boxplot graphically shows the spread of a distribution by plotting a box, whose upper and lower limits define the first quartile and the third quartile of the series. The line that is drawn through the box is known as the median of the series. The lines that extend from the upper and lower part of this box, known as whiskers, define the adjacent values, which are the highest and lowest observations that are still within the region. The lower limit of the region is defined by:

$$Q_1 - 1.5(Q_3 - Q_1)$$

Equation 4. 20

and the upper limit is defined by:

$$Q_3 + 1.5(Q_3 - Q_1)$$

Equation 4. 21

Where Q_1 is the first quartile of the series and Q_3 is the third quartile of the series. The stars on the diagram represent outliers in the data, which are outside any of the regions described.

A box plot comparing the spread of all three series can be found in Fig. 4. 7. The boxplot of the series was constructed in MINITAB and shows quite clearly the spread of the series. By examining the median of each series, it can be seen that the first and second order predictions make a good comparison with the real series. The median value of the real series is 8.726m^3/s, while the first order predictions have a median value of 9m^3/s. The second order predictions report a slightly higher value for the median at 10.5m^3/s, which is a result of the higher flows suggested by the second order method. However, the boxplots show clearly that the higher flows are being over predicted; this can be seen by comparing the number of outliers plotted by each method. Both the first and second order methods tend towards this over prediction but it can be explained by investigating the original series, which was used to construct the transition matrices. These transition matrices were created from data that was recorded during a comparatively wet period on the river, and so the higher flow transitions were slightly more prevalent than during the period 1970-1980. The higher occurrences of extreme flows are reflected in the transition matrices, which in turn affect the series produced. The first order predictions again show a better comparison with the real series than those predicted by the second order transition matrices.

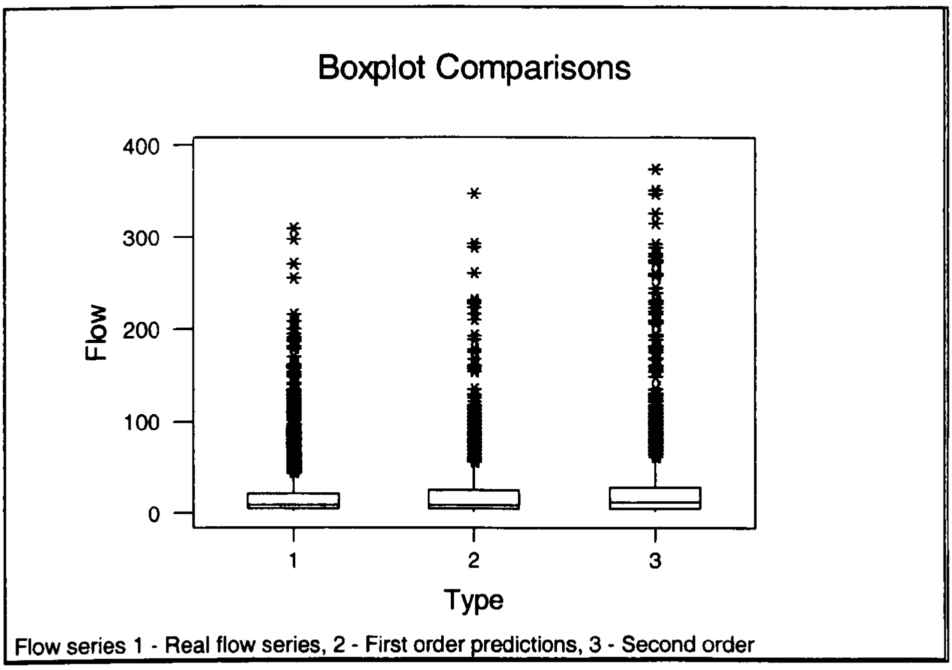


Fig. 4. 7 Boxplot comparisons of the real flow series (1970-1980) with the flow series predicted using first and second order transition matrices

The spread of the quartiles, on the other hand, does not show as good a comparison as the median. Both the predicted series demonstrate a larger spread of flows than the real series. The spread of the quartiles for the real flow series is defined by the lower quartile at 4.522m^3/s and the upper quartile at 20.16m^3/s. This shows that there is large number of low flows bunched at the left side of the distribution and the distribution has a long tail to the right. While this distribution shape is mirrored in the first and second order series distributions, the spread of flows over the quartiles is somewhat wider. The values of the upper and lower quartiles for the first order series are 24.0m^3/s and 4.0m^3/s respectively and for the second order series they are 27.0m^3/s and 5.0m^3/s. A closer look at these values reveals that the lower quartile is well represented, while the upper quartile is over estimated by both synthetic series. This result can be partly attributed to the drier nature of the comparison data series. This reinforces the earlier hypothesis that the bulk of the data is being modelled well with only the extreme flows being slightly over-estimated.

4.1.3.4 Autocorrelation Functions

One of the more important statistical features of hydrological series is the autocorrelation coefficients of the series as it investigates the structure of the flow series. It examines the short-term reproduction of events in the series such as periods of flooding. Correlation is a dimensionless measure of a linear association between two variables. This value can lie between 1 and –1, where zero represents no correlation and a negative number means that one variable is increasing as the other decreases. Thus the autocorrelation coefficients are correlation coefficients between two variables as a function of the time lag that separates them. In this case the autocorrelation coefficients investigated are the lag one coefficients, which means the series (X_t) is being compared to the series (X_{t-1}) with regards to correlation. The correlogram of a series is a plot of all the autocorrelation coefficients against the number of lags. This type of plot can be a very useful tool for investigating the structure of a time series as it can show how observations separated by fixed periods of time are interrelated (Kottegoda, 1980). Comparing the correlogram of the real series with those of the first order and second order series, will give another view of the effectiveness of the Markov chain method for predicting flow series.

Fig. 4. 8 shows a graph of the calculated lag one autocorrelation coefficients. The short-term autocorrelation is reproduced reasonably well, meaning that short-term flow structures such as hydrograph peaks are modelled well. This is perhaps unsurprising given that the model is a Markov model. Over the first few lags it is obvious that both the first and second order predictions are slightly underestimating the autocorrelation coefficients for the series. It is possible that the short-term autocorrelation could be improved using four matrices instead of two as a method of introducing seasonality. However there are problems in trying this, especially for the second order method, where the problem of dilution of the data through the matrices occurs. This stems from the need for each state to intercommunicate, which has been discussed further in section 4.1.2.

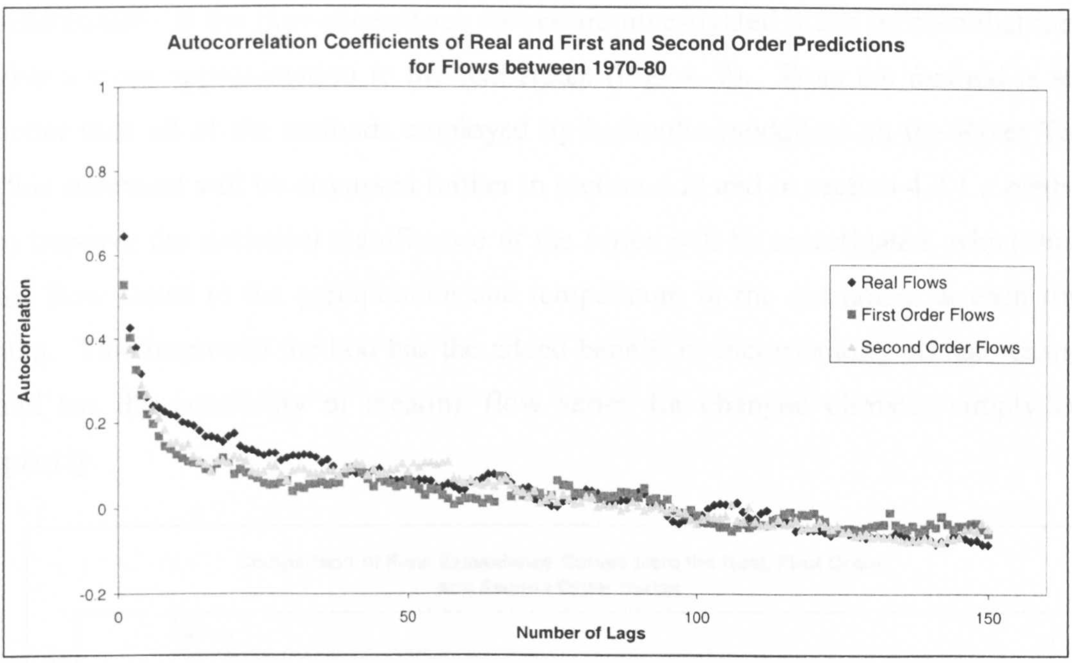


Fig. 4. 8 Correlogram comparing the lag-one autocorrelation coefficients of the real, first order and second order flow series

From the correlogram it can be seen that the predicted series have a similar overall structure to the real series. While the distribution of the series and the descriptive statistics have been checked and show good agreement with the real series, it is very important that the overall structure of the predicted series compares well with the real series. The structure of the series is what makes it unique, for example if the same values of flows as those predicted could be ordered from highest to the lowest, this series would still give the same descriptive statistics as the predicted series investigated here, however the correlogram would show up the drastic difference between that and the real series. The correlogram for the ordered series would show a very slow, regulated, drop off from a starting autocorrelation coefficient of close to 1, instead of the rapid initial drop off from a high autocorrelation coefficient, and then a slower more regulated decrease after 10-20 lags. This can be seen clearly in Figure 4.10. Therefore the fact that a reasonable comparison between the correlogram of the real series and those of the predicted series can be observed is encouraging for the Markov chain method, as it shows that the structure of the series is reproduced satisfactorily

Additionally, if the flow exceedence curves are investigated it can be seen that these give a close approximation to the real series (Fig. 4. 9). Thus the method is still better than all of the methods employed by hydraulic modellers on the River Tees (this statement will be discussed further in section 4.2) and in section 4.3.1 a method to improve the statistical significance of the series will be investigated, which links the flow series to the precipitation and temperature in the catchment at each time step. This improved method has the added benefit of incorporating climate change and has the possibility of creating flow series for changed climates simply and quickly.

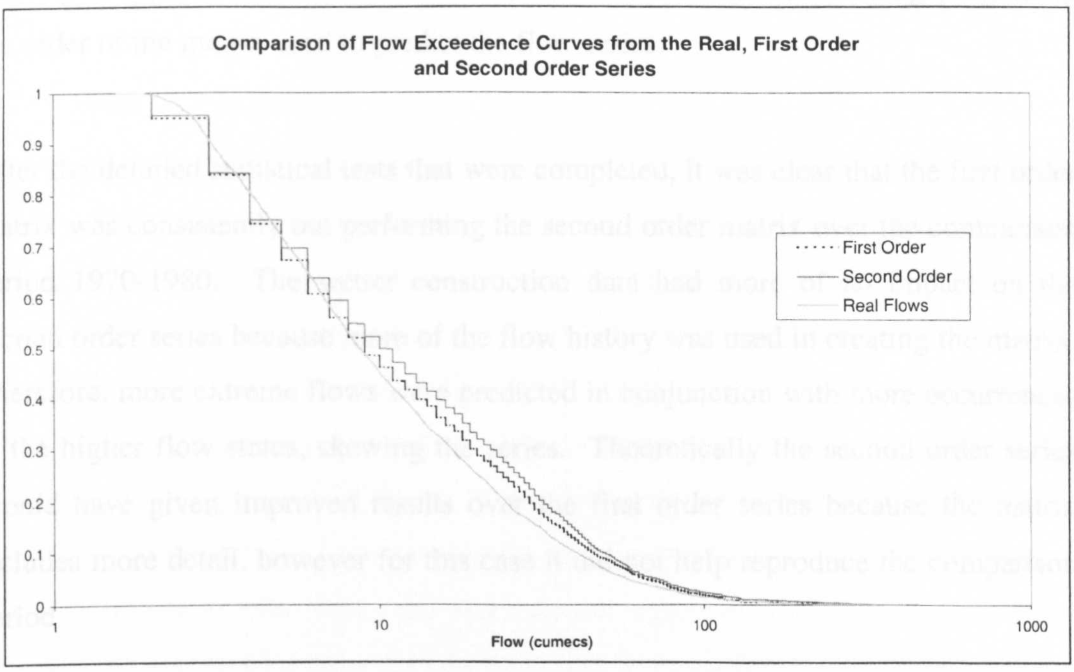


Fig. 4. 9 Flow exceedence curves from the real, first order and second order series

In conclusion:

- The Chi Square test disproved the hypothesis that the created series was significantly similar to the observed series. However, it was decided that the test provided insignificant evidence to categorically dismiss the hypothesis.
- The moments of the series show that the bulk of the data is modelled well.
- The kurtosis and the boxplots show that the extreme flows are slightly over-estimated, which is perhaps a legacy of the data that was used to build the models.

- The autocorrelation shows that the structure of the series is modelled well. In particular the short-term correlation.
- Overall the Markov Chain model produces series with similar characteristics to the historical series.

4.1.4 First Order or Second Order?

Following the statistical investigation of both of the Markov chain predicted series, it was important that one method alone was chosen to predict the upstream flow series for the boundary condition at Low Moor under the present climate conditions. Subsequently, a decision had to be made, based on the statistical findings, regarding the order of the matrix used to predict the flow series.

After the detailed statistical tests that were completed, it was clear that the first order matrix was consistently out performing the second order matrix over the comparison period 1970-1980. The wetter construction data had more of an impact on the second order series because more of the flow history was used in creating the matrix. Therefore, more extreme flows were predicted in conjunction with more occurrences in the higher flow states, skewing the series. Theoretically the second order series should have given improved results over the first order series because the matrix includes more detail, however for this case it did not help reproduce the comparison period.

The second order series did not perform as well as the first order series throughout the statistical testing; consequently the flow series predicted using the first order Markov chain was used as the upstream boundary condition. This meant that the matrices described in Equation 4. 8 and Equation 4. 9 were used to create the flow series, because they both predict series that statistically resemble the historical data as required (Lawrance & Kottegoda, 1977). The first order matrix is a square [7x7] matrix, which is mathematically simpler and more useful than the second order [49x7] matrix. This decision impacts on the climate change investigations undertaken later and discussed in section 4.3.

4.2 Justification of the Markov Chain Technique

The Markov Chain model is intended for simulating long time series of flow for the upstream boundary of the ISIS sediment and flow routing model. It has been shown that it reproduces most of the flow statistics, however several short-comings were highlighted in the previous section. Despite these short-comings it is demonstrated below that when time series generated by the Markov model are used as boundary flows in the hydraulic model, they produce significantly more physically realistic sediment and flow predictions than models previously employed by hydraulic modellers for the Tees (HR Wallingford, 1988) and elsewhere (Meadowcroft et al. 1992).

4.2.1 Model Construction

The model was constructed using the calibrated ISIS model for the River Tees, which is described in detail in chapter 5. This was used as the basis of the model and three different upstream flow boundaries were; one generated by the Markov model, one by the flow exceedence curve method, and the other using real observed flows. The flow exceedence curve method (Meadowcroft et al. 1992, HR Wallingford, 1988; Copeland, 1989), creates a flow series from the flow exceedence curve for the river by estimating a series of steady flows. This method maintains the moments of the distributions of flows, however it does not take account of the serial correlation of the flow series. The flows are fed into the upstream end in decreasing order starting with the highest flow for one year and repeated for the desired number of years. Section 2.6.1.5 describes and criticises this method in more depth, however it is important to understand that this method was picked as the best method currently utilised by consulting hydraulic modellers. Furthermore, the flow exceedence curve has been used in a previous study (HR Wallingford, 1988) to predict the effect of the barrage on the Tees. The HR Wallingford report (1988) indicated that after 60 years, the impoundment would experience a rise in bed levels around Yarm and the Leven confluence and over time this sediment bar would move further downstream depositing sediment.

The comparison period chosen was a five year period from the start of 1994 until the end of 1998, where flows were continually recorded at Low Moor. The flow exceedence curve was created for the flows over this period and this was transferred into a series of steady flows on a yearly loop, starting with the highest flow and decreasing following the method described in section 2.6.1.5. A second five-year flow series was created using the Markov chain method with a first order transition matrix. Two synthetic flow series and the real flows were used as upstream boundary conditions for Low Moor. The Leven boundary condition was estimated to be 10% of these flows following the estimation made in the HR Wallingford report, 1992 (see section 5.3.1 for more details).

To calculate the sediment input to the system the low sediment rating curve was used. The equation for this curve is defined in equation 3.7, and is discussed in section 3.4.1.2 and section 5.5.2. The same equation was used to calculate the sediment load for each input so a reliable comparison could be made.

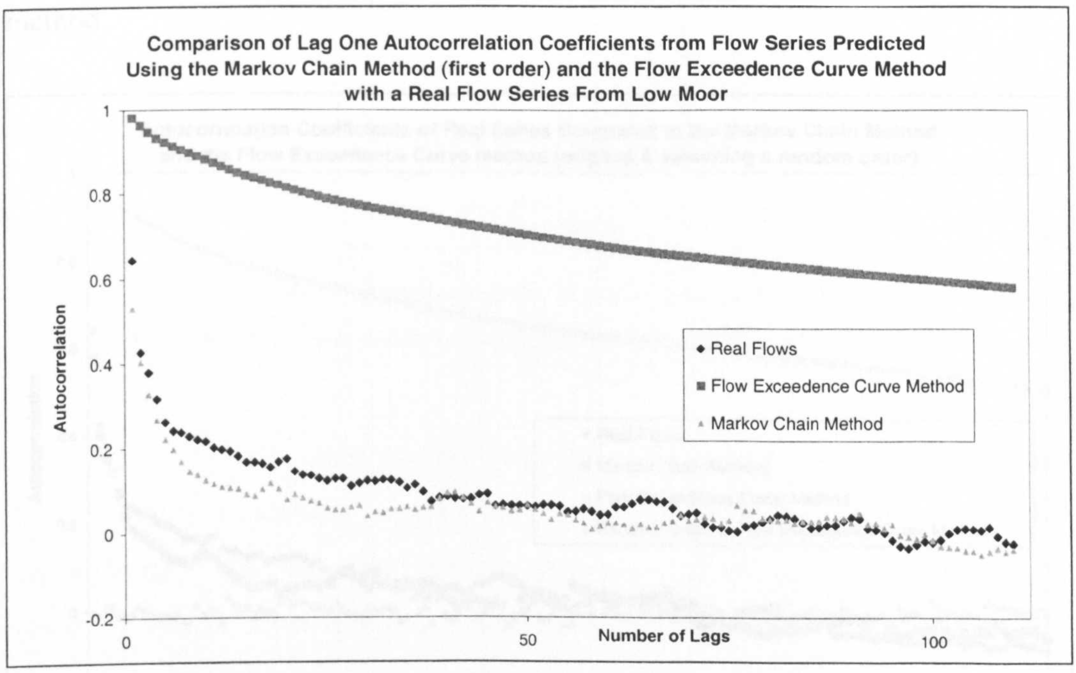


Fig. 4. 10 Comparison of the lag one autocorrelation coefficients from the Markov chain method and flow exceedence curve method with the real flow series

Before the three different models were run, a comparison was made of the lag one autocorrelation coefficients of each of the series. The correlogram, which is shown in Fig. 4. 10, is used to investigate the overall structure of the series. The flow exceedence curve method is based on the assumptions that:

- the ordering of the flows does not matter,
- the data is independent,
- and no account is made for the seasonal nature of flow.

The ordering of the flows in the flow exceedence curve method builds in a high serial correlation which does not exist in the original data (Fig. 4. 10), and this creates a series with no short term reproducibility of the serial correlation. If the assumption that the ordering of the flows does not matter is taken one step further and instead of ordering the flows from highest to lowest, the flows are ordered randomly, a new correlogram can be created (Fig 4.11). By randomly ordering the series it has added a stochastic element to the series, while preserving the assumption that the ordering of the series does not matter. Figure 4.11 shows the new correlogram which shows that even if a stochastic element is added, the autocorrelation coefficients show that the structure of the series is not realistic. Therefore the Markov chain method predicts a flow series with an improved structure over the flow exceedence curve method.

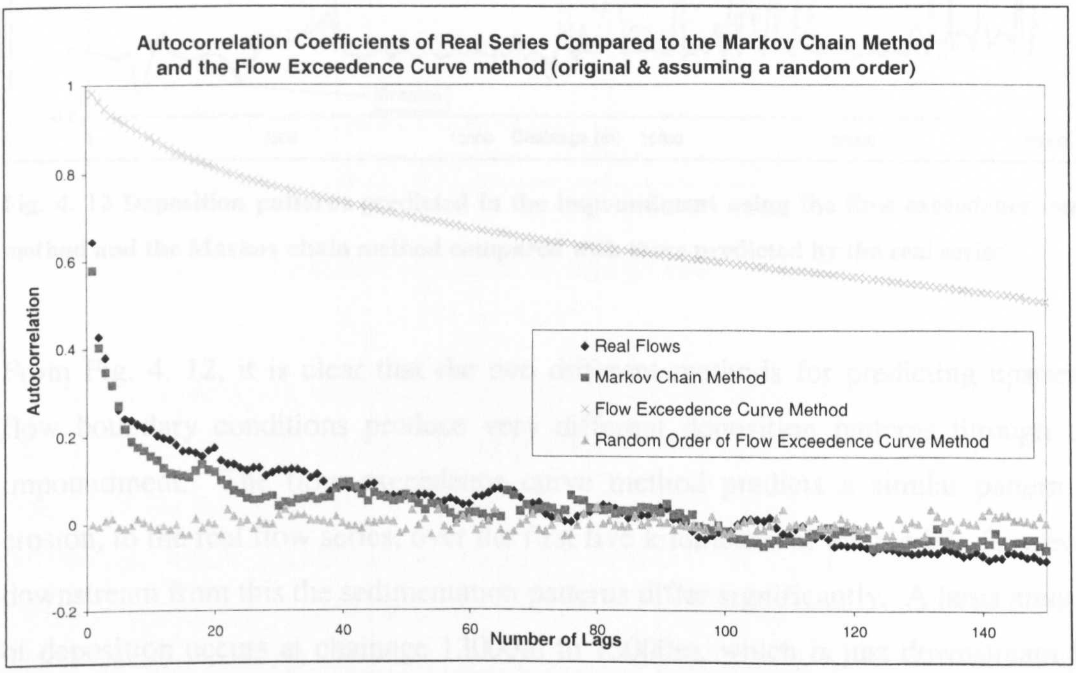


Fig. 4. 11 Comparison of the lag one autocorrelation coefficients from the Markov chain method and flow exceedence curve method (both original and assuming a random order) with the real flow series

The three flow time series (real, Markov, Flow Exceedence) were used as the upstream boundary condition for the three different ISIS models. The models were then run for five years each, using a time step of 900 seconds for every run. A prediction of the sedimentation patterns produced can be seen in Fig. 4. 12. The graph shows the areas of relative erosion and deposition through the impoundment, with erosion occurring at the upstream end (near Low Moor) and deposition happening further downstream towards the barrage.

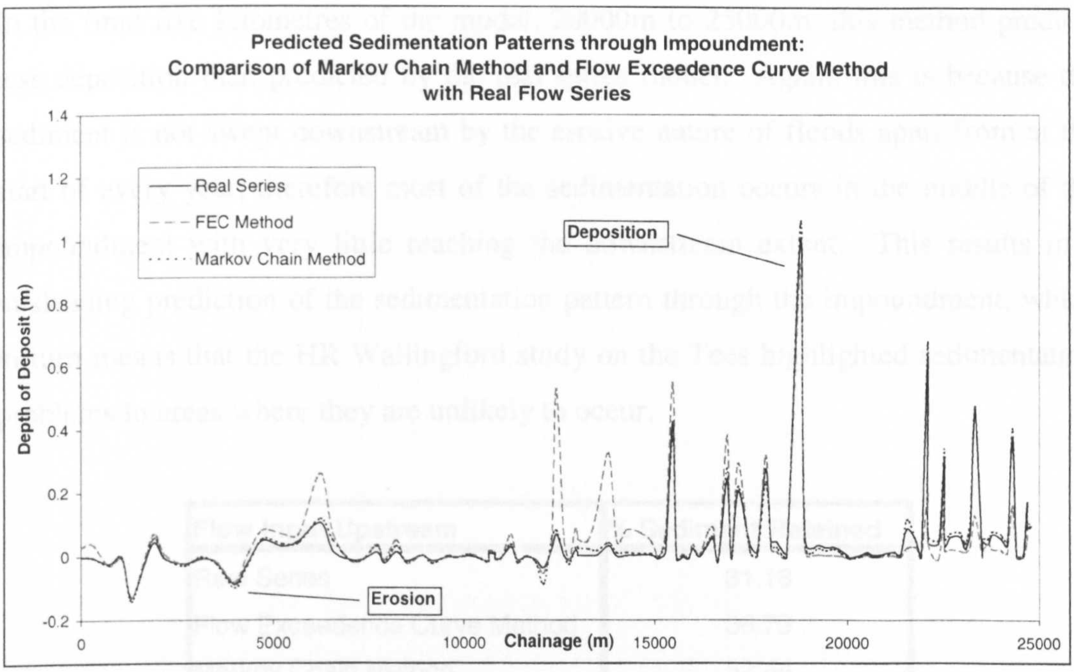


Fig. 4. 12 Deposition patterns predicted in the impoundment using the flow exceedence curve method and the Markov chain method compared with those predicted by the real series

From Fig. 4. 12, it is clear that the two different methods for predicting upstream flow boundary conditions produce very different deposition patterns through the impoundment. The flow exceedence curve method predicts a similar pattern of erosion, to the real flow series, over the first five kilometres of the model. However, downstream from this the sedimentation patterns differ significantly. A large amount of deposition occurs at chainage 13000m to 15000m, which is just downstream for the Leven confluence. This deposition is not in agreement with that predicted by the real series, however it is in very good agreement with the predictions made in the HR Wallingford report EX1744 (1988). The poor predictions of deposition can be attributed to the poor representation of serial correlation in the flow series at the upstream boundary. All the high flows are modelled at the beginning of the year and, therefore, the sediment is not re-suspended regularly and swept further down the river as it would do naturally during a flood. The natural re-distribution of sediment through the impoundment by medium-high flows is not modelled realistically by the flow exceedence curve flow series and as such the predicted distribution appears to be a poor representation of the future of the impoundment. If the sedimentation predictions were viewed after the annual floods were modelled (i.e. at the start of the year) a different pattern may have been shown where less deposition was predicted. In the final five kilometres of the model, 20000m to 25000m, this method predicts less deposition than predicted by the real series model. Again, this is because the sediment is not swept downstream by the erosive nature of floods apart from at the start of every year, therefore most of the sedimentation occurs in the middle of the impoundment with very little reaching the downstream extent. This results in a misleading prediction of the sedimentation pattern through the impoundment, which in turn means that the HR Wallingford study on the Tees highlighted sedimentation problems in areas where they are unlikely to occur.

Flow Input Upstream	% Sediment Retained
Real Series	31.16
Flow Exceedence Curve Method	36.79
Markov Chain Method	32.44

Table 4. 4 Percentage of sediment retained in the impoundment over the 5 year test period

On the other hand, the sedimentation pattern predicted using flows generated by the Markov chain method reproduces that predicted using real flows more closely. The erosion at the upstream end is reporduced well. There is a slight over prediction of deposition, which occurs around chainage 13500m and again at the downstream extent of the model. This over prediction may be partly due to the fact that the flows predicted from the Markov chain method may be slightly higher resulting in a higher sediment inflow. However, the sedimentation distribution throughout the impoundment is well reproduced using the Markov chain method, because the short-term variability caused by floods has been modelled. This is because the Markov model retains the serial correlation in flows as well as the moments of the distribution.

These model runs were used to investigate the trapping efficiency of the impoundment. The aim of this was to examine which method predicted the most realistic trapping efficiency of the impoundment. The sediment components of the impoundment and the downstream flow boundary are being modelled exactly the same way throughout this investigation therefore, the method of information input into the model is being scrutinised. The results of this can be found in Table 4. 4. The Markov chain method simulates the trapping efficiency of the impoundment better than the flow exceedence curve method.

The flow exceedence curve method, whilst preserving the moments of the distribution, builds in an unrealistic autocorrelation structure. As a consequence, when used to generate an upstream boundary for the ISIS sediment routing model it leads to poor predictions of sediment deposition and trapping efficiency. The Markov model, on the other hand, is good at reproducing the short-term autocorrelation of the real flow data. Upstream flows generated by this model lead to the simulation of deposition and trapping efficiency that are a significant improvement over the flow exceedence curve method. The Markov model is stochastic, thus each realisation of the flow created by it is likely to be different, but have the same statistical properties. This has the advantage of allowing the inherent variability of the real flow series to be simulated. To fully utilise this many simulations using the Markov Chain and ISIS would need to be conducted in a Monte Carlo analysis. These could then be summarised to give ensemble average predictors of sediment deposition and estimates of confidence limits. This is computationally expensive and outwith the scope of this PhD project, however, it is likely to provide a fruitful avenue for further research.

4.2.2 Time Dependency of Flows

As described above the Markov Chain Method creates a series of states that reproduce the historical statistics of the series. If it is used to create flow boundaries for hydraulic models, it will produce a different, but representative, flow series each time a series is generated. The flow series will have very similar descriptive statistics and flow structure to the source data. This means that the main difference that will occur in the generated series is that there will be different times between peak flows. As no aspect of the sediment modelling employed here is time dependent, for example consolidation, this will not affect the overall predictions of sediment retention within the impoundment. To demonstrate this, simulations have been repeated twice with different flow series.

4.3 Climate Change

In the present economic climate, and as the evidence for climate change increases, it is necessary to plan and design for the possibility of changed climate scenarios. The result of climate change may produce more extended periods of extreme flows or low flows, which need to be accounted for when planning any type of construction near water. Consequently, when investigating long-term effects of structures in or around waterways, an assessment of the effect of climate change should be built in to the analysis. A discussion of the methods presently used to predict climate change effects on water resource planning can be found in chapter 2, section 2.3.3. These methods, while detailed, can be time consuming and subsequently are not used by hydraulic modellers. Therefore there is a need to find quicker techniques that are just as effective at producing a prediction of how the flow series might change in rivers. In particular, an estimate for the effect of climate change on the flows in the river Tees is desirable for this project. However, while considering climate change modelling, it is necessary to remember that climate change modelling is fraught with uncertainty due to the nature of the research. Two new methods for modelling climate change in the flow series have been investigated. Both techniques are proposed as a development of the Markov chain method for creating flow series for existing climate conditions.

The first method was pursued independently and constituted a significant research effort on behalf of the author. It was based on the hypothesis that, given the transition probability matrix of a Markov Chain for current conditions, its eigenvectors could be perturbed in a physically meaningful way to create a new matrix that would generate flow time series that conform to climate change predictions. However, ultimately the method proved to have too many degrees of freedom to find a unique matrix for a perturbed climate. Therefore, this research has been reported in Appendix (A). The second method was developed in collaboration with Dr. Nicole Augustin of the Statistics Department at the University of Glasgow and is reported in full below.

4.3.1 Climate Change - Autoregressive Multinomial Logit Model

Revisiting the Markov Chain model within the framework of an Autoregressive Multinomial Logit Model (Fahrmeir & Tutz, 2001) allows, in essence, transition probabilities between flow states to be conditional on precipitation and temperature data. Previously, a similar model has been applied to predict the spatial dynamics of vegetation (Augustin, Cummins & French, 2001). It used a multinomial logit transition model to make the transition probabilities, for the change in vegetation dynamics over a period of time, a function of several different explanatory variables. Thus, for the River Tees catchment, given precipitation and temperature predictions for a future climate, a series of flow states modified for the future climate can be generated

4.3.1.1 Multinomial Logistic Regression

A multinomial logit model is a type of generalised linear model. In its simplest form a generalised linear model specifies the (linear) relationship between a dependent (or response) variable Y, and a set of predictor (or explanatory) variables, the *X*'s, so that:

$$\mathrm{Y} = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k$$

Equation 3.4

There are two main reasons why a simple linear model may not be appropriate to describe a particular relationship. Firstly, the effect of the predictors on the dependent variable may not be linear in nature. Secondly, and importantly in this case, the dependent variable of interest may have a non-continuous distribution. In this case, the dependent variable can only take on distinct, discrete values (categorical), and then distribution of the dependent variable is said to be multinomial. If the categories for the response variable can be ordered then the distribution of that variable can be termed ordinal multinomial. Therefore using generalised linear models results in two main advantages over a simple linear regression; firstly, the distribution of the response variable can be explicitly non-normal, and does not have to be continuous; and second, the dependent variables are predicted from a linear combination of predictor variables, which are connected to the dependent variable via a link function.

The link function is an essential part of the generalised linear model as it is the link between the distribution of the response variable and the component of the explanatory variables. It defines how $\mu = E(Y)$ relates to the explanatory variables in the linear part of the equation (Agresti, 1996). The formula of a generalised linear model states:

$$g(\mu) = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_k X_k$$

Equation 4. 22

Where $g(\mu)$ is called the link function. The link function that has been utilised in this model is known as the logit link (Equation 4.26).

$$\log\left(\frac{\pi(x)}{1 - \pi(x)}\right) = b_0 + b_1 x_1 + \cdots + b_k x_k$$

Equation 4. 23

Where $\pi(x)$ is restricted to the range (0,1). This equation implies that $\pi(x)$ increases or decreases as an S-shaped function of x, similar to a cumulative probability distribution.

A multinomial logit model has been utilised here, rather than an ordinal logit model, because despite the fact that the response variable is ordered (the categorical flow data is ordered from lowest to highest) the proportional odds ratio requirement for the model was not satisfied. This requirement states that:

$$\frac{P(Y \le r|x_1)/P(Y > r|x_1)}{P(Y \le r|x_2)/P(Y > r|x_2)} = \exp\{(x_1 - x_2)'\beta\}$$

Equation 4. 24

Where Y is the predicted response, r is the number of states in the predicted response sample, β is a vector of coefficients and x_1 and x_2 are explanatory variables. This states that the ratio of the cumulative odds for two populations is the same for all of the cumulative odds, which gives a strict stochastic ordering of populations (Fahrmeir & Tutz, 2001).

As a result a multinomial logit model has been used which does not require the categorical data to be ordered.

A Markov model for categorised flows y_t with k possible categories can be defined as a multicategorical time series:

$$y_t = (y_{t1}, y_{t2}, \cdots, y_{tq})', q = k - 1$$

Equation 4. 25

where;

$$y_{tj} \begin{cases} 1, & \text{Category } j \text{ has been observed} \\ 0, & \text{Otherwise, } j=1, \dots, q \end{cases}$$

Equation 4. 26

The inverse link function that was used in the Tees model takes the form:

$$p_{tj} = \frac{\exp(\mathbf{Z}_t \beta_j)}{\sum_{s=1}^{k} \exp(\mathbf{Z}_t \beta_s)}$$

Equation 4. 27

With the matrix $\mathbf{Z}_t = diag(z_t')$, where z_t for this model contains the lagged response variable (because the model is autoregressive) and the explanatory variables:

$$z_t' = (1, y_{t-1,1}, y_{t-1,2}, \cdots, y_{t-1,7}, temp_{t-1}, prec_{t-1})$$

Equation 4. 28

And the vector of parameter coefficients is defined:

$$\beta_j = (1, \beta_{t-1,1}, \beta_{t-1,2}, \cdots, \beta_{t-1,7}, \beta_{t-1,temp}, \beta_{t-1,prec})$$

Equation 4. 29

This formulation yields a non-homogenous (i.e non-stationary transition probabilities) Markov chain of first order with k unordered states.

4.3.1.2 The Tees Catchment Climate Data for Model Building

To build climate conditions into the Markov model it was necessary to collect continuous times series of catchment temperature and precipitation. This was supplied in a number of formats. The precipitation data was available in daily increments from 16 rain gauges in the Tees catchment for the period 1990-2000. However the mean catchment temperature data was only available in monthly averages for the period 1960-2000. Daily flow data was already available for the Tees, as it had been supplied by the National River Flow Archive. This data was already categorised and ready for use for the period 1970-2000.

4.3.1.2.1 Mean Catchment Temperature Data

The Met. Office provided the mean catchment temperature time series. This data was available in 5km gridded time series format for the whole of the UK from 1960 to 2000. The Tees catchment was identified within the UK dataset and the values were downloaded from the file. Each of the 5km grids had a mean temperature averaged for that area for each month between 1960 and 2000. Once these grids were identified for the Tees, the temperature values were then averaged across the catchment to give a mean monthly catchment temperature. These 5km grid temperature data are compiled from the network of temperature gauges that the Met. Office and the Environment Agency operate across the UK.

Once a catchment mean temperature had been established for each month a rolling average was calculated. 2-day, 10-day and 30-day means were calculated by taking an average of the previous 2, 10 or 30 days respectively. This did not include the day in question t, rather it always started from day $t-1$ and used the preceding 2,10 or 30 days to calculate the average. The 30-day mean catchment temperature was used in the multinomial logit model constructed for the Tees.

4.3.1.2.2 Total Catchment Daily Precipitation Data

The catchment precipitation data was available in daily format from 16 different gauges around the upper Tees catchment. These gauges are detailed in Table 4.5.

	Rain Gauges					
	ID	NAME	XPR	YPR	ELEVATION	TYPE OF GAUGE
1	32822	Harpington Hill *	433600	526700	90.0	15mins - AWS
2	30377	Lingfield Way *	432200	514600	54.0	15mins - AWS
3	28185	Lartington Filters *	401100	518300	220.0	15mins - AWS
4	26644	Cow Green *	381700	529100	494.0	15mins - AWS
5	29156	Raby Castle *	412800	522100	140.0	daily - d.rain
6	27882	Eggleston *	400100	523700	260.0	daily - d.rain
7	28408	Barnard Castle *	405600	516400	171.0	daily - d.rain
8	29581	Broken Scar *	425800	514200	48.0	daily - d.rain
9	30581	South Park *	428600	513400	30.0	daily - d.rain
10	30001	Balderhead	392900	518700	343.0	daily - d.rain
11	30002	Brignall	407100	512200	209.0	daily - d.rain
12	30003	Gilmonby West Gates	398800	512800	280.0	daily - d.rain
13	30004	Grassholme Resr	394600	522400	285.0	daily - d.rain
14	30005	Grenhills Farm	383800	532000	444.0	daily - d.rain
15	30008	Newton Ketton	431400	520600	73.0	daily - d.rain
16	30009	Redworth	424900	523700	123.0	daily - d.rain

Table 4. 5 Table showing the location and type of each rain gauge used for the Tees catchment (AWS - Automatic Weather Station, d.rain - daily rain gauge)(* denotes data from the EA)

The automatic weather stations record 15-min precipitation data and send it automatically to a logger. In contrast the d.rain stations record the total daily precipitation, which is measured every day at 9am. This raw data was collated, averaged over 24 hours where required and any missing data was infilled using correlations from nearby stations by Dr. Julie Carter from Cranfield University. The Environment Agency and the British Atmospheric Data Centre provided all the precipitation data for the Tees catchment. The gauges with suffix * in Table 4.5 were provided by the Environment Agency, the remaining data was provided by the

British Atmospheric Data Centre (BADC). The data was only available continuously for the period 1990 to 2000. More historical data was available in the form of monthly catchment means, however accurate daily precipitation data was considered vital for the model therefore the shorter, more detailed record was used.

To convert this data from separate gauges into a catchment rainfall value it was necessary to use the Theissen Polygon method to average the point data over the catchment (Wilson, 1974). The Theisson Polygon method defines the zone of influence of each gauge within the catchment. Once this has been allocated, the proportion of this area to the area of the entire catchment is calculated. Each value of precipitation from each station is then multiplied by the proportion of the catchment it influences, thereby giving an area-averaged catchment value. The precipitation data was available continuously from 1990-2000. This was the shortest time period available for any of the three datasets, therefore the precipitation dataset dictated the time period on which the model was built.

4.3.1.3 The Multinomial Logit Model for the Tees – Model Creation, Selection and Validation

Dr. Nicole Augustin from the Department of Statistics at Glasgow University implemented this model into computer code.

It was then calibrated on past and present climatic conditions to allow for non-stationary transition probabilities that were a function of two explanatory variables: mean temperature and total daily precipitation. The explanatory variables were averaged over a differing number of days to allow for the best model to be selected: 2-day, 10-day and 30-day means were calculated for the explanatory variables (ensuring that the present day value was not used, thus allowing the model to work in forecasting mode). The model selection was completed using a backward selection based on the Bayes Information Criterion (BIC). Two models were chosen at this stage, the simple Markov model which uses no explanatory variables and a more sophisticated model using 30-day mean temperature and the daily total precipitation for the catchment as explanatory variables. Development of more detailed models could improve the predictions and should be investigated in the future.

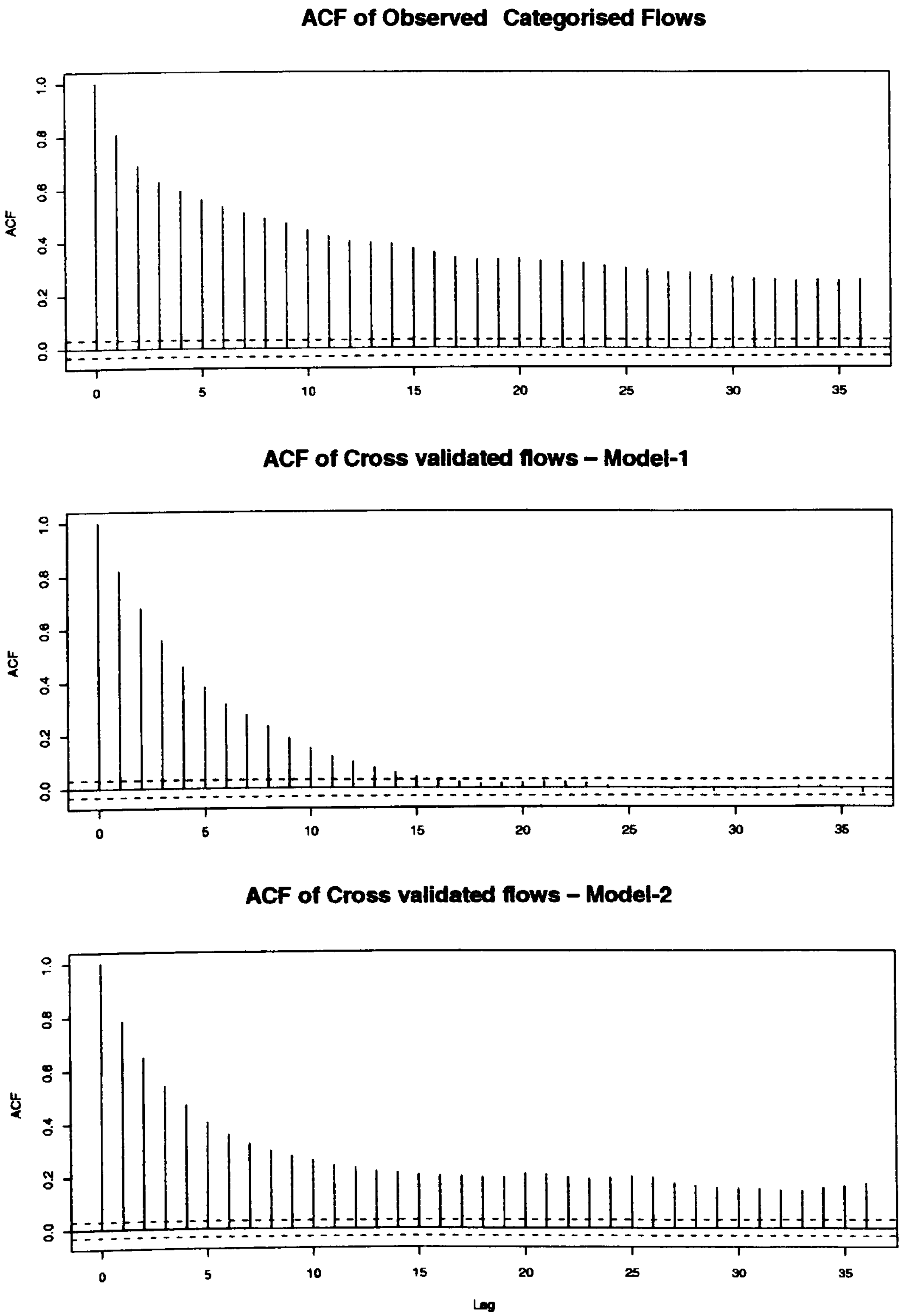


Fig. 4. 13 Autocorrelation functions as predicted by both model 1 (simple Markov Model) and model 2 (Markov with temperature and precipitation) compared with the observed series ACF

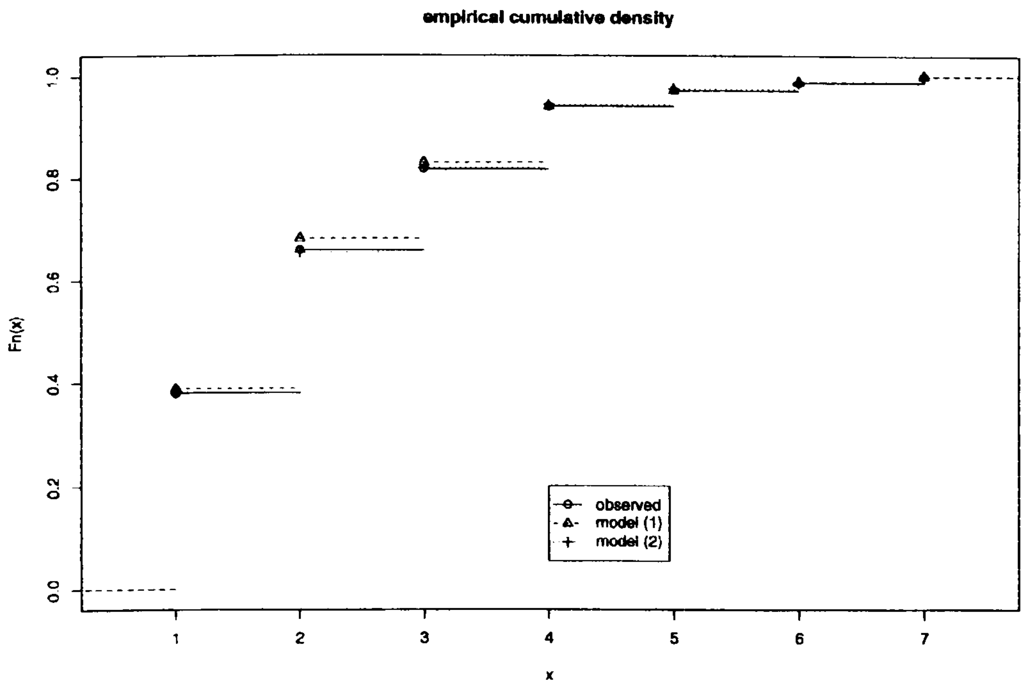


Fig. 4. 14 Empirical Cumulative Density Function as calculated using the categorised data - Comparison of Model 1 and 2 with the observed data

The validation of the model was completed using k-fold cross-validation (Davison & Hinkley, 1997). The observed times series are split into k=20 blocks of similar size. This resulted in small blocks of 201 days. One block of 201 days was then set as the test series D^{test} and the rest of the observed series was used to fit the model D^{build}. Using the model progressive series of 201 days are predicted to create a series of the same length as the original series. This predicted series is then checked against the test data. The predicted set of data was checked against the test data using the autocorrelation function (to investigate the time dependence of flows) and the cumulative density function (to check the descriptive statistics). This procedure ensured that a simulated time series was obtained for all the days between 1990 and 2000. The autocorrelation functions predicted by this method are shown in Fig. 4. 13. It can be seen from this figure that the series created with the second model (which uses temperature and precipitation as explanatory variables) results in an autocorrelation function, which matches the observed series autocorrelation function more closely than model 1 (the simpler Markov Model). Additionally, investigating the empirical density function (Fig. 4. 14) shows that including temperature and precipitation as explanatory variables improves the model's capability of reproducing this.

The resulting transition probabilities from Model-2 are shown in Fig. 4. 15, Fig. 4. 16 and Fig. 4. 17. This shows how the transition probabilities change as a function of precipitation and temperature. For example, keeping the precipitation the same, as the temperature increases in the impoundment the transition probabilities show that less water makes it to the river resulting in lower flows.

4.3.1.4 The Climate Change Data - Temperature and Precipitation

The Hadley Centre UK provided the temperature and precipitation data for the future climates. The Hadley Centre is where most of the climate change prediction work is completed for the UK and the data is available through the Climate Impacts LINK project. This is run by the Climate Research Unit (CRU) and linked to the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre.

Research at the Hadley Centre involves large-scale global climate models (GCM), which are validated to the baseline data from 1961-1990. These models are then simulated for many years into the future using different emissions scenarios. Several different emissions scenarios exist, however the data was only available for two future scenarios. These scenarios will be discussed in detail in section 4.3.2.4.1. These large-scale Global Coupled Climate Models such as the Hadley Centre's HadCM3, have a resolution of 2.5°x3.75°, and the results from these are then used in an atmosphere only model such as HadAM3 which has a resolution of 1.25°x1.875°. Features on the landscape such as hills and mountains can influence local climate, but due to the coarse resolution of the GCMs it is difficult to account for these types of issues. Therefore regional climate models (RCM) are set up to provide more detailed information over a smaller area for a limited period of time (it can be impractical to run detailed models for long periods of time). The results from the GCM and atmosphere only models are then used to dynamically downscale the predictions using an RCM. HadRM3 is the Hadley Centre's RCM which predicts possible future climate changes for Europe at a resolution of 50km.

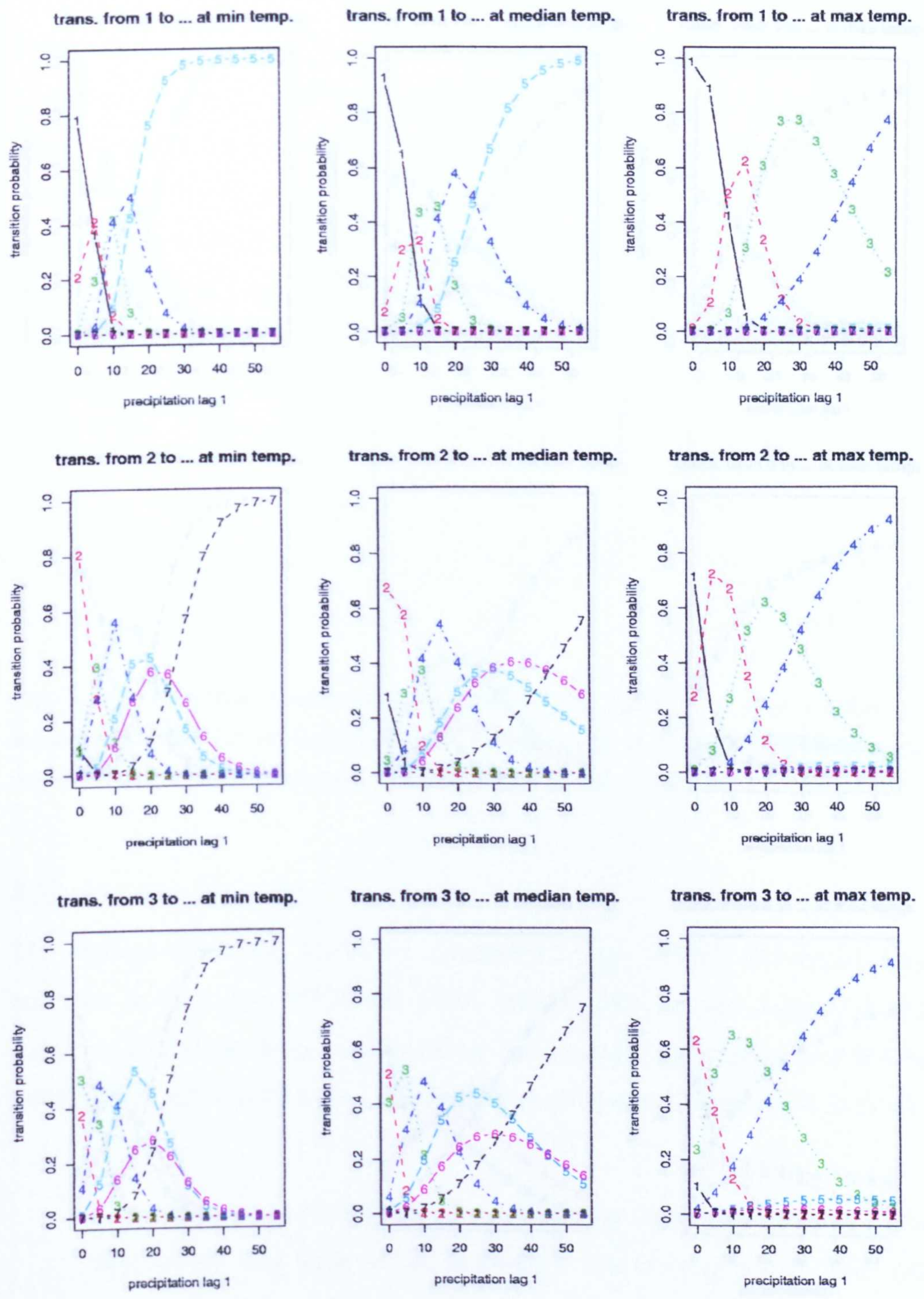


Fig. 4. 15 Transition Probabilities as predicted by model-2 at min, median and max temperatures with increasing precipitation (transitions for states 1-3). The numbers in the figure represent the transition probability of state 1 (or 2 & 3) into state 1-7 respectively.

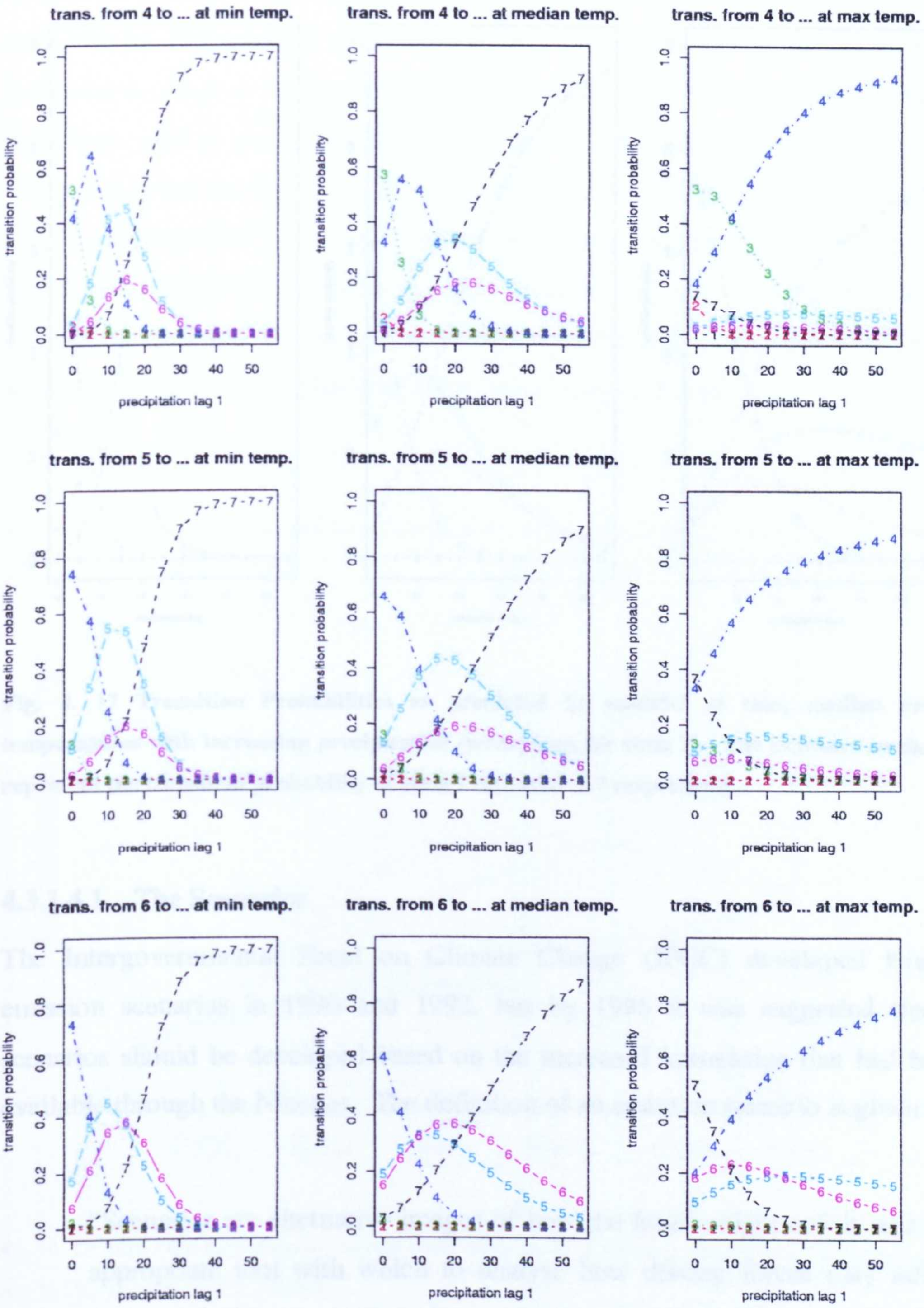


Fig. 4. 16 Transition Probabilities as predicted by model-2 at min, median and max temperatures with increasing precipitation (transitions for states 4-6). The numbers in the figure represent the transition probability of state 4 (or 5 & 6) into state 1-7 respectively.

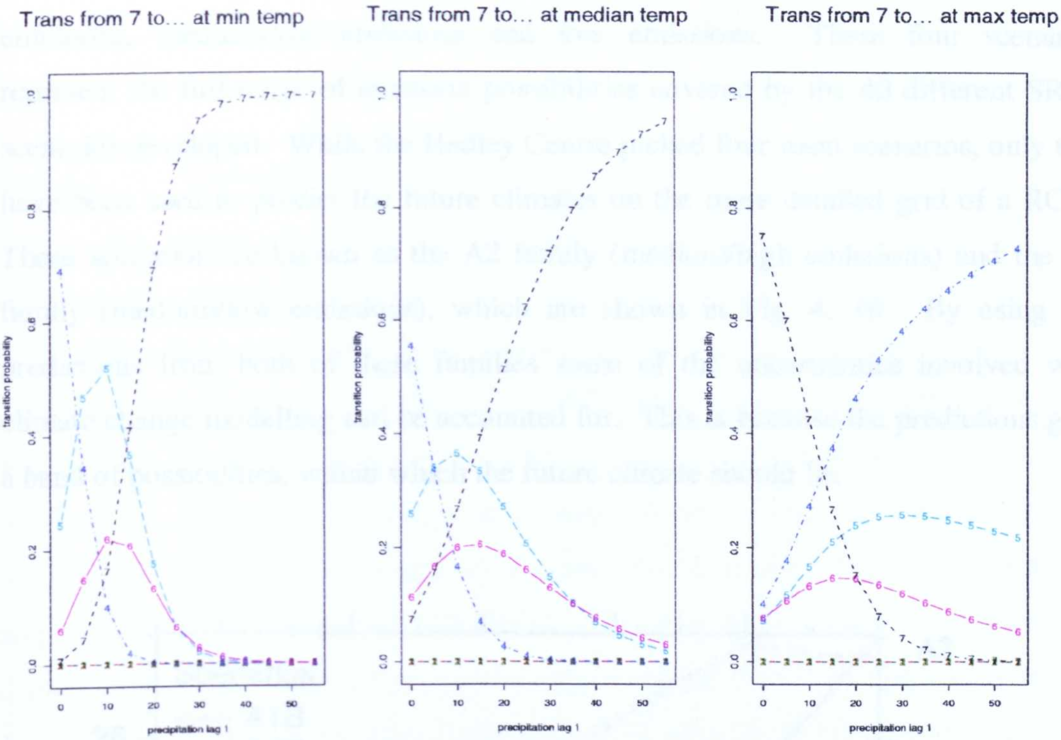


Fig. 4. 17 Transition Probabilities as predicted by model-2 at min, median and max temperatures with increasing precipitation (transitions for state 7). The numbers in the figure represent the transition probability of state 7 into state 1-7 respectively.

4.3.1.4.1 The Scenarios

The Intergovernmental Panel on Climate Change (IPCC) developed long-term emission scenarios in 1990 and 1992, but by 1996 it was suggested that new scenarios should be developed based on the increased knowledge that had become available through the Nineties. The definition of an emission scenario is given by:

> "Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties." (Special Report On Emissions Scenarios, 2000)

Many different scenarios were developed, encompassing a variety of possible future outcomes with regards to social, economic, technological, demographic and environmental developments. The Hadley Centre's work on climate change prediction has used four main scenario possibilities; high emissions, medium/high emissions, medium/low emissions and low emissions. These four scenarios represent the full range of emission possibilities covered by the 40 different SRES scenarios developed. While the Hadley Centre picked four main scenarios, only two have been used to predict the future climates on the more detailed grid of a RCM. These scenarios are known as the A2 family (medium/high emissions) and the B2 family (medium/low emissions), which are shown in Fig. 4. 18. By using the predictions from both of these families some of the uncertainties involved with climate change modelling can be accounted for. This is because the predictions give a band of possibilities, within which the future climate should lie.

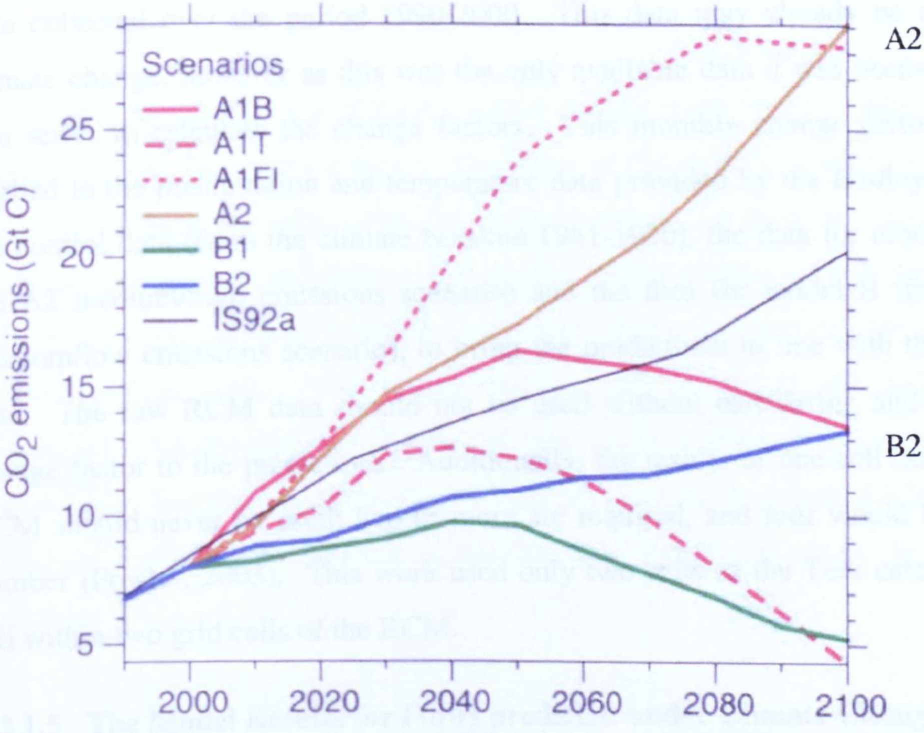


Fig. 4. 18 Different emissions scenarios (SRES) as used in climate change modelling (taken from the IPCC website (IPCC, 2003)

The RCM had been simulated for a period of 31 years for each scenario. For the A2 scenario this had been repeated 3 times. These three simulations for the same scenario could then be run together to give a simulation for 93 years (Fowler, 2003). The B2 scenario was only simulated once, however this was also run together to give 93 years worth of predictions under an altered climate. For comparison purposes a baseline scenario was also simulated using the RCM, which should compare to the observed values of temperature and precipitation in the catchment between 1961-1990.

4.3.1.4.2 Correction of the Climate Change Data

Due to the nature of RCMs, the prediction of rainfall can be unpredictable. Therefore it is necessary to correct the climate change data by applying a factor to the monthly mean averages for precipitation and temperature (Fowler, 2003). The factor was calculated by comparing the difference between the control data as predicted by the GCM for the period 1961-1990 with the observed data from the same period. Unfortunately, the same comparison period was not available for the precipitation data, thus the means for the observed data were calculated using the data collected over the period 1990-2000. This data may already be affected by climate change, however as this was the only available data it was necessary to use this series to calculate the change factors. This monthly change factor was then applied to the precipitation and temperature data provided by the Hadley Centre for the control data (from the climate baseline 1961-1990), the data for model A (from the A2 medium/high emissions scenario) and the data for model B (from the B2 medium/low emissions scenario), to bring the predictions in line with the observed data. The raw RCM data should not be used without calculating and applying a change factor to the predictions. Additionally, the results of one cell only from the RCM should never be used; two or more are required, and four would be the ideal number (Fowler, 2003). This work used only two cells as the Tees catchment only fell within two grid cells of the RCM.

4.3.1.5 The Model Results for Flows predicted under Climate Change

After the model was created and validated it was possible to use the temperature and precipitation predictions for future climate scenarios, as provided by the Hadley Centre, to produce new flows for the River Tees under future climates. Precipitation and temperature series existed for 93 years for Model A (from the A2 medium/high emissions scenario), Model B (from the B2 medium/low emissions scenario) and the control series (from the climate baseline 1961-1990). To investigate the climate data, the control series was first compared against the observed series for the catchment for the period 1970-2000. This period was used as it took account of the observed flows in the river, and gave a long, established record with which to compare. A similar test was completed for both Climate Model A and B so that the difference in the four series could be identified. Firstly a comparison of the descriptive statistics for each series was compiled (Table 4. 6). This can be seen graphically in Fig. 4. 19.

	Summary Statisitics			
	Climate Model-A	Climate Model-B	Climate Control	Observed
Mean	18.363	19.200	21.113	19.987
St. Dev	28.822	28.221	27.890	27.060
Skew	5.265	4.863	4.480	4.556
Kurtosis	45.011	39.624	32.890	34.782

Table 4. 6 Comparison of summary statistics for each of the climate models and the control model with the observed series for the Tees

The results show that the climate control model gives similar results to those calculated from the observed series. The mean of the series is higher than the flows observed, however the other statistics compare well. The skew and the kurtosis of the series are a good indicator of the spread or distribution of the series. If the control series is compared to the observed series it can be seen that the skew of the series compares well. This means that the asymmetry of the series is well reproduced. Additionally the kurtosis of both series matches, which in turn means that the tails are weighted similarly. This means that the climate control model represents the flows in the Tees reasonably well when comparing the descriptive statistics.

	Flow Structure	% of overall record		
	Climate Model-A	Climate Model-B	Climate Control	Observed
1	45.242	41.296	31.654	33.249
2	22.289	23.702	26.859	26.153
3	14.583	15.879	19.544	20.863
4	12.193	13.442	15.783	13.867
5	3.220	3.220	3.674	3.456
6	1.455	1.553	1.622	1.509
7	1.019	0.908	0.863	0.903

Table 4. 7 Comparison of the categorised data between the climate models and the observed data for the Tees

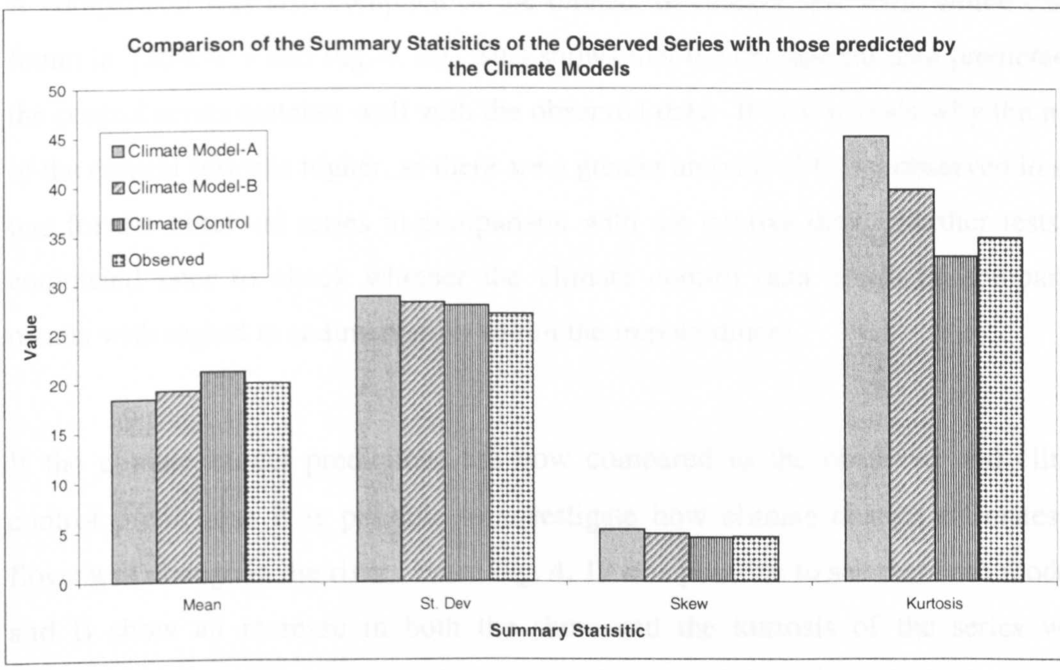


Fig. 4. 19 Graphical portrayal of the summary statistics for the two different climate models, the control model and the observed series for the Tees.

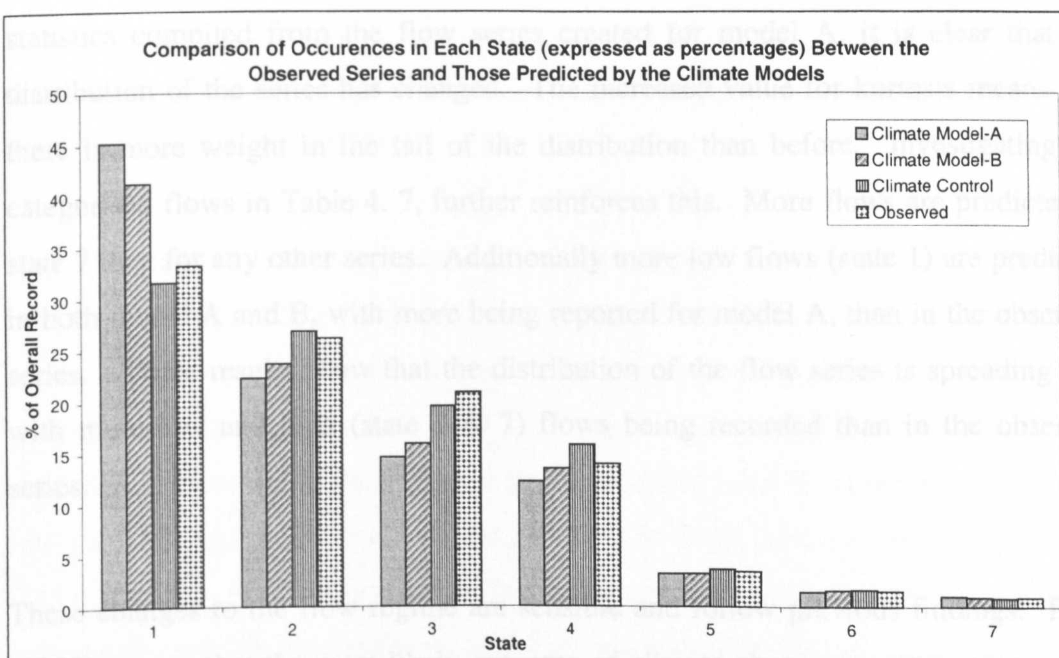


Fig. 4. 20 Graphical portrayal of the comparison of categorised data as predicted by the climate models and the observed series for the Tees

A comparison was also compiled of the binned, or categorised, data, which can be found in Table 4. 7 and Fig. 4. 20. This shows that the categorical data predicted by the control series matches well with the observed data. It also reveals why the mean of the control series is higher, as there are a greater amount of flows observed in state one for the observed series in comparison with the control data. Further tests are completed later to check whether the climate control data produces comparable results with regard to sedimentation within the impoundment.

If the climate model predictions are now compared to the observed and climate control predictions it is possible to investigate how climate change estimates the flows will change in the river. From Fig. 4. 19 it is possible to see that both model A and B show an increase in both the skew and the kurtosis of the series while maintaining a similar value for the mean and standard deviation. In both cases the more extreme value is reported with model A. This is sensible, as model A should show more change when compared to model B. This is because Model A uses a more extreme prediction of future emissions than Model B. From the descriptive statistics compiled from the flow series created for model A, it is clear that the distribution of the series has changed. The increased value for kurtosis means that there is more weight in the tail of the distribution than before. Investigating the categorised flows in Table 4. 7, further reinforces this. More flows are predicted in state 7 than for any other series. Additionally more low flows (state 1) are predicted in both model A and B, with more being reported for model A, than in the observed series. These results show that the distribution of the flow series is spreading out, with more low and high (state 1 & 7) flows being recorded than in the observed series.

These changes to the flow regime are sensible and follow previous findings. Price (1998) reports that the most likely outcome of climate change is wetter winters and drier summers, which means that the distribution of flows will be stretched with more of both extremes. Similarly, Arnell (2003) explains that the effect of climate change will be felt more on the low flows rather than the mean flows in the river. The Q95 (flows exceeded 95% of the time) will decrease with climate change, which results in the frequency of low flows increasing. Black & Burns (2002) investigated the effect of climate change to Scottish catchments; this research suggests that the frequency of extreme high flows or POT flows will increase in many catchments. Similar results have been reported by Arnell (1996; 1999), Arnell & Reynard (1996) and Pilling & Jones (1999).

4.3.1.6 Comparison of the Climate Control Morphological Predictions with those of the Markov Chain

As a check on the validity of the climate change results for flows, the predicted climate control flows were used to simulate 50 years of suspended sediment movement through the Tees impoundment using the ISIS model. The check was completed using the high sediment supply scenario. The model was run for 50 years using the same time step that was used in all the simulations, which was 900 seconds.

	Inflow (tonnes)	Outflow (tonnes)	Deposited (tonnes)	Retained %
Climate Control	4279253	4074704	204549	4.79
Markov Chain	4618494	1377618	240876	5.22

Table 4. 8 Results of the climate control model flow predictions run through the ISIS model to compare morphological predictions

The results showed a very similar deposition prediction through the impoundment in conjunction with a comparable sediment retention rate for the impoundment. These results can be seen graphically in Fig. 4. 21 and the throughput of sediments in the impoundment are detailed in Table 4. 8. These results show that the climate change predictions from the Hadley Centre for 1961-1990 used in conjunction with the multinomial logit model result in similar flows to those predicted using the Markov Chain model. Additionally these flows then produce very similar sedimentation patterns through the impoundment and show a comparable amount of sediment being retained. The reason the climate control model shows less sediment entering the impoundment in the first place is that the climate predictions from the Hadley Centre are based on a 360-day year. This results in a fifty-year simulation running for 18000 days in comparison to a simulation time of 18263 days which is the case when using a 365 day year and including leap years.

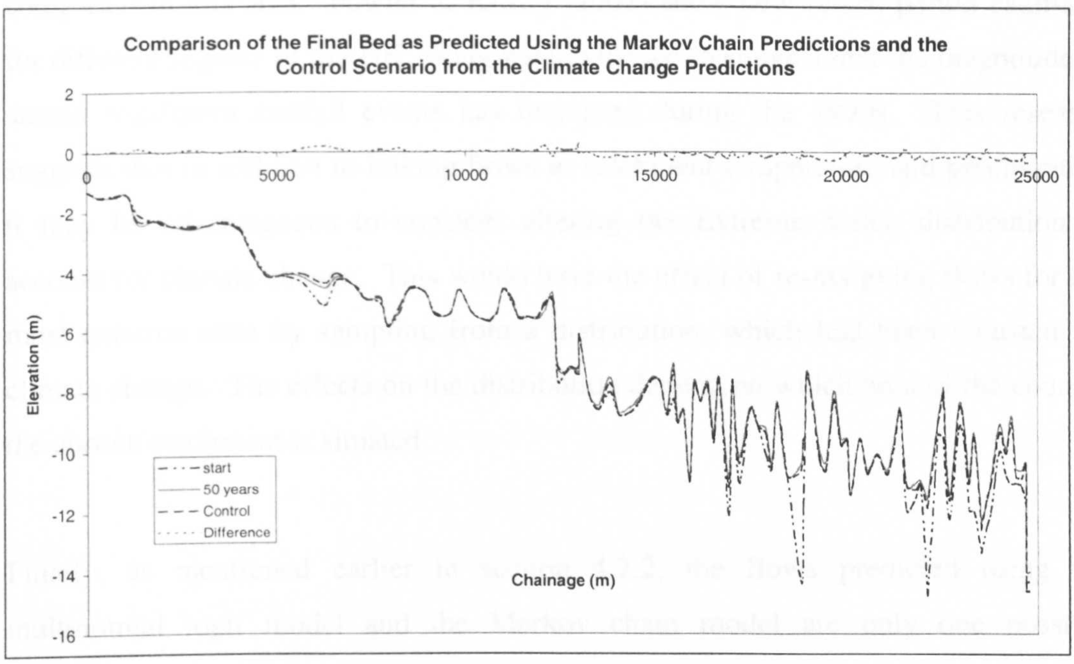


Fig. 4. 21 Comparison of the final bed in the impoundment as predicted using the Markov Chain flow predictions and the Climate Control flow predictions

4.3.1.7 Future Work for Climate Change Modelling

Using the multinomial logit model to link temperature and precipitation to flows in the Tees catchment has allowed for climate change to be accounted for when forward predicting flow datasets.

A few improvements to this method could be developed in the future. Firstly more detailed catchment climate data could be used to construct the model. Climate change predictions exist for many different parameters such as specific humidity, maximum and minimum temperatures, convective snowfall and catchment wind speed. Existing datasets of these types of parameters could be used in the construction of the model as explanatory variables. While this should improve the forecasting power of the model, it could be difficult to collect a long enough dataset of these parameters for an individual catchment.

Secondly, the categorised data has been subject to modification using climate change predictions in this method, but when re-assigning the flows, an historical extreme distribution have been used. This has implications on the return periods of extreme events, which may be modified under climate change. Some work has been completed in this area. Fowler & Kilsby (2002) show new return period estimates for different regions of the UK, along with evidence to suggest that the magnitude of annual maximum rainfall events has increased during the 1990s. This research suggests that in addition to linking flows to catchment temperature and precipitation it may be advantageous to consider altering the Extreme Value distribution to account for climate change. This would have the effect of re-assigning flows for the most extreme state by sampling from a distribution, which had been adjusted for climate change. The effects on the distribution depend on which area of the country the chosen catchment is situated.

Finally, as mentioned earlier in section 4.2.2, the flows predicted using the multinomial logit model and the Markov chain model are only one possible realisation of the flows in the Tees for the future. Each time a flow series is predicted it will be different despite the descriptive statistics and the structure of the series being well reproduced. While for each case the sediment runs have been repeated to validate the morphological predictions using these flows, there will be variability each time different flows are used for simulations. This is because the time between the erosive peaks of extreme flows will differ. To extend this work further it would be sensible to complete a Monte Carlo simulation to investigate the effect of the sensitivity of the morphological method with regard to morphological sustainability to time dependent processes such as sediment consolidation.

4.4 Summary

The aim of this chapter was to present the method that has been developed during the course of this research for extending historical flow boundaries for the purpose of simulating sedimentation processes using one-dimensional hydraulic models. The method uses a Markov chain method, which is a generic modelling technique that uses the statistical properties of a historical series to forward predict existing datasets.

Firstly, the Markov chain method was discussed and the data prepared. This was followed by a detailed examination of the predicted flows, which investigated the similarity of the predicted series with that of the observed flows recorded in the impoundment. These investigations compared the descriptive statistics, the flow structure and distribution of each series. From this work a decision was made to use the flow predictions created using the first order transition matrix as an upstream boundary for the ISIS model. These flows were used to predict the morphological future of the impoundment under present climate conditions detailed in Chapter 6.

To justify the use of the Markov chain method for extending flows for use by engineers a model was set up to compare the sedimentation results achieved using a flow series created by this method and one created using the flow exceedence curve method. The flow series created using the Markov method showed an improved structure of the series and it was shown that the order of flows input into the model effects the depositional results.

Finally, two different methods were investigated to account for the effect of climate change on the flow predictions. The method chosen involved collaboration with a statistician from the University of Glasgow and used a multinomial logit model to link catchment temperature and precipitation to the flow transition probabilities. This meant that climate change predictions of temperature and precipitation from the Hadley Centre's RCMs could be used to predict representative flows in the catchment under climate change. These flows could then be used as an upstream boundary in the ISIS model to investigate the effect of climate change on sedimentation within the impoundment. The results of the climate change predictions were validated using the climate control temperature and precipitation predictions for the period 1961-1990 (from the RCM) to create a flow boundary for the ISIS model. The morphological results were compared with those predicted by the Markov chain method for present climate condition and it was shown that this model produced comparable results in terms of both sediment retention and distribution within the impoundment.

The flows created using the information in this chapter can now be used in conjunction with the sediment details from Chapter 3, and the ISIS model, which is described in Chapter 5 to create long-term morphological predictions for the Tees impoundment.

Chapter 5: ISIS Model

5.0 Introduction

The aim of this chapter is to detail the construction of a Tees model using the one-dimensional hydrodynamic package ISIS. The geometric data for the river Tees was collected in the summer of 2000 (described in Chapter 3), while the suspended sediment data and flow data has been collected on site by both the University of Durham and the Environment Agency. All of this information is required for the construction of the ISIS Model, which is then used to assess the long-term sustainability of the Tees barrage impoundment with regard to sedimentation.

5.1 One-Dimensional Models

A one-dimensional code was chosen over a two or three-dimensional code for reasons of computational efficiency. Simulations with a one-dimensional model can be undertaken very quickly using standard desktop computing facilities compared to a two-, pseudo-three- or fully three-dimensional computer model. For long-term modelling, detailed models (2D and 3D) are impractical, as they are so computationally intensive that simulating 50 to 100 years would take a very long time to run. The disadvantage of one-dimensional models is that flow predictions are averaged across the cross section. This in turn means that the predictions for the sedimentation will also be section averaged. The consequences of this need to be taken into account when analysing the predictions, see chapter 6.

Before the hydrodynamic model was chosen for this project, some background research was undertaken to examine the types of model available and their individual specifications. There are several widely used one-dimensional hydrodynamic models on the market; namely, the Hec suite, Mike 11, and ISIS. For this project it was also conceivable that a one-dimensional reservoir model would have been a suitable choice of software, for example RESSASS developed at HR Wallingford Ltd. For this project, there were some important features that the hydrodynamic model had to include; for example, a sediment module which calculated cohesive as well as non-cohesive transport, the capacity to model unsteady flow, a facility to incorporate tributaries and the ability to model the influence of bridge structures on the in-channel hydraulics and use a gated weir as a downstream boundary.

5.1.1 Hec-Ras and Hec 6 Models

Hec-Ras and Hec 6 were both developed by the U.S. Army Corps at the Engineers Hydrologic Engineering Centre. Hec-Ras is an integrated hydraulic software package with an easy to use graphical interface. It models one-dimensional water surface profiles for steady and unsteady flow conditions and has the capability to simulate the change in water surface profile around bridges, levees and culverts. It does have the capacity to model weirs, but it lacks the ability to account for sediment transport. At the moment this package can only model scour at bridge piers and has not been expanded to include a comprehensive sediment transport module. Obviously, the fact this software cannot simulate sediment transport prohibits its use in this study.

One the other hand, Hec 6 is a movable boundary open channel flow model, which can simulate sediment transport, including scour at bridge piers. Hec 6 calculates water surface and sediment bed surface profiles by computing the interaction between sediment material in the streambed and the flowing water sediment mixture. Despite this, the package only has the capacity to simulate steady flows; an unsteady event, like a flood hydrograph passing downstream, is modelled by taking the continuous flow record and sectioning off flows into a series of steady flows. While the sediment package is very comprehensive, the model's inability to simulate unsteady flow was considered a significant disadvantage for the present study.

5.1.2 Mike 11 Model

Mike 11 is very advanced and easy to use modelling software. It simulates hydrodynamic flows, water quality and sediment transport in rivers, estuaries and open channels. It was first developed by the Danish Hydraulics Institute (DHI) in 1979 and is now used by government agencies and consulting firms worldwide. The main part of the programme is the hydrodynamic module, which uses an implicit, finite difference scheme to simulate unsteady flows, both subcritical and supercritical flows can be modelled, allowing weirs to be incorporated. The model solves the one-dimensional Saint Venant non-linear equations, but also incorporates other flow methodologies; for example, kinematic wave and diffusive wave. These components were not required for this particular project and so were not considered relevant; nevertheless, elements that were useful include its ability to model tributaries and bridges, both of which occur on the River Tees.

Mike 11 includes sediment transport modelling capabilities. A non-cohesive sediment transport module exists in addition to the main hydrodynamic module, which has 5 different equations embedded into it. Cohesive transport could also be modelled in conjunction with the advection dispersion module. Thus, Mike 11 obviously fulfils all the software requirements that this project required.

5.1.3 ISIS Model

The ISIS river modelling software was developed jointly by Halcrow Ltd and HR Wallingford Ltd. The hydrodynamic module was previously known as ONDA. ISIS solves the one-dimensional Saint Venant equations to predict the flows and water levels in open channels and estuaries. The ISIS flow module has the capability to model unsteady flows, and can simulate branched or looped systems including the incorporation of tributaries. One of ISIS's main strengths is its capability to model an extensive range of hydraulic structures. This includes many different types of weir; for example, gated, sharp crested, broad crested, siphon and crump weirs in addition to bridges and sluice gates.

ISIS incorporates a sediment module, which runs in conjunction with the ISIS flow module. It predicts sediment transport rates, changes in bed elevation (erosion and deposition) throughout the channel system. Four main transport equations are embedded in the package with one of them being specifically for cohesive sediment transport. Similar to Mike 11, ISIS satisfies all the criteria required of a hydrodynamic model for this project.

5.1.4 RESSASS Model

RESSASS was developed at HR Wallingford for the express purpose of modelling sediment deposition in reservoirs. As such it was developed to meet the needs of reservoir planners and is a combination of three programmes: a volume analysis package, a volume prediction package and a numerical model. The sediment trapping efficiency of the reservoir is calculated by Brunes Curves. In addition the numerical model calculates the flow surface profile and sediment transport within the reservoir to give a detailed understanding of the processes at work. This type of model, while relevant for this project as the barrage acts to impound the riverine water as in a reservoir, is perhaps not as flexible as the other more generic models. It does not include the ability to model bridges or tributaries, but does give the added benefit of estimating the trap efficiency.

5.1.5 Model Justification

After each of these software packages had been assessed, Hec-Ras was found to be unsuitable because it contained no sediment transport module; Hec 6 was discounted as the package could only simulate steady flow; and as regards RESSASS, this was a more specialised package, which meant less flexibility existed (for example no bridge units were available to take account of the numerous bridges on the River Tees as this is not a concern when modelling reservoirs).

On the other hand, both ISIS and Mike 11 had all the components that were considered necessary for this project. Choosing between them came down to the fact that the Civil Engineering Department at Glasgow University has strong ties with HR Wallingford Ltd and Halcrow Ltd, and in fact, several ISIS computational coding projects have been undertaken here in the past few years. As a result, there exists knowledge and expertise in ISIS use in the department, which made it a sensible choice of model for this project.

5.2 One-dimensional Modelling Theory

To model mathematically the flow in rivers it is necessary to set up and solve a series of mathematical relationships, which express the movement of water. For example, the passage of a hydrograph down a river. As mentioned in chapter 2 there are many levels of hydraulic modelling but the type considered here is one-dimensional only. The construction and data requirements of such a model are discussed in more detail later in this chapter, however a river can be described for modelling purposes as a number of cross-sections, taken perpendicular to the flow and two boundary conditions, upstream and downstream, as shown graphically in figure 5.1. The figure also shows areas of storage and bridges along the modelled reach.

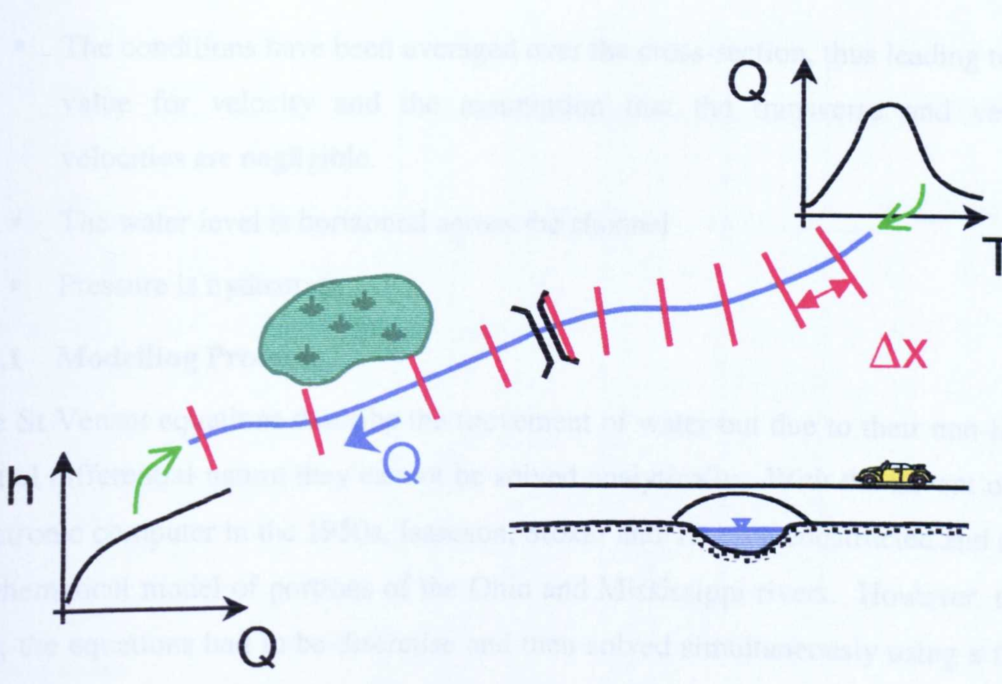


Fig. 5. 1 Graphical portrayal of numerical river model

If modelling is considered in only one dimension, then two non-linear, partial differential equations describe the translation of a flood wave along a river channel.

These equations are known as the St Venant equations, named after the French mathematician who derived them in 1871. They are the continuity equation:

$$\frac{\partial h}{\partial t}+\frac{1}{\mathrm{b}}\frac{\partial Q}{\partial \mathrm{x}}=0$$

Equation 5. 1

And the momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial \mathrm{x}}\left[\beta\frac{Q^2}{A}\right]+gA\frac{\partial h}{\partial \mathrm{x}}+gA\frac{Q|Q|}{\mathrm{K}^2}=0$$

Equation 5. 2

Where A is the cross-sectional area, b is the channel top width, g is gravity, h is the water depth, K is conveyance, Q is flow, t is time, x is distance along the channel and β is the momentum correction coefficient. A full derivation of the one-dimensional St Venant equations can be found in Forbes, 2000 or a derivation of the fully three-dimensional forms of the Navier-Stokes equations can be found in Vardy, 1990.

The assumptions on which these area-averaged or one-dimensional equations are based are:

- The conditions have been averaged over the cross-section, thus leading to one value for velocity and the assumption that the transverse and vertical velocities are negligible.
- The water level is horizontal across the channel
- Pressure is hydrostatic

5.2.1 Modelling Process

The St Venant equations describe the movement of water but due to their non-linear partial differential nature they cannot be solved analytically. With the advent of the electronic computer in the 1950s, Isaacson, Stoker and Troesch constructed and ran a mathematical model of portions of the Ohio and Mississippi rivers. However, to do this, the equations had to be discretise and then solved simultaneously using a finite difference scheme. Discretisation can be described as "the process of expressing general flow laws, written for a continuous medium, in terms of discrete values at a finite number of points in the flow field" (Cunge et al. 1980). There are a few different types of discretisation, namely finite difference, finite element and finite volume, however the discretisation implemented in the ISIS package is finite difference.

The foundation of the finite difference method is, that the: "functions of continuous arguments which describe the state of flow are replaced by functions defined on a finite number of grid points within the considered domain. The derivatives are then replaced by divided differences" (Cunge et al. 1980). This means that the differential equations are replaced by algebraic finite difference relationships. The derivatives and integrals can be expressed in different ways using discrete functions, each of which is called a finite difference scheme. The computational grid used in such schemes is a finite set of points sharing the same domain in the (x,t) plane as the continuous argument functions. It is desirable for a computational grid to be non-uniform in space (i.e. along the x axis) because it would be difficult, if not impossible to survey equally distanced cross-sections along a river. In addition, it is beneficial to survey extra cross sections at places of hydraulic interest for example, at hydraulic structures or where rapid narrowing or widening of the channel occurs. An example of a typical computational grid for simple one-dimensional problems is demonstrated in figure 5.2.

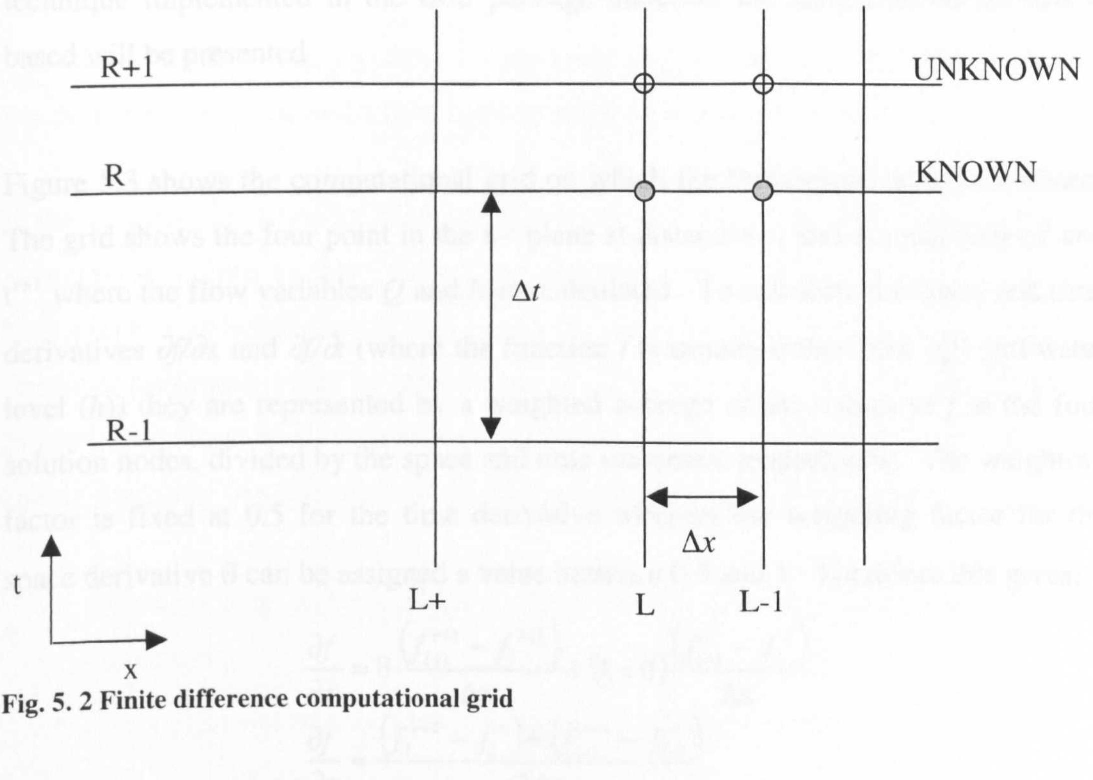


Fig. 5. 2 Finite difference computational grid

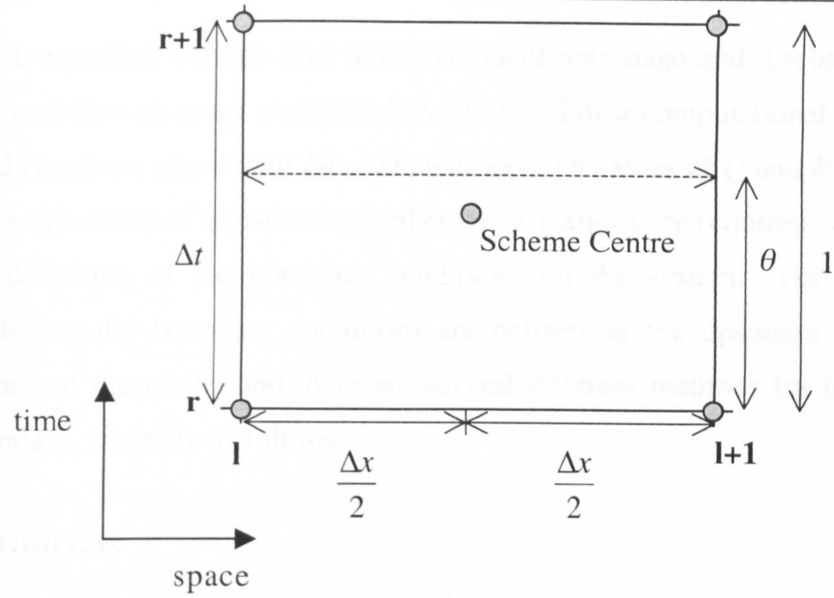


Fig. 5. 3 Preissmann four point implicit grid

5.2.2 Preissmann Four-Point Implicit Scheme

There are several different techniques available which allow the partial differential equations to be replaced by divided differences. Preissmann, Abbot-Iconescu, Gunaratnam-Perkins and Delft Hydraulics Laboratory are just some of those who have developed these methods over the years, the details of which can be found in Cunge et al. 1980. The Preissmann four point implicit scheme is the solution technique implemented in the ISIS package therefore the theory on which this is based will be presented

Figure 5.3 shows the computational grid on which the Preissmann scheme is based. The grid shows the four point in the x-t plane at distances x_l and x_{l+1} and times t^r and t^{r+1} where the flow variables Q and h are calculated. To calculate the space and time derivatives $\partial f/\partial x$ and $\partial f/\partial t$ (where the function f is usually either flow (Q) and water level (h)) they are represented by a weighted average of the values of f at the four solution nodes, divided by the space and time increment respectively. The weighting factor is fixed at 0.5 for the time derivative whereas the weighting factor for the space derivative θ can be assigned a value between 0.5 and 1. Therefore this gives:

$$\frac{\partial f}{\partial x} \approx \theta \frac{\left(f_{l+1}^{r+1} - f_l^{r+1}\right)}{\Delta x} + (1-\theta)\frac{\left(f_{l+1}^{r} - f_l^{r}\right)}{\Delta x}$$

$$\frac{\partial f}{\partial t} \approx \frac{\left(f_l^{r+1} - f_l^{r}\right) + \left(f_{l+1}^{r+1} - f_{l+1}^{r}\right)}{2\Delta t}$$

Equation 5. 3

These equations contain four unknown quantities: stage and discharge at time level $r+1$ and flow at space positions l and $l+1$. For a computational grid of R points, $2R$-2 equations containing $2R$ unknowns exist (R values of Q and R values of h). To solve this series of equations a further two equations are required, which come from the definition of the boundary conditions for the system. For one-dimensional modelling the boundary conditions are defined as the upstream and downstream extents of the model and there are several different methods for implementing the boundary, these are as follows:

Downstream

- $h_{ll}^{r+1} = f(t)$ - Stage Hydrograph
- $Q_{ll}^{r+1} = f(t)$ - Flow Hydrograph
- $Q_{ll}^{r+1} = f(h_{ll}^{r+1})$ - Rating Curve

Upstream

- $Q_{l}^{r+1} = f(t)$ - Flow Hydrograph
- $h_{l}^{r+1} = f(t)$ - Stage Hydrograph

For the purposes of this research a stage hydrograph boundary was implemented at the downstream extent and a flow hydrograph at the upstream extent.

If the original equations are then combined with the boundary conditions, this gives sufficient equations to solve them simultaneously across all of the grid points. The final point to be highlighted is that due to the non-linear nature of these equations an iterative technique must be employed for the solution. The Newton Raphson iterative technique is often used for calculation, and is completed by computer using matrix methods. An overview of the Preissmann method is given below.

- Construct the system of $2R$-2 finite differenced momentum and continuity equations
- Set up the boundary conditions to give 2 extra equations
- Solve simultaneously the $2R$ equations using the matrix methods for the next timestep

- Iterate using the Newton Raphson method until convergence is achieved (convergence and tolerance set in the model)
- Repeat above for each timestep through the full simulation

Cunge et al. 1980 contains a more detailed description of the Preissmann four point implicit scheme along with alternative techniques.

5.3 The ISIS Model of the River Tees

The ISIS model was constructed using the data collected in the survey over the summer of 2000 (detailed information on this can be found in Chapter 3). In total 110 cross sections were used to construct the 25km long model, which extended from Low Moor gauging station at the upstream end to the Barrage at the downstream end. Several bridges were included in the model, along with one tributary, the River Leven. The barrage was modelled as a gated weir just upstream of the downstream boundary.

5.3.1 Tributary

The River Leven was the only tributary of any consequence in the modelled reach and its inflows were included in the model. Unfortunately, inflow data, both water and sediment, had to be estimated as the EA monitoring station was out of commission for the project period. Previous work (HR Wallingford, 1992), had estimated flow in the Leven, as being around 10% of the yield of the Tees. In the absence of more accurate information this scaling was adopted in this project.

5.3.2 Bridges

There are six bridges, which require to be included in the modelled length of the Tees under investigation. Two were railway bridges, one that crossed the Tees at the lower end, near the barrage and another that crossed the river at Yarm. The railway bridge near the barrage was situated adjacent to a road bridge, which had the effect of creating one large bridge. At Yarm, there also existed a road bridge next to the rail bridge; however, because these were older structures they had sufficient space between them to require to be modelled separately. The other two road bridges were situated just upstream of the barrage in the urban area of the catchment. In fact four of the six bridges were located over a three kilometre stretch just upstream of the barrage.

To gain enough information to model these bridges within ISIS, detailed drawings were required. As a result, Railtrack, The Highways Agency and Stockton Borough Council were contacted for the plans of each bridge. Once the plans were received it was possible to transfer the data into ISIS.

ISIS has two methods for modelling bridges, namely the Arch Bridge method and the US BPR method. The first method was developed by HR Wallingford Ltd. The second, more popular method uses the methodology developed by the US Bureau of Public Roads, which calculates the bridge afflux. All the bridges in the ISIS model have been modelled using the second bridge option. To model the bridge the survey requires to have taken a cross section just upstream and just downstream of the structure. In addition to this, data on the piers (type, shape and size), the skew of the bridge, soffit and springing levels and abutment details are required.

Within ISIS there exists a practical expression for the backwater formed by a bridge, which is constricting the flow; the equation takes the form:

$$h_1^* = K^* \alpha_2 \frac{V_B^2}{2g} + \alpha_1 \left[\left(\frac{A_B}{A_4} \right)^2 - \left(\frac{A_B}{A_1} \right)^2 \right] \frac{V_B^2}{2g}$$

Equation 5. 4

Where, h_1^* is the total backwater or afflux, K^* is the total backwater coefficient, α_1 is the kinetic energy coefficient at the upstream section, α_2 is the kinetic energy coefficient in the constriction, V_B is the average velocity in the constriction, A_B is the gross water area in the constriction, A_4 is the water area in the downstream section and A_1 is the total water area in the upstream section including that which is produced by the backwater curve. Applying the principle of conservation of energy between the upstream end of the backwater's influence and the bridge allows this expression to be formulated. K^* has to be estimated, within the program, from such factors as the stream constriction, the type of abutments, the orientation of the piers, the eccentricity of the bridge and its skew.

This method of modelling bridges is considered to be reasonably valid (Halcrow, 1997), when the river in the vicinity of the bridge is essentially straight, the cross section does not change dramatically and the gradient of the bottom is approximately constant. All of these conditions are satisfied for the bridges in the Tees model.

5.3.3 Weirs

For this specific project, careful consideration was given to the method to be used to model the barrage. The barrage is one of the most important parts of the river model as it affects the flow regime of the impoundment. The way in which the barrage is operated on site was discussed with the then Barrage Manager, Mr John Dixon from British Waterways. From these discussions, it was understood that the barrage was operated to keep the water level upstream between +2.35m and +2.85m above ordnance datum (AOD) at all times, apart from at times of water and sediment flushing. The barrage itself is total exclusion, which means that no saline intrusion occurs from downstream. This means practically, that the tides are excluded and need not be considered for the downstream boundary of the model. However, the barrage consists of four separate gates, which can be raised or lowered individually or all together. This can be modelled in ISIS by splitting the model into four parallel, weir units. Despite this, the barrage was considered to be one full-length weir, which extended 54 metres, because for the long-term runs the only condition by which the weir would be controlled is the upstream water level. So for simplicity, one full length weir unit was implemented, which keeps the array size small, therefore cutting down the run time considerably.

The type of weir unit, which best represents the barrage for this particular project, was considered to be one which had the flexibility to vary the crest through the duration of a run. As a result of this, the type of weir utilised for the Tees was a gated weir section incorporated in the ISIS model. The gated weir afforded many options but the main advantage was that the crest elevation of the weir could vary with time. The gate crest could either be moved manually or automatically, which meant the information to move the gate could be input in crest height and time data pairs. Unfortunately, this was not practical for the long-term simulations required for this project. Indeed, within ISIS there is a limit on the number of gate height and time pairs allowed This limit dictated the length of model that could be run because the gate had to be moved on a much finer time increment than that of the flow to maintain the upstream water surface at an acceptable level. In addition to this, the gate had to been moved by manually calculating the gate height at each time point, which became very time consuming. To cut down on the time and work needed for this section, one of the types of control for this weir was utilised. There are several options that are possible to use in ISIS, namely control over the gate opening set by a downstream or upstream water level, a water level at a remote node or a set of logical rules. The most obvious method to use for the project's purpose was to use the upstream water level in conjunction with a set of logical rules to dictate the gate openings.

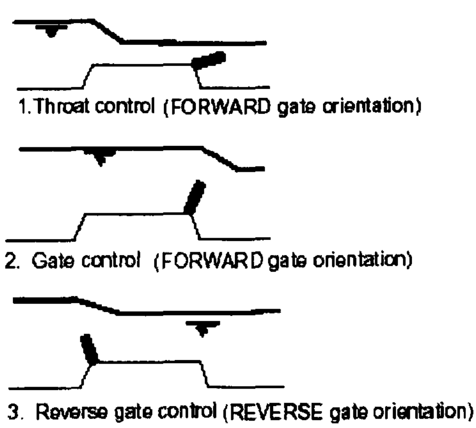


Fig. 5. 4 Three gate orientations offered by the gated weir unit in ISIS (from the Halcrow, 1997)

At the barrage, the water level upstream is maintained by a SCADA system, which sends information of water heights at a set interval to the barrage and then controls the four gates accordingly. Since this is the system that is on site it made sense to set up a similar situation for the model using the gated weir function; this required writing some rules to control the gate movement. These rules can be found in (Appendix B). While these rules will not recreate the exact movement of the barrage as it would occur, they do however maintain the overall requirements for water level for the system. The rules had to move the gate incrementally, ensuring that the gate was never moved too much in one interval so as to cause instability in the model or to result in a situation where there is zero flow over the weir. The ISIS flow module can deal with zero flow without terminating the run, however, ISIS sediment must have flow at all units throughout the whole period of the run otherwise the run will finish with an error. Some manipulation was required with these rules before a satisfactory set was found.

The gated weir is a very flexible unit as three flow regimes can be observed for flow over this type of weir, although during a run the unit cannot change between these modes. The first mode occurs when the gate is lowered to ensure the weir acts as a broad crested weir where critical depth is found through the structure. The second is defined by critical depth occurring at the gate crest, and the third is when the flow is reversed meaning the water flows from the downstream end to the upstream end (see Fig. 5. 4). For this project the weir operated solely in mode two for the whole modelled time period with critical depth only occurring at the gate. The equation, which defines the flow over this structure, takes the form:

$$Q_{gate} = C_{gt}\mathrm{b}(\mathrm{y}_1 - \mathrm{y0})^{1.5}\, psi\sqrt{g}$$

Equation 5. 5

Where Q_{gate} is the free weir flow in gate control, g is gravitational acceleration, C_{gt} is the coefficient of calibration for the gate; b is the breadth of the weir, y_1 and $y0$ are defined in (Fig. 5. 5), and if $wtheta \geq 30$ then:

$$psi = 0.711(1 - phi) + 0.58phi(1 + 0.13hp)$$

Equation 5. 6

otherwise;

$$psi = 0.711$$

Equation 5. 7

Where $phi = \dfrac{(wtheta - 30)}{60}$, $wtheta = 57.3\sin^{-1}\dfrac{(\mathrm{y0} - z_c)}{h_{gate}}$, h_{gate} is the height of the gate, z_c is the bed level at the weir site, and $hp = \dfrac{(\mathrm{y}_1 - \mathrm{y0})}{(\mathrm{y0} - z_c)}$

These equations for this unit were derived from a physical model. This work is described in HR Wallingford Ltd's Report EX1296 (cited in Halcrow,1997).

The crest of this gate weir was controlled by a set of rules, which were written into the control section of the unit. These rules were in what is termed as logical mode, and each rule was checked and updated every time the polling time interval elapsed. This polling time interval was user defined but would not be checked more frequently than the overall time step used for the model.

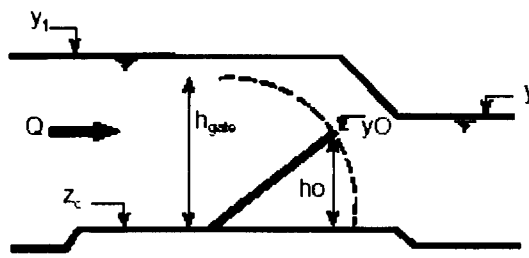


Fig. 5. 5 Gate dimensions in ISIS (from Halcrow, 1997)

It was possible to set a maximum movement rate for the crest, which should not be set too fast otherwise instabilities could appear. For this situation a speed of 0.05m/s was used as it proved to give a stable solution and move the gate sufficiently to satisfy the overall barrage conditions. A height, a minimum and a maximum opening for the gate are all required; the height was taken from the gate depth to be 8.1m, and the openings were chosen to be between 7.73m and 3m, which allowed enough room for the gate to maintain the water level upstream between +2.35m and +2.85m. Within the model, a different co-ordinate scheme for the z co-ordinate has been utilised which relates directly to the results of the survey campaign. The co-ordinate scheme means that the upstream water level in the model must be maintained between –2.1m and –2.6m, which relates directly to the ordnance datum values quoted earlier with only a +4.95m translation. In addition to this a calibration coefficient for the gate was required the value of which could set be between 0 and 1.

This was set to 1 for the Tees model as recommended through discussions with ISIS support.

5.3.3.1 Identification of a Software bug in ISIS v. 2.1

While using the gated weir unit in Version 2.1 of ISIS, a bug was encountered. If a weir section using rules in logical mode is inserted into the model as normal, then excessive erosion in the upstream section was observed. However if the weir is operating under the manual mode then the weir behaved as normal. To solve this problem, when using the logical mode a junction unit is included just upstream of the gated weir section, which stops the excessive erosion and allows the unit to work correctly. This bug seemed to be introduced when switching from version 1.4 to version 2.1, as it was not noticed when the model was running using version 1.4.

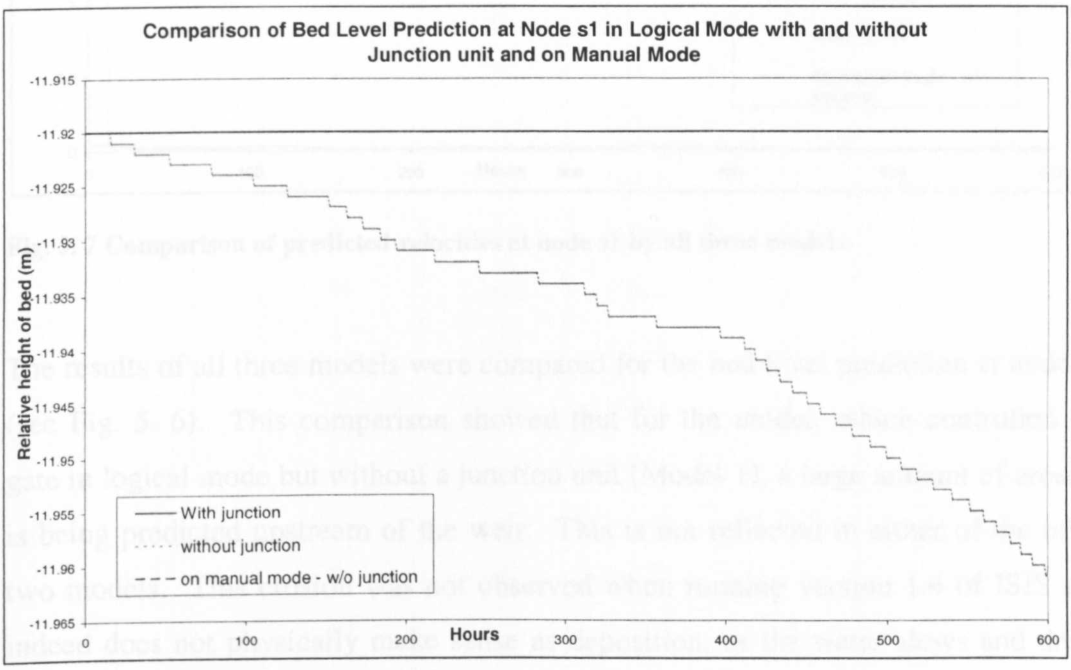


Fig. 5. 6 Comparison of the bed level prediction at node s1 to investigate the bug in ISIS

This bug was tested using the Tees model, which was run for 600 hours on three separate occasions. The first model had a gated weir incorporated, which had no junction unit upstream and was set to work in logical mode. The second had a gated weir controlled in logical mode in exactly the same way as the first but with a junction unit upstream. Finally, the third used a gated weir in manual mode (using the same weir crest settings as in the other two models) with no junction unit upstream. Both of the models using the rules section in logical mode were specified to have period of 13 hours at the beginning of the run where they were controlled by the manual command. All three of the tested models had exactly the same upstream boundary condition for flow and sediment.

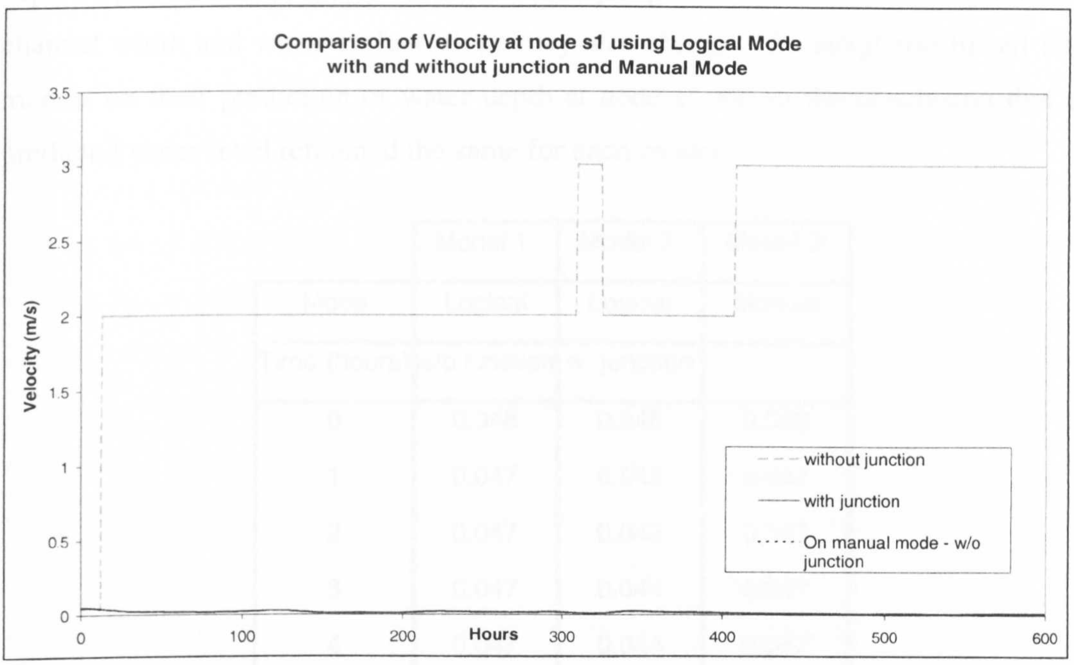


Fig. 5. 7 Comparison of predicted velocities at node s1 by all three models

The results of all three models were compared for the bed level prediction at node s1 (see Fig. 5. 6). This comparison showed that for the model, which controlled the gate in logical mode but without a junction unit (Model 1), a large amount of erosion is being predicted upstream of the weir. This is not reflected in either of the other two models. This erosion was not observed when running version 1.4 of ISIS and indeed does not physically make sense as deposition, as the water slows and drops sediment out of suspension, rather than, erosion would be expected upstream of a weir.

Sediment transport of the cohesive sediments, which were the fraction size of sediments in suspension as predicted by ISIS, are described in ISIS by the Westrich-Jurashek (1985) total load equation (Equation 5. 14). This states that the sediment transport is controlled by; the water surface slope, the velocity of the water, the width of the channel, the water depth, the specific gravity of the sediment and the settling velocity of the sediment size. It was known for all three models that both the specific gravity and the settling velocity had remained constant. This left the hydraulic parameters; water depth, channel width, water surface slope and velocity to be considered. Three of these properties depend on each other; for example, if the water depth is predicted differently at one section by a particular model then the value for channel width and water surface slope may also change. Investigation for all three models on their prediction of water depth at node s1 led to the conclusion that the predicted water level remained the same for each model.

	Model 1:	Model 2:	Model 3:
Mode	Logical	Logical	Manual
Time (hours)	w/o junction	w. junction	
0	0.048	0.048	0.048
1	0.047	0.042	0.047
2	0.047	0.043	0.047
3	0.047	0.044	0.047
4	0.047	0.044	0.047
5	0.046	0.045	0.046
6	0.046	0.044	0.046
7	0.045	0.044	0.045
8	0.045	0.044	0.045
9	0.044	0.043	0.044
10	0.043	0.042	0.043
11	0.042	0.042	0.042
12	0.041	0.041	0.041
13	2	0.04	0.04
14	2	0.039	0.039
15	2	0.038	0.038
16	2	0.037	0.037
17	2	0.036	0.036
18	2	0.035	0.035

Table 5. 1 Table comparing velocity predictions from ISIS at node s1

The results of the three models were compared for the predicted velocity at node s1 (see Fig. 5. 7). This study found strange results. Model 1 showed rather higher velocity predictions at this node after hour 13 where the model became controlled in the logical mode, which can be seen clearly in Table 5. 1. Model 2 and model 3 both carry on predicting the same magnitude of velocity after hour 13.

These discoveries lead to the conclusion that the problem occurs when the rules section is utilised without having a junction unit upstream. What appears to happen is that using the rules section somehow means that the velocity predicted at the weir node is being saved to the upstream node, thereby over-predicting the velocity and causing the excessive erosion. If a junction node is included this erosion does not happen and the model predicts a sensible solution, which can be verified by checking the predictions against those simulated with the weir in manual mode. This junction node is one which is commonly used to introduce a tributary but it can be used for this purpose without problem as it does not hydraulically change the system in any way. This hypothesis cannot be entirely verified without investigating the code thoroughly, however once this problem was noticed and understood it was reported to the ISIS support desk, who in turn passed it on to the development team for investigation.

5.3.4 Boundary Conditions

For this particular project the upstream boundary conditions for the future have taken the form of a separate piece of research, which is detailed in depth in chapter 4. For the downstream boundary condition some hypothesis had to be made in order to model the downstream extent of the model simply, yet realistically.

The downstream boundary for the impoundment in the field is the barrage, but to end an ISIS model with a weir function is not possible. The downstream extent could have been modelled as a flow with head boundary, otherwise known as a rating curve boundary, and the weir unit omitted. This would have had the effect of controlling the discharge in relation to the stage height in a similar way to a barrage, however, it does not model the effect of a weir in terms of it being a barrier to flow and sediment in the same way. As a result, the weir unit discussed in the previous section was modelled in the position of the barrage, and the model was extended 100 metres further downstream to where the boundary was situated.

This downstream boundary was modelled as a fixed head-time boundary, which can be justified by the fact that the barrage is a total exclusion barrage, meaning the lip of the barrage is always higher than the tide flow propagating upstream. This means that the flow will be critical over the barrage lip for most, if not all, of the duration of the long-term runs. This boundary was held stationary throughout all simulations.

5.4 Validation of Hydrodynamics

Mathematical models are discrete, simplified representations of continuous physical processes, and as such need calibration to represent these processes as well as possible. Calibration for one dimensional flow models is completed by adjusting the empirical hydraulic coefficients available, so as to reproduce flow conditions observed on the river as closely as possible (Cunge et al. 1980). Observed events are usually observed water levels for different flow events, and these can then be compared to the model's predictions. For one-dimensional modelling the roughness coefficient is usually used for calibration purposes; this coefficient is the only value which can be adjusted in one dimension, whereas two and three-dimensional models take account of turbulence making calibration more difficult.

5.4.1 Collection of Calibration Data

To calibrate the constructed Tees model, stage data along the river was required. The Environment Agency has no gauging stations downstream of Low Moor on the modelled length of the Tees, and as a result, during the surveying process, calibration stations were set up at nine points down the river. These calibration stations were carefully positioned so as to allow maximum accessibility while maintaining a coherent picture of the flow profile for the entire river. Unfortunately, the upper end of the river becomes increasingly wooded making access difficult, thus there are no calibration stations over the upper five kilometres. This leads to a partially incomplete water profile of the river for calibration.

Two observed profiles were taken, one on the 31st of August 2000 and another during a period of higher flow on the 6th of December 2000. The average flow on both of these days was 5.5m^3/s and 81.8m^3/s respectively. These hydrographs are detailed in Fig. 5. 8. The gauging station at Low Moor provided the flow data for the upstream boundary of the model, while for the downstream extent it was necessary to contact the Barrage Manager. Following a personal communication with Mr John Dixon, the barrage crest heights were ascertained for both of these periods, along with upstream water level predictions for the barrage on those days.

	Calibration Data: Tees		**Date**	31/08/00	**Date**	06/12/00
Node	**Station**		(m)	**Time**	(m)	**Time**
s91	Low Worsall	reading on stage board	-2.090	15:55	-1.109	15:00
s82	Ailsaby	peg beside the steps	-2.180	14:15	-1.396	14:15
s77	Yarm Bridges	reading on stage board	-2.175	15:00	-1.633	14:25
s66	Tees/Leven confl.	red mark on pavement	-2.179	15:40	-1.999	14:40
s48	Prestonpark	red mark on concrete slab	-2.300	13:30	-2.096	13:45
s17	Rowing Club	red marker	-2.282	11:30	-2.182	13:25
s11	same station	wl opposite ship	-2.333	11:05	-2.188	13:07
s10	Naval Ship	wl at road bridge	-2.351	11:00	-2.202	13:05
s6	PGM 2	near barrage (red triangle)	-2.340	10:45	-2.223	12:05
s1	Barrage	from Barrage Manager	-2.356	15:00	-2.351	11:00

Table 5. 2 Water surface profiles surveyed for calibration on the Tees (all heights to model datum)

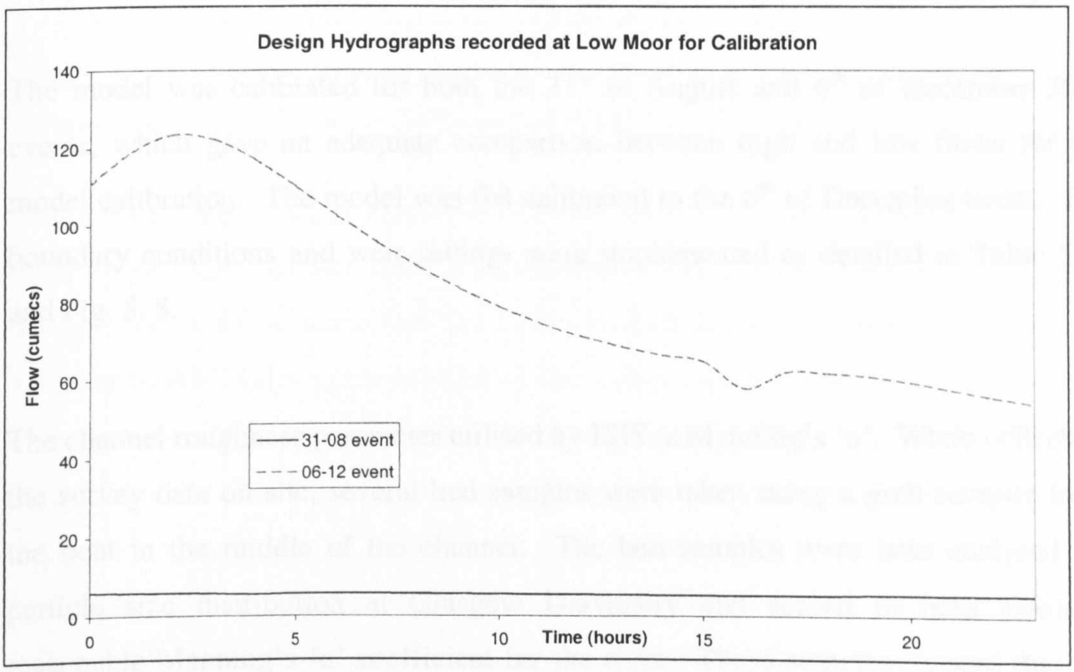


Fig. 5. 8 Inflow hydrographs for calibration periods; 31 August and 6 December 2000

Date	6th Dec		31st Aug
Time gates @ setting	0-15hrs	15-23hrs	0-23hrs
No. gates open	4	4	1
Gate lip height m AOD	2.12	1.7	2.44

Table 5. 3 Gates setting for calibration purposes

These recorded water levels gave one more calibration point, giving ten in total. The observed profiles are detailed in Table 5. 2, with the barrage crest heights used for calibration in Table 5. 3

5.4.2 Calibration of the Tees Model

The calibration of a numerical model is completed by systematic adjustment of the channel roughness parameter to alter the predicted water levels until a reasonable agreement is obtained to the observed water levels. For a good calibration a large amount of observed data is required as the calibration will only be as good as the observed information. As previously mentioned, the data collected for the River Tees fails to capture the upper five kilometres of the modelled reach, which does compromise some of the accuracy of the calibration. Despite this, it is important to calibrate the model as well as possible using the information available, as in real life detailed data is difficult to collect.

The model was calibrated for both the 31^{st} of August and 6^{th} of December 2000 events, which gave an adequate comparison between high and low flows for the model calibration. The model was fist calibrated to the 6^{th} of December event. The boundary conditions and weir settings were implemented as detailed in Table 5. 3 and Fig. 5. 8.

The channel roughness parameter utilised by ISIS is Manning's 'n'. While collecting the survey data on site, several bed samples were taken using a grab sampler from the boat in the middle of the channel. The bed samples were later analysed for particle size distribution at Glasgow University and served to help assess a reasonable Manning's 'n' coefficient for the river. These samples showed that the riverbed at the lower end of the model was mainly silt and sand based, whereas near

Yarm and the Leven confluence (see Fig 3.1 for positioning of Yarm and the Leven on the River Tees) the bed became much coarser, consisting mainly of cobbles. Further upstream the bed became finer again; in fact around Low Worsall and Low Moor the bed samples were predominantly gravel and sand. These findings helped to gain an idea of the bed roughness down the river. The floodplains were predominantly wooded in the upper section of the modelled reach, whereas downstream the banks are more urban; however, this urban section close to the barrage is unlikely to flood as the barrage controls the water levels at all times.

		6th of December 2000			
Node	Chainage (m)	Observed (m)	Calibrated (m)	Difference (m)	%
s91	5684.5	-1.109	-0.965	-0.144	12.985
s82	8913.5	-1.396	-1.314	-0.082	5.874
s77	10575	-1.633	-1.679	0.046	2.817
s66	12767	-1.999	-2.077	0.078	3.902
s48	16392	-2.096	-2.205	0.109	5.200
s17	22102	-2.182	-2.26	0.078	3.575
s11	23204	-2.188	-2.26	0.072	3.291
s10	23333	-2.202	-2.259	0.057	2.589
s6	24001	-2.223	-2.24	0.017	0.765
Barrage	24702	-2.351	-2.217	-0.134	5.700

Table 5. 4 Table detailing the comparison of predicted and observed water levels after calibration for the 6th December 2000 event (all heights to model datum)

A best fit for the 6th of December event was obtained using a 'n' value of 0.03 for most of the main channel, apart from between node s80 and node s60. This area, between just outside Yarm and the Leven confluence was represented using a 'n' value of 0.045 which takes account of the rather rougher bed found here. These values are considered to be reasonable for a river channel from reference to Chow (1956). For the floodplains a value of 0.08 to 0.1 was used along the river, but it was impossible to calibrate, as the higher flow event of the 6th of December was an in-bank event. Therefore, these values have been estimated with reference to Chanson (1999), who states that typical values of Manning's 'n' for floodplains with light brush and trees lie between 0.05 and 0.15.

The results of the calibration of the 6th December event can be found in Table 5. 4 and Fig. 5. 9. These shows that a reasonable level of agreement has been found between the predicted and observed values for the river. The maximum difference found was at the upstream extent of the model, where –0.144m was found, which is a 12.985% error.

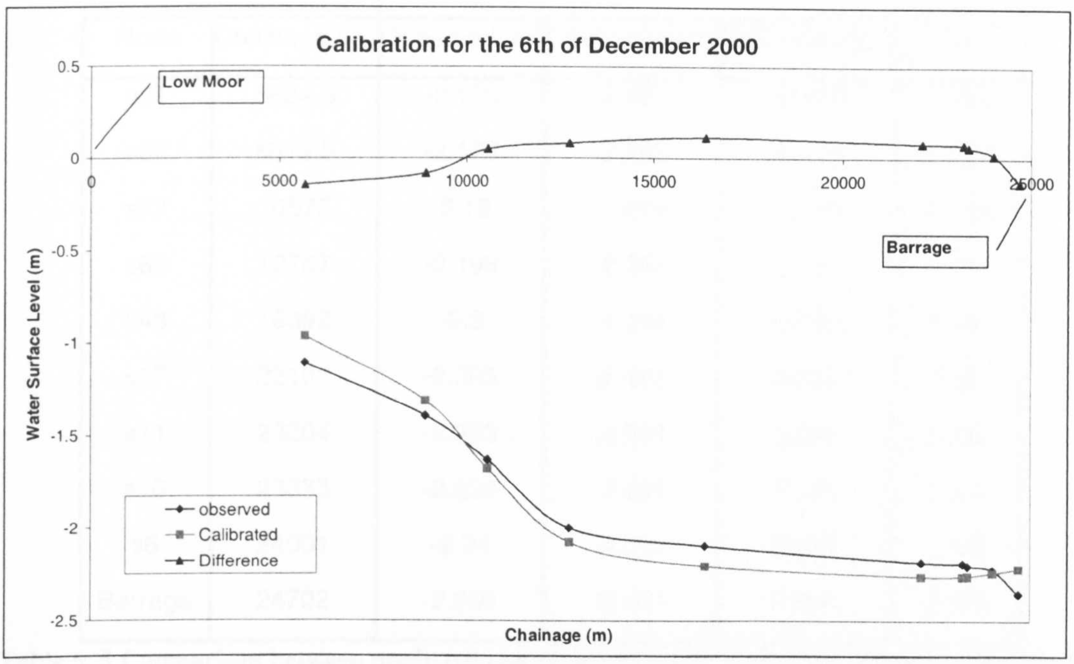


Fig. 5. 9 Comparison of observed and predicted water levels for the 6th December event (heights to model datum)

After satisfactory values were obtained for the 6th of December event, the model was then tested for the low flow conditions that were found on the 31st of August 2000 on the Tees. The flow on this day was almost steady state with a value of 5.5m^3/s. The model was set up using the boundary conditions and weir settings detailed in Table 5. 3 and Fig. 5. 8. The weir was only operating one gate as the flow rate was very low. As a result it was necessary to shorten the length of the weir to 13.5m for this calibration run.

Following the calibration of the model to the 31st August event a couple of adjustments were required to the Manning's 'n' values. A slight extension of the rough area of the bed was required so that the sections with a Manning's 'n' of 0.045 now stretch from node s83 to node s62. This was checked for the 6th of December event but no appreciable difference in the predictions was noticed. The comparison between observed and predicted water levels can be found in Fig. 5. 10. Again the largest error was found at node s91 with a difference of –0.159m being recorded. This comparison can be considered reasonable.

		31st of August 2000			
Node	Chainage (m)	Observed (m)	Calibrated (m)	Difference (m)	%
s91	5684.5	-2.123	-2.282	-0.159	7.489
s82	8913.5	-2.175	-2.293	-0.118	5.425
s77	10575	-2.18	-2.299	-0.119	5.459
s66	12767	-2.199	-2.304	-0.105	4.775
s48	16392	-2.3	-2.302	-0.002	0.087
s17	22102	-2.305	-2.303	0.002	0.087
s11	23204	-2.333	-2.301	0.032	1.372
s10	23333	-2.334	-2.301	0.033	1.414
s6	24001	-2.34	-2.301	0.039	1.667
Barrage	24702	-2.356	-2.301	0.055	2.334

Table 5. 5 Comparison between predicted and observed water levels -31st August event (heights to model datum)

The calibration of the model to both reasonably high and low flows should mean that the calibration is good for this model. The values that have been predicted for the Tees show a reasonable comparison with the observed levels meaning that the model is calibrated to within an acceptable error. However, the upstream end, at node s91, for both calibration events shows the largest error. Due to the fact there is no calibration station further upstream, it is impossible to tell whether the calibration of the model will become unreasonable further upstream, but if more observed data had been collected this could have been investigated. Therefore it is necessary to conclude that with the data available the model has been calibrated as well as possible, giving a robust ISIS model for the River Tees.

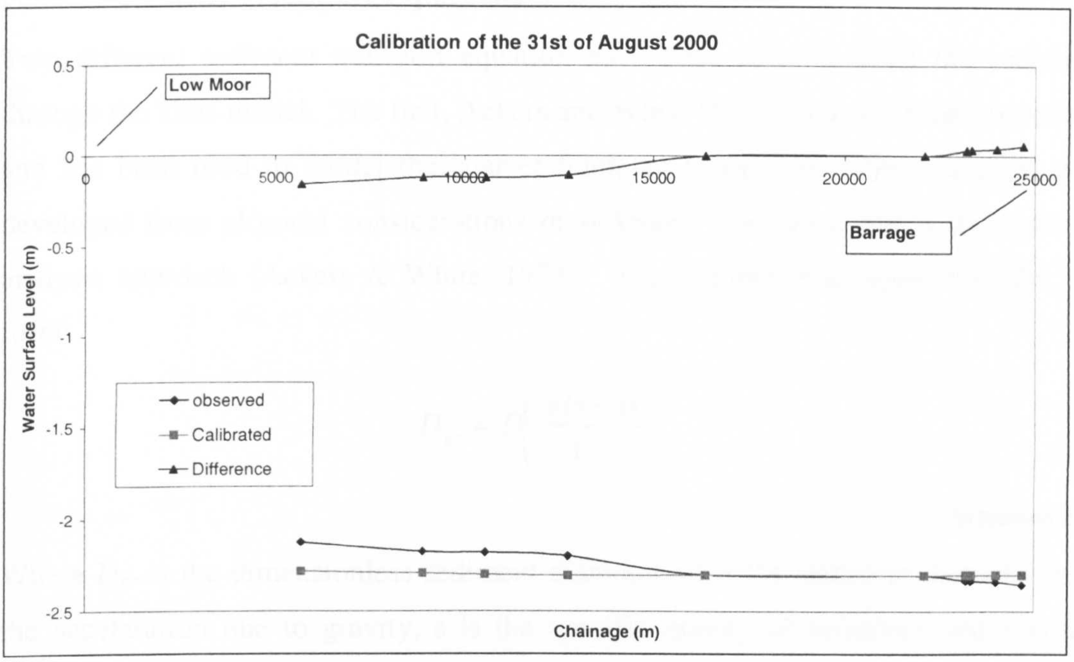


Fig. 5. 10 Comparison of Predicted and observed water levels after calibration for the 31st August 2000 event (heights to model datum)

5.5 Validation of the Sediment Transport Module

The sediment transport module must be calibrated to ensure that the model is predicting as robustly as possible the sediment transport dynamics in the River Tees. This calibration procedure was completed after the calibration of the hydrodynamics was finished as sediment transport predictions rely heavily on the prediction of flow in the model. After ISIS solves the one-dimensional version of the shallow water flow equations, information on the hydraulic parameters at each time step is fed into the sediment transport solver which routes the sediment through the impoundment. There are four sediment transport equations embedded in ISIS, two of which have been utilised for this project. Once these sediment transport equations have been decided upon they must be calibrated, however it can be notoriously difficult to gain good sediment calibration data. The Tees model has been calibrated in two different ways; the first calibrates the model to a previous study completed on the Tees impoundment and the second calibrates the long-term predictions to sediment core data taken on the Tees.

5.5.1 Sediment Transport Equations

Two different sediment transport equation have been used to route the sediment through the Tees model. The first, Ackers and White (1973) is a total load equation, and has been used to model the coarser fractions in the bed. This equation was developed from physical considerations of sediment movement and a dimensional analysis approach (Ackers & White, 1973). The implemented equations take the form:

$$D_{gr} = D\left(\frac{g(s-1)}{\upsilon^2}\right)^{1/3}$$

Equation 5. 8

Where D_{gr} is the dimensionless sediment diameter, D is the sediment diameter, g is the acceleration due to gravity, s is the specific gravity of sediment and υ is the kinematic viscosity of water. Once the dimensionless sediment diameter has been calculated the transition component η, the initial motion parameter A, and the coefficient and exponent in the sediment transport function (c and M respectively) can be determined.

For $1 \leq D_{gr} \leq 60$

$$\eta = 1 - 0.56\log_{10} D_{gr}$$
$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14$$
$$M = \frac{6.83}{D_{gr}} + 1.67$$
$$c = 10^{(2.79\log_{10} D_{gr} - 0.98(\log_{10} D_{gr})^2 - 3.46)}$$

Equation 5. 9

For $D_{gr} > 60$

$$\eta = 0$$
$$A = 0.17$$
$$M = 1.78$$
$$c = 0.025$$

Equation 5. 10

Next the particle mobility can be determined, F_{gr}

$$F_{gr} = \frac{V_*^{\eta}}{\sqrt{gD(s-1)}}\left(\frac{V}{\sqrt{32}\log_{10}(10h/D)}\right)^{1-\eta}$$

Equation 5. 11

Where V_* is the shear velocity, V is the mean flow velocity and h is the depth of flow. From this the dimensionless sediment transport rate G_{gr} can be calculated.

If A < F_{gr} then:

$$G_{gr} = c\left(\frac{F_{gr}}{A} - 1\right)^{M}$$

If A ≥ F_{gr} then:

$$G_{gr} = 0$$

Equation 5. 12

which leads to the volumetric sediment transport rate G by means of equation 5.10.

$$G = K\frac{QG_{gr}D\left(\frac{V}{V_*}\right)^{\eta}}{h}$$

Equation 5. 13

Where Q is the flow in m^3/s and K is a calibration coefficient for the equation.

This method of predicting sediment transport is a popular and frequently used method (White, Milli & Crabbe, 1975; Bettes & White, 1981; Bechteler & Vetter, 1989), consequently it has been utilised in the Tees model to calculate the sediment transport of the sediment sizes larger than 63μm.

To model the fractions smaller than this another equation must be specified within ISIS. The only equation implemented in ISIS that can simulate fine sediment transport is the Westrich-Jurashek (1985) total load equation. This equation was developed from laboratory experiments on the transporting capacity of rigid boundary channels using only fine sediments. An energy balance equation was fitted to the results, which gave an equation of the form:

$$G = K\frac{0.0018SV^2Wh}{(s-1)V_s}$$

Equation 5. 14

Where V_s is known as the settling velocity of the sediment particles, h is the depth of flow, V is the velocity, S is the water surface slope and W is the top width of flow. Once the decision had been made on which equation would be used for the Tees model the sediment calibration procedure could begin.

5.5.2 Calibration using Previous Model Studies

HR Wallingford completed an in depth study on the River Tees pre-impoundment (HR Wallingford, 1992), which investigated the potential effects of the barrage on the sediment regime. It used particular design hydrographs for the river in conjunction with sediment rating curves constructed from sampled suspended sediment to predict the overall amount of sediment deposited upstream of the barrage.

The information from this report was utilised to see if the results could be replicated to gain confidence in the calibration of the ISIS model. Two design hydrographs were compared; the 1:1 year flood (350 m^3/s peak flow) and a 100 m^3/s flood. Since no particle size distribution for the suspended sediment was available, information provided by Durham was utilised to estimate this. This distribution was determined using a coulter system laser granulometer, which is described in section 3.2.3.

Hydrograph	Inflow (tonnes)	Deposit (tonnes)	% Retained
1:1 year flood	9275	1501	16
100 cumec flood	585	473	81

Table 5. 6 Sediment results from HR Wallingford (1992), used for calibration purposes

To calibrate the model settling velocities for the suspended sediment were changed until the desired calibration was found. However these velocities could only be moved within a sensible band width of values, taken to be in the range of 0.3-0.5mm/s from the HR Wallingford report. These relatively high settling velocities were attributed the mix of organic particles in with the silt and clay particles.

The results from HR Wallingford's report (see Table 5. 6) were used to match to the results predicted by ISIS. Manipulation of the suspended sediment's settling velocities within the model was completed systematically until a reasonable calibration of the sediments was found for both inflow hydrographs. The final settling velocities used were 0.31mm/s and 0.5mm/s for the two fractions smaller than 63μm specified in the model. These smaller fractions along with the 63μm fraction defined the size of the sediment inflow. Using these specifications the results that were predicted with ISIS are presented in Table 5. 7

Hydrograph	Inflow (tonnes)	Deposit (tonnes)	% Retained
1:1 year flood	9077.98	1711.55	18
100 cumec flood	683.37	556.28	81

Table 5. 7 Predictions from ISIS sediment following calibration of the Tees model

Comparing these results shows that the total inflow of sediment predicted by ISIS is not exactly the same as predicted by the HR Wallingford report. The discrepancies are a function of the manually interpretation of the graphs presented in the report. However, what can be seen is a reasonable comparison between the percentages of sediment retained predicted by ISIS and from the HR report. ISIS predicts 81% retained for the $100m^3/s$ hydrograph, which is the same as the HR prediction. For the $350m^3/s$ hydrograph ISIS predicts the barrage retains 18% of the sediment whereas the HR report states 16% should be retained. These results show that the model reproduces the sediment regime reasonably well when compared against the previous study completed by HR Wallingford.

5.5.3 Calibration to the Sediment Cores

Sediment cores were taken just upstream of the barrage by Durham University, the results of which are discussed in section 3.2.3. These cores showed a distinct change in bed material at a depth of around 50-55cm (refer to fig 3.6). This was taken to represent the level of sedimentation since barrage closure. Therefore in the last eight years a depth of 50-55cm of sediment has accreted just upstream of the barrage. This core was taken in 2002 at a position in the river, which corresponds to node 4 in the ISIS model. This meant that a comparison could be made with the model's predictions and the *in-situ* observations.

To compare the results of the model with the core data, an eight year run was prepared. The flow data was taken directly from the Low Moor flow data, which was supplied in the form of daily flow values. This flow data became the upstream flow boundary for the eight year period. From this flow data, each of the four sediment rating curves were used as four separate sediment boundary conditions (see section 3.4.1.2). These four models were simulated for the eight year period between the end of 1994 (when the barrage was closed) and 2002 (when the sediment cores were taken in the river).

From 1994-present		Prediction
Data	Curve	(cm)
Pre-October 2000	Normal	31
	Upper 95% (Low Scenario)	57
Post-October 2000	Normal (Medium Scenario)	75
	Upper 95% (High Scenario)	121

Table 5. 8 Showing amount of deposition predicted from 1994-2002, to compare with core data

The details of amount of deposition predicted by each of the sediment rating curves after these eight year runs can be found in Table 5. 8. These results are the predicted deposition for node s4 which corresponds to the position in the river from which the core was sampled. From the table it is obvious that the sediment rating curve, which is predicting the deposition rate closest to real life is the upper 95% curve, which was constructed from the pre-October 2000 suspended sediment data (see Chapter 3 section 3.4). The curve predicts 57cm of deposition over the eight year period and is taken to represent the normal or low sediment input for the river.

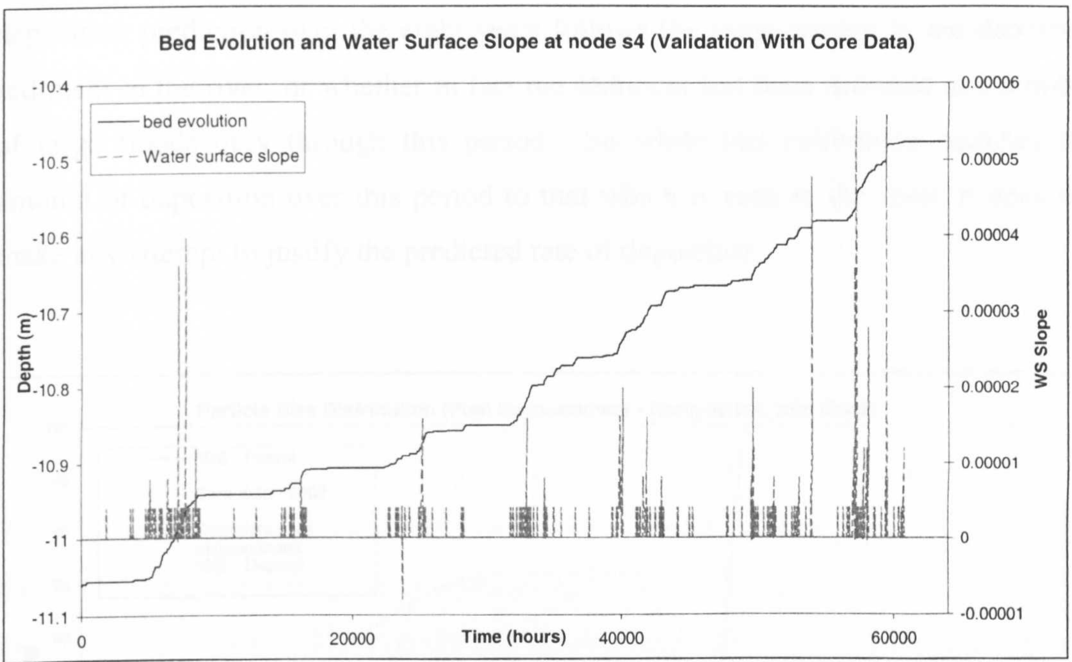


Fig. 5. 11 Bed evolution with water surface slope through the eight year calibration period for node s4 (sediment rating curve – pre-October 2000, upper 95%-Low Sediment Supply Scenario)

While this is one way to calibrate the sediment rating curves there is no way of telling whether the rate and timing of the sediment deposition predicted by ISIS accurately mimics that, which is occurring on the Tees. For example, the rate of sediment deposition predicted by ISIS is detailed in Fig. 5. 11, from this it can be seen that there exists a relatively linear deposition pattern apart from during periods with a high water surface slope where more sediment deposition occurs. These high water surface slopes usually indicate high flow conditions, and with high flow comes higher sediment concentrations. The cross-section is trying to achieve some kind of dynamic equilibrium of sediment deposition and accretion. Within these eight years, this equilibrium has not been found and, as such, mainly accretion is observed. Accretion is mainly observed during the simulation, as the cross-section has not yet begun to find its dynamic equilibrium. Insufficient deposition has occurred through the run to force increased water surface slopes at this node, which, being one of the major controls on sedimentation, results in more deposition being predicted. This will continue until the water surface slopes are forced to increase by the changing bed, or the sediment starts being moved by shallower water surface slopes. This can be observed in some of the longer runs completed in chapter 6.

There is no way of telling, from the information provided, whether the sediment deposition prediction over the eight years follows the same pattern as the deposited sediment in the river, or whether in fact the sediment has been accreted in a number of large floods only through this period. So while this calibration matches the amount of deposition over this period to that which is seen in the river, it does not make any attempt to justify the predicted rate of deposition.

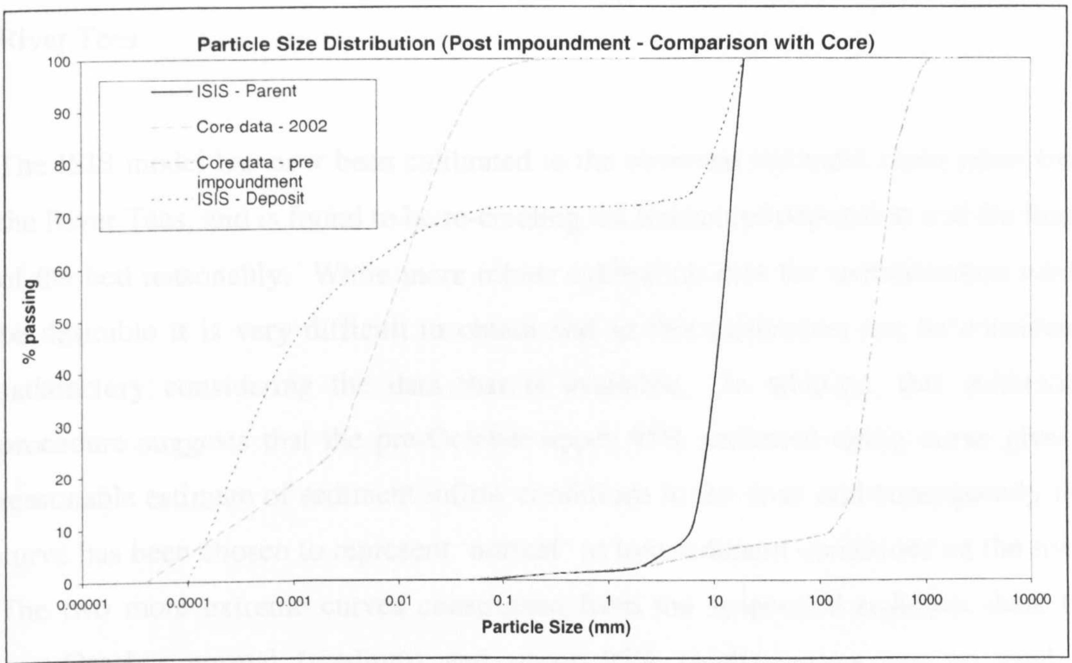


Fig. 5. 12 Comparison between core psd and the psd predicted by ISIS

From analysing the sediment deposited in the core a particle size distribution was found. This was checked against the model's prediction for the particle size distribution of the bed at the same place. ISIS sediment only allows the bed to be defined in terms of a particle size distribution of ten different diameter sizes, whereas the real bed consists of many different sediment sizes. Fig. 5. 12, shows the comparison between the ISIS predictions (parent defines the start bed and deposit defines the bed at the end of the run) and the analysed core data. The ISIS predictions indicate that the particle size distribution has become much finer over the period of the calibration run, however because there are only ten particle size categories within ISIS it would be impossible to re-create exactly the distribution found for the core. In addition, in using the sorted algorithm within ISIS, a parent bed is defined at the start of the run, the model then uses this, a deposited layer an active layer and a section of material in transport. Within ISIS the sediment is then exchanged between these layers depending on whether erosion or deposition is occurring during the simulation. The parent bed is considerably coarser than the inflowing suspended sediment and as a result these sediments will not be moved down the river. As this fine sediment is deposited, the new bed within ISIS is still considered to consist of some coarser sediment although the percentage of those represented will decrease. Over a longer period of time the predicted deposit layer in the model will become increasingly fine, until it is closer to that recorded in the River Tees.

The ISIS model has now been calibrated to the observed sediment cores taken from the River Tees, and is found to be re-creating the amount of deposition and the fining of the bed reasonably. While more robust calibration data for sedimentation would be desirable it is very difficult to obtain and so this calibration can be considered satisfactory considering the data that is available. In addition, this calibration procedure suggests that the pre-October upper 95% sediment rating curve gives a reasonable estimate of sediment inflow conditions to the river and consequently this curve has been chosen to represent 'normal' or low sediment conditions on the river. The two more extreme curves constructed from the suspended sediment data, the post-October normal (medium) and upper 95% (high) curves can be used to investigate more extreme sediment loads for the Tees, which may occur as a consequence of climate change or a change in sediment sourcing.

5.6 Sensitivity Analysis on the Flow Data

Flow data was obtained from different sources for the Low Moor gauging station, namely, The University of Durham, the Environment Agency and the National River

Flow Archive. Unfortunately the flow information came in different forms; for example the National River Flow Archive supplied daily flow values while Durham University collected flow data every fifteen minutes for the duration of the project. Durham University collected the more detailed information, however the data collection period only lasted two years, and a longer flow data set was required for this project. On the other hand, the flow information provided by the National River Flow Archive (NRFA) extended back to 1970 with only one break of nine months in the series between 1973-74. This data came in daily flow format where the flow is averaged over the day from 9am to 9am, which is known as the water day. Obviously, this less detailed information fails to record the extremes of the flow accurately, but a longer data set was desirable due to the need for as much historical data as possible for the Markov Chain predictions (discussed previously in Chapter 4). Therefore the longer, less detailed data set was utilised for this project. As a result a sensitivity test was devised to investigate the effect on the predictions of using daily averaged flows as oppose to 12 hour averaged flows, 6 hour averaged flows or 1 hour averaged flows.

The sensitivity test took flow data recorded at Low Moor for the year January 2000 to January 2001. Upstream hydrographs were then formed by averaging the data over periods of 24 hours, 12 hours, 6 hours and 1hour. Four separate models were created, each of which had the same sediment rating curve attached to it thereby maintaining a comparable sediment inflow. These four models were run for one year, each using a timestep of 300 seconds, and their results compared.

Flow Averaged Over	Sediment Inflow Tonnes	Sediment Outflow Tonnes	% Retained
1 hour	111450.00	76711.85	31.169
6 hours	108916.30	72997.29	32.978
12 hours	106982.60	67829.21	36.598
24 hours	95969.50	53899.23	43.837

Table 5. 9 Comparison of the sensitivity analysis

The results of the four runs are shown in Table 5. 9, which compares the amount of sediment coming into, leaving and being retained in, the impoundment. At this point, it should be observed that the flows averaged over 1hour bear a more realistic resemblance to the flows recorded on the river, which means that during this sensitivity study the results should be compared with the 1hour model.

Firstly it is clear from Table 5. 9, that the sediment arriving in the impoundment is different for each run. This is due to the fact that, as the period of time over which the flow is averaged reduces, more extreme flows will be observed. Therefore, this allows more sediment to be carried into the impoundment on these higher flows. Sediment outflow for each of the models also varies, which again can be considered as a function of the inflow sediment and water. If high flows are predicted through the reach then sediment is more likely to be re-entrained along the river. Consequently, the 1 hour averaged model should predict more sediment passing out the bottom end of the model because higher flows will be predicted resulting in a higher sediment transport capacity for the river. With this knowledge, the results predicted by the sensitivity study can be explained. The 1 hour averaged run records the highest sediment inflow, but also the most sediment outflow from the impoundment. The percentage retained for the 1 hour averaged run is 30.169%, whereas the 24 hour averaged model retains 43.837%. This model records the lowest sediment inflow and the lowest outflow.

Figures: 5.13, 5.14 and 5.15 show the difference in predicted sedimentation down the river for each run. Each model has been compared with the 1 hour model specifically to show the effect of averaging the flow over longer periods of time.

These three graphs show that the 1 hour averaged model predicts more erosion at the top end of the model (near Low Moor) and less deposition at the lower end of the model (near the barrage) than any of the other three models. As the period over which the time is averaged becomes smaller, the closer the predicted deposition becomes to that forecast for the 1 hour model.

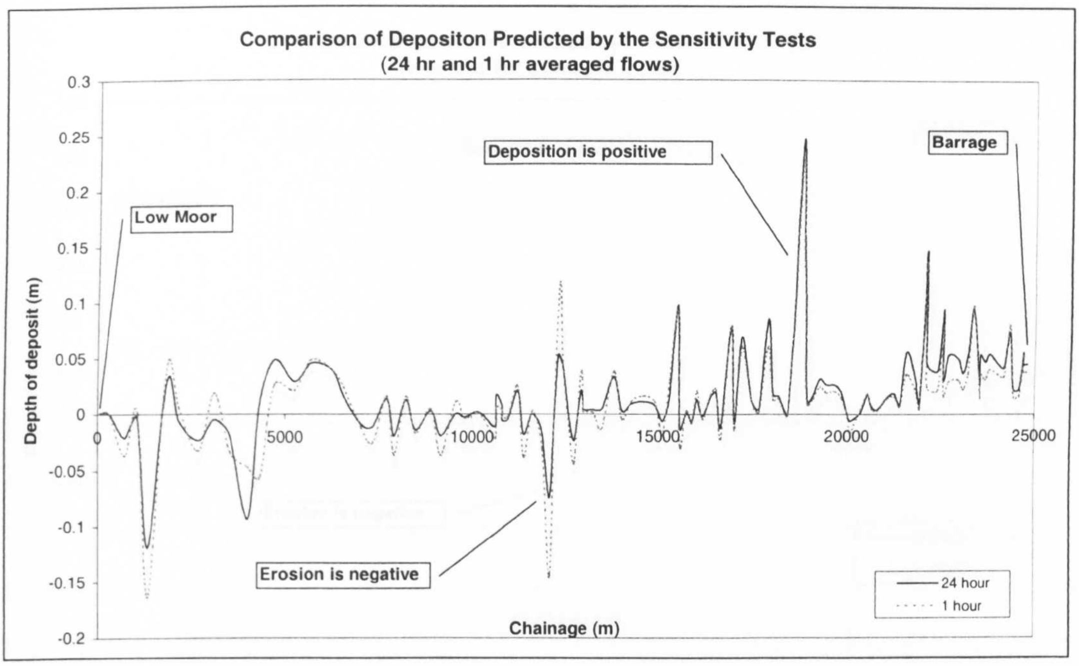


Fig. 5. 13 Comparison of deposition predicted by sensitivity study, 24hr and 1hr averaged flows

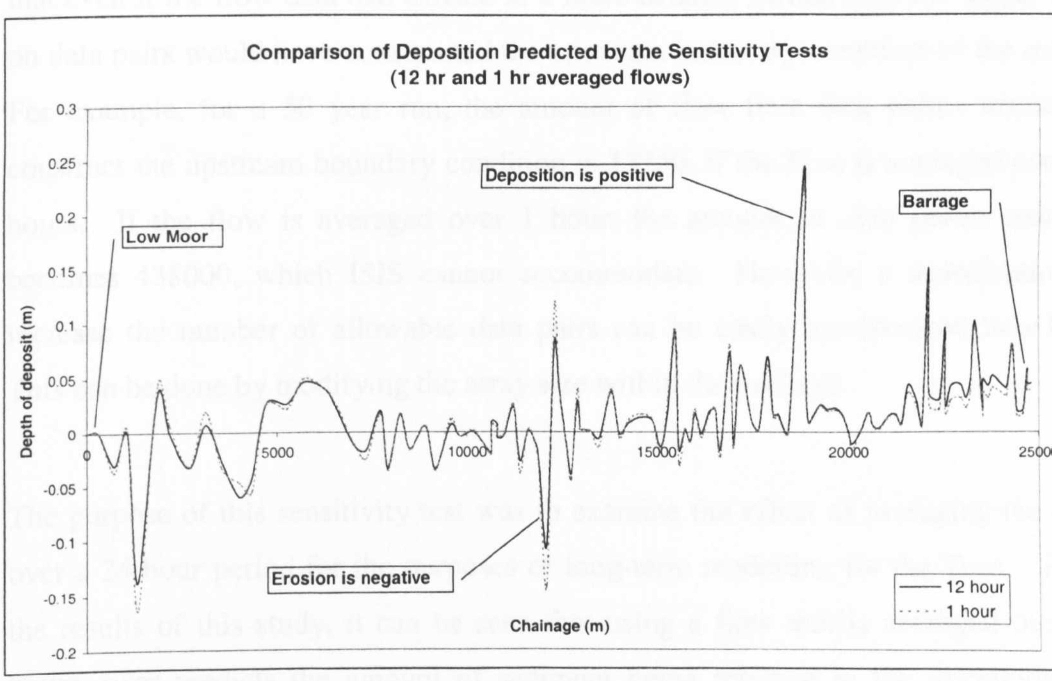


Fig. 5. 14 Comparison of deposition predicted by sensitivity study, 12hr and 1hr averaged flows

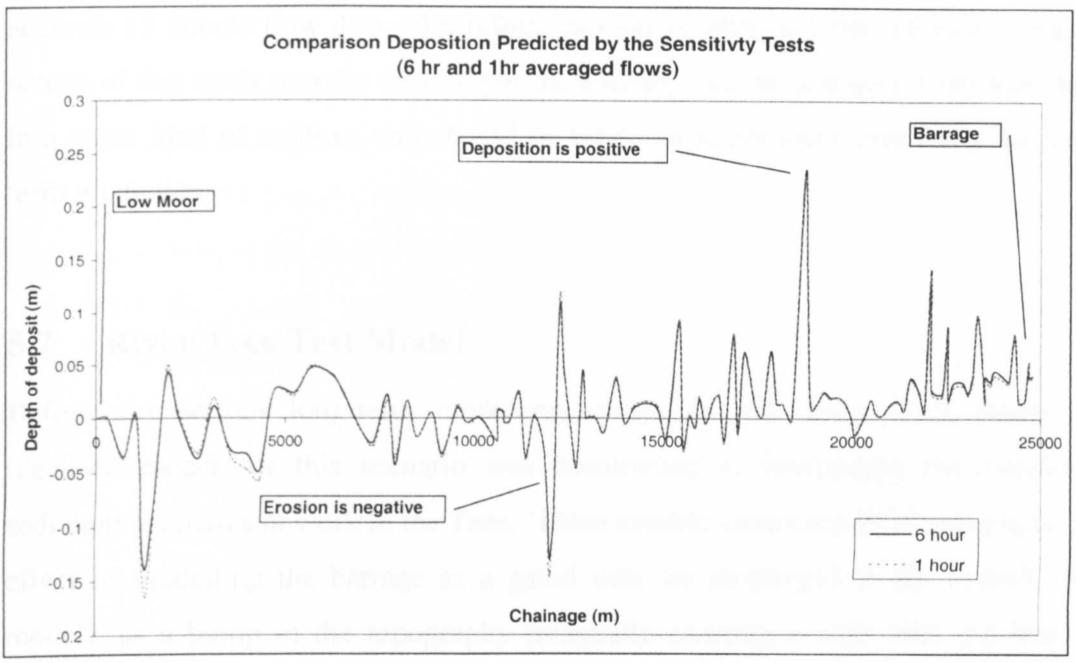


Fig. 5. 15 Comparison of deposition predicted by sensitivity study, 6hr and 1hr averaged flows

Whilst using ISIS it was discovered that in its current configuration the maximum amount of flow time pairs allowed for the upstream boundary was 60000. The meant that even if the flow data had existed in a more detailed format then this upper limit on data pairs would have constrained the upstream boundary condition of the model. For example, for a 50 year run, the amount of flow time data points needed to construct the upstream boundary condition is 18250, if the flow is averaged over 24 hours. If the flow is averaged over 1 hour, the amount of data points required becomes 438000, which ISIS cannot accommodate. However, a modification to increase the number of allowable data pairs can be easily incorporated into ISIS. This can be done by modifying the array size within the package.

The purpose of this sensitivity test was to examine the effect of averaging the flow over a 24 hour period for the purposes of long-term modelling for the Tees. From the results of this study, it can be seen that using a flow that is averaged over 24 hours, over predicts the amount of sediment being retained in the impoundment. However it under predicts the amount of sediment reaching the impoundment in the first place. For this study 24 hour averaged flows were available for a long period of time at Low Moor and in conjunction with the constraint found in ISIS for the upstream boundary, this resulted in these flows being used as oppose to the more accurate 15 minute flow data. Therefore the over prediction of the 24 hour averaged results of this study must be used to put the overall, long-term results from this study into some kind of context, and should be borne in mind when analysing the long-term predictions.

5.7 River Tees Test Model

Before any serious long-term modelling started for the River Tees model, an idealised model for this scenario was constructed to investigate the simplified sediment processes at work in the Tees. Three models were created to investigate the effect of modelling the barrage as a gated weir (as employed in the overall Tees model), as a bump in the topography (manually creating a weir with the bed) or simply as a head with time downstream boundary condition. Once these results had been analysed, this model was employed to investigate the long-term effect of the sediment and flow inputs on the deposition patterns for an idealised model for the Tees.

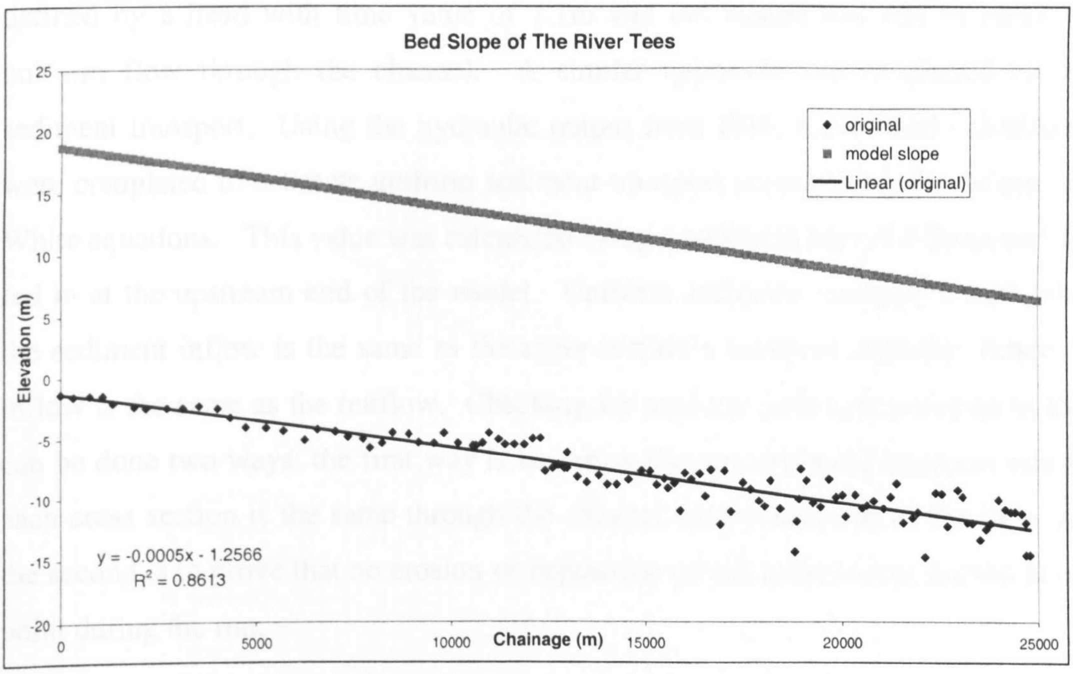


Fig. 5. 16 Bed slope of the River Tees for use in constructing idealised model

5.7.1 Idealised Model Construction

To construct the idealised model, firstly an average slope was found from the minimum channel depth for each cross section. The minimum depths for each cross section were plotted down the length of the modelled reach, through these points a best fit line was constructed. This produced a linear equation, which could be used to estimate the average bed slope for the idealised model. The equation gave an estimated bed slope of 1:2000. Next an idealised version of the Tees channel was estimated by assuming a 50m wide by 10 m deep, rectangular channel, which had a uniform Manning's 'n' value of 0.045. Putting these two approximations together and entering the information into ISIS created the geometric components of the idealised model.

To understand the fundamentals of the system, the hydraulic and sediment upstream boundaries were kept simple at the outset. For the upstream flow boundary, uniform flow for the channel was calculated assuming a 1.1m head down the whole channel and entered using a flow with time boundary. The downstream boundary was defined by a head with time value of 1.1m and the model was run to check for uniform flow through the channel. A similar approach was employed for the sediment transport. Using the hydraulic output from ISIS, some hand calculations were completed to estimate uniform sediment transport according to the Ackers and White equations. This value was calculated using a sediment size of 0.2mm and was fed in at the upstream end of the model. Uniform sediment transport occurs when the sediment inflow is the same as the cross section's transport capacity; hence the inflow is the same as the outflow. Checking for uniform sediment transport in ISIS can be done two ways; the first way is to ensure that the sediment transport rate for each cross section is the same through the channel for the duration of the flow, and the second is to prove that no erosion or deposition occurs at any cross section at any point during the run.

Once uniform flow and uniform sediment transport had been found, three different models were created. The first simply increased the downstream water level to 7m using a head with time boundary. This depth was chosen as a representative depth of an average cross section. The second model used a gated weir section to increase the water surface level to 7m above the bed, while the third represented the weir section as a bump in the topography. This was achieved by manually distorting the topography at the downstream end to create a bump in the channel bed, whose crest was fixed at 6.56m above the channel bed. This crest was the same height as the weir crest in the second model. For the third model, the bed was specified as a hard bed in ISIS, which has the effect of fixing the bed and allowing no erosion of the bump in the topography, otherwise this bump would have been eroded away.

5.7.2 Idealised Model Results and Discussion

Using the three models described in the previous section; the model with a simple downstream boundary, the model with a gated weir and the third, which modelled the barrage as a bump in the topography, some simulations were completed. The upstream sediment and flow boundaries were kept the same and two year runs were completed. Logically, if the models were previously predicting uniform flow and sediment transport and the downstream boundary has been raised, deposition would be expected at the downstream end as the sediment is dropped out of suspension. This sediment should be deposited as the velocity decreases and the depth of water increases. The results are shown in Fig. 5. 17, Fig. 5. 18 and Fig. 5. 19.

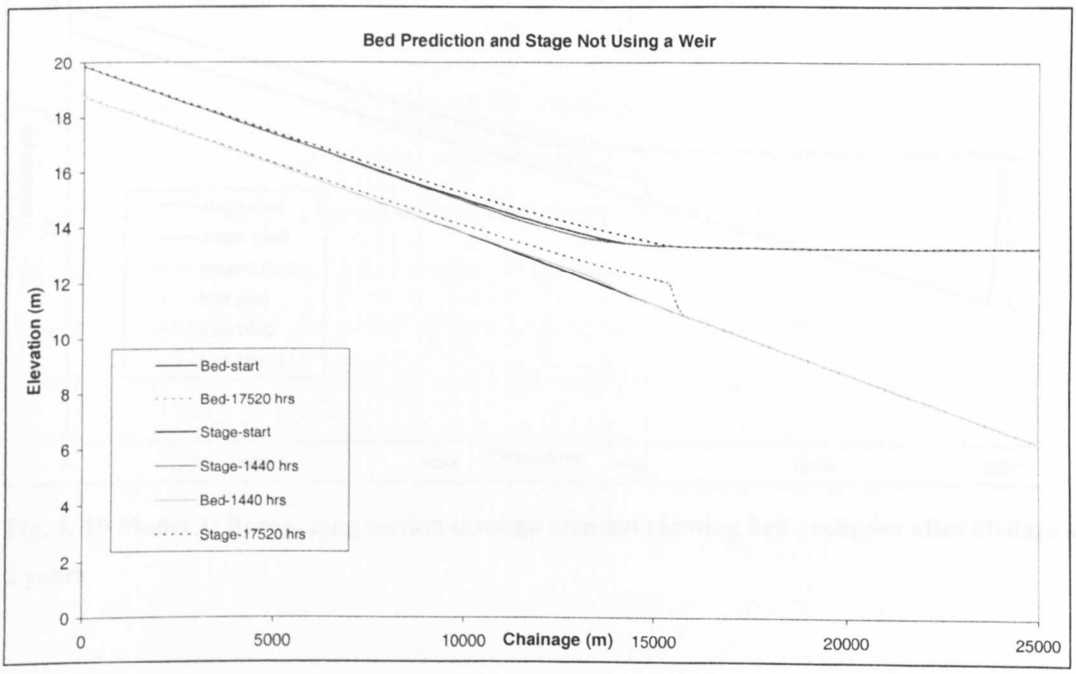


Fig. 5. 17 Model 1: No weir, long section through channel showing bed evolution after 60 days and 2 years

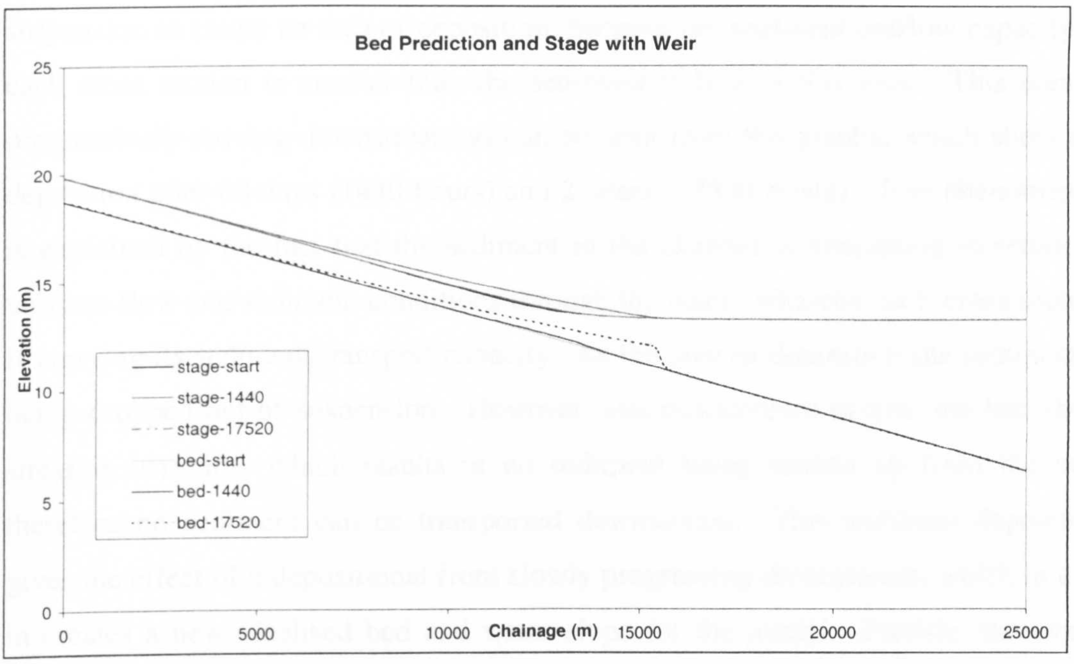


Fig. 5. 18 Model 2: Weir, long section through channel showing bed evolution after 60 days and 2 years

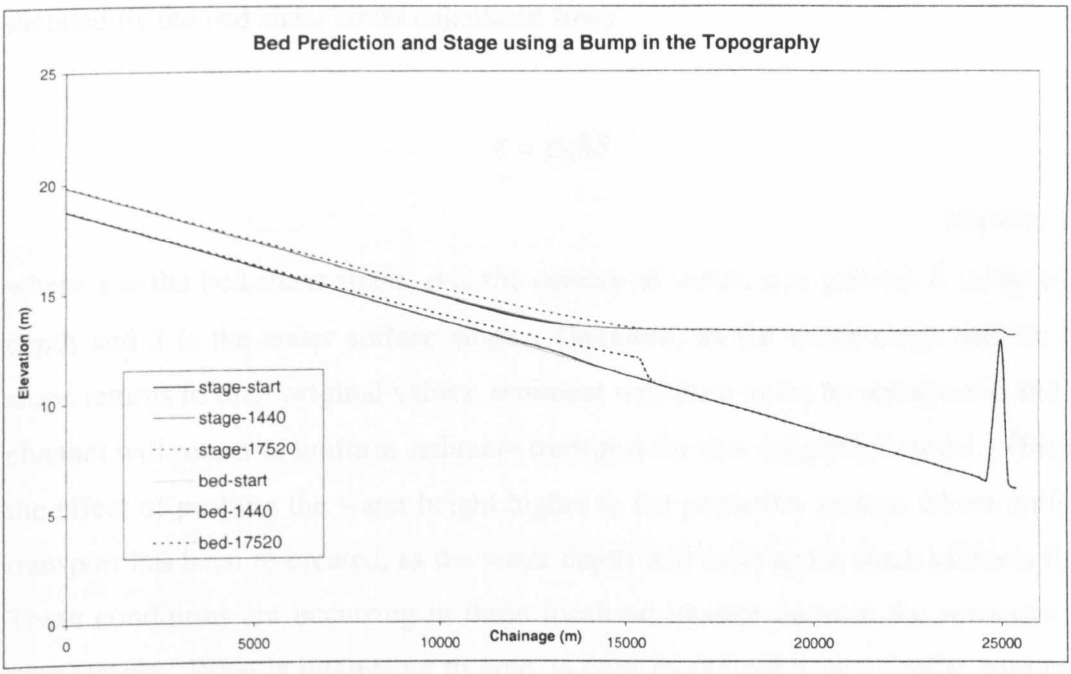


Fig. 5. 19 Model 3: Bump, long section through channel showing bed evolution after 60 days and 2 years

These results show that an area of deposition is occurring at the point where the backwater curve from the weir joins the uniform flow section of the model. So at the point where the water depth deepens, sediment is being dropped out of suspension to create an area of deposition, because the sediment outflow capacity of each cross section is smaller than the sediment inflow in this area. This area is progressively moving downstream as can be seen from the graphs, which show the deposition after 60 days (1440 hours) and 2 years (17520 hours). This phenomenon is explained by the fact that the sediment in the channel is attempting to return to uniform flow and sediment conditions through the reach, whereby each cross section is carrying its sediment transport capacity. At the area of deposition the sediment is being dropped out of suspension. However, just downstream of this, the bed shear stress is very low which results in no sediment being picked up from the bed, therefore no sediment can be transported downstream. This sediment deposition gives the effect of a depositional front slowly progressing downstream, which in turn in creates a new idealised bed and water slope for the model. Particle movement (from the bed) occurs when the applied shear stress increases above the critical shear stress for the bed sediment. For uniform sediment transport conditions to return sediment must again be picked up from the bed, this threshold for the model is dictated by the bed shear stress calculated from:

$$\tau = \rho g h S$$

Equation 5. 15

where τ is the bed shear stress, ρ is the density of water, g is gravity, h is the water depth and S is the water surface slope. Therefore, as the water slope and the bed slope returns to their original values, sediment will once again be transported and the channel will return to uniform sediment transport for this simplified model. This has the effect of pushing the water height higher at the particular section where uniform transport has been re-created, as the water depth will once again reach uniform flow. These conditions are occurring in these idealised models because the scenarios are very simple. What is interesting to note, is each model predicts a similar amount of deposition after both 60 days and 2 years. All three models predict the same backwater curve giving a similar water slope at each cross section, which drives the sediment transport. Therefore, each model predicts comparable sedimentation results, which means that the weir function in ISIS is a suitable function to use for sediment transport modelling the Tees barrage and subsequent impoundment. While ISIS predicts the same backwater curve from a weir as would be expected from a bump in topography or from the downstream water level being held high, the ISIS manual states that any hydraulic structure is considered as a two noded junction. Thus, the outflow sediment transport rate at the upstream end equals the inflow transport rate at the downstream node, which ignores the issue of whether bed and suspended load can in reality pass downstream. This means that the model is accounting for the weir's affect on the water surface slope and the resulting loss of energy, but when it comes to sediment it models the transport purely from the behaviour of the hydraulic system. This means that the barrage is not considered to be a physical barrier, rather the transport is calculated from the hydraulics upstream and this is then passed downstream. However, this project is only interested in the sedimentation effects upstream of the barrage, and as such this is not an issue.

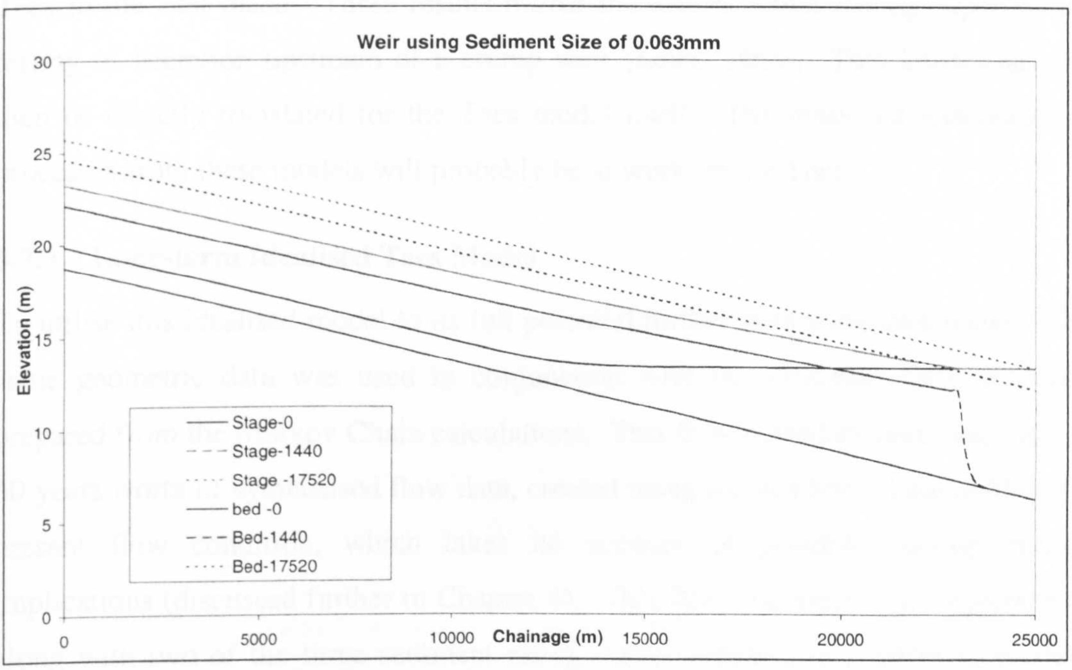


Fig. 5. 20 Model 4: Weir with sediment size of 0.063mm, long section through channel showing bed evolution after 60 days and 2 years.

To prove the hypothesis, whereby the channel is attempting to return to a new regime, further, another model was developed using the same geometric and upstream flow data as models 1-3. This time a sediment size of 0.063mm was chosen for the bed and inflow conditions. Similar to the process for model 1-3 uniform sediment transport was calculated for the channel when uniform flow conditions existed. Then a gated weir unit was inserted at the downstream extent, with its crest fixed at 6.56m above the channel bed as for model 2. Due to the fact that the channel's capacity for transporting sediment of diameter 0.063mm is much higher, after two years a more extreme situation should arise.

The results shown in Fig. 5. 20, demonstrate that this hypothesis does indeed hold true for these conditions. After 60 hours the channel can be seen to have almost returned to uniform sediment transport and flow conditions, whereby the sediment has deposited up to the height of the weir crest. After 2 years both uniform flow and sediment transport conditions have returned to the reach, which means that the water slope and bed slope have returned to the same gradient displaced only by the height of the weir. This slope relates directly to the original bed slope calculated for the Tees in the first place. These results mirror the results found during experimental testing of accretion upstream of a crump weir (Lean, 1965). This knowledge can then be directly translated for the Tees model itself. The observed sedimentation processes from these models will probably be at work on the Tees.

5.7.3 Long-term Idealised Tees Model

To utilise this idealised model to its full potential further tests were undertaken. The same geometric data was used in conjunction with the upstream flow boundary prepared from the Markov Chain calculations. This flow boundary takes the form of 50 years worth of synthesised flow data, created using the Markov Chain method for present flow condition, which takes no account of possible climate change implications (discussed further in Chapter 4). This flow boundary was implemented along with two of the three sediment rating curves creating two different models. The first model used the lowest sediment rating curve giving the low sediment scenario, while the second used the highest or most extreme sediment rating curve leading to the high sediment scenario. For both the bed and inflow sediments, the particle size distribution used was the same as used in the Tees model. Similarly, the model uses the gated weir function, which is controlled by the same rules that control the weir in the Tees model, thus creating the same weir and boundary conditions as for the Tees model itself but using simplified geometry to understand what is happening.

5.7.4 Long-term Idealised Model Results and Discussion

These two models were run for 50 years into the future, and their results were analysed. These results are shown in Fig. 5. 21 and Fig. 5. 22. There is an area of erosion at the top end of the model and a much larger area of deposition at the downstream end of the model near the barrage. The sedimentation that is building up in these models is occurring lower down the model than in the previous test models. Instead of the deposition occurring at the point where the backwater curve meets the river flowing in as was previously observed, the sediment is being deposited closer to the barrage.

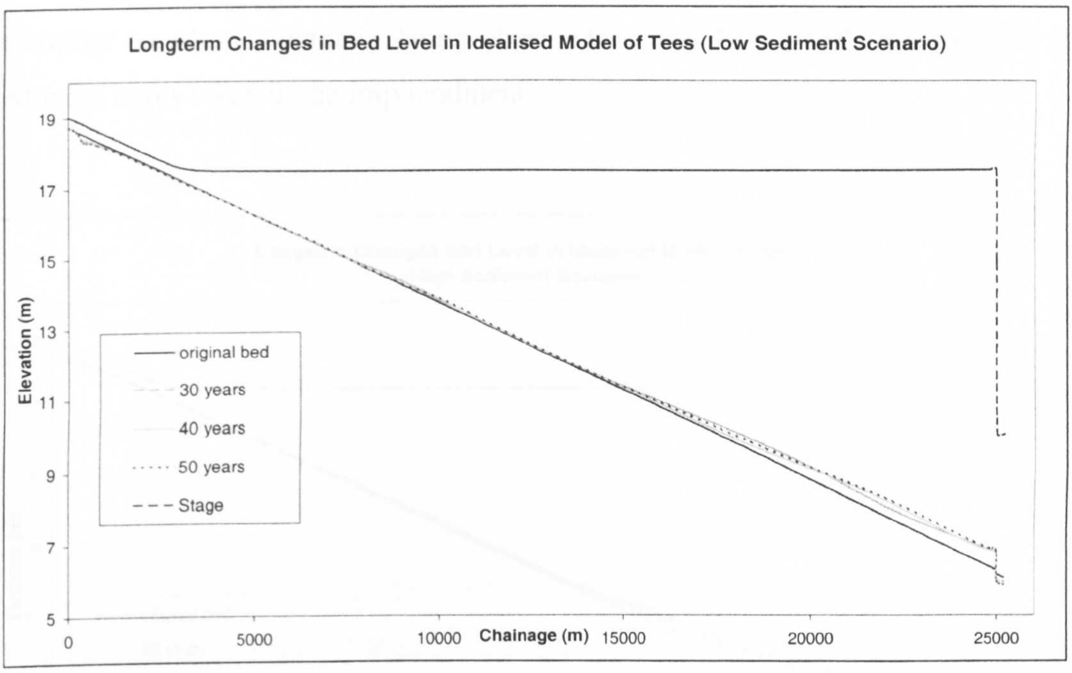


Fig. 5. 21 Long-term idealised model: Low Sediment Supply Scenario, long section through the reach showing relative areas of deposition and erosion

This is partly due to the fact that the sediment make-up of the inflow has changed. Where once the sediment inflow modelled was strictly non-cohesive, now the inflow has a predominantly cohesive nature as is present in the Tees. This means that the cohesive sediment takes a longer period of time to drop out of suspension due to the fact cohesive particles are much smaller. In saline water the behaviour of these smaller fractions is affected by flocculation. This changes how quickly these particles find their way to the bed whilst dropping out of suspension. The effect is controlled by Van der Waals forces and turbulent shear, otherwise known as Brownian motion. However, as the Tees impoundment is predominantly freshwater and because ISIS is only a one dimensional model and as such cannot take account of such detailed effects, there is only one equation, which allows the incorporation of cohesive sediments (sediment particles smaller than 0.063mm). This equation is the Westrich-Jurashrek equation (Equation 5. 14), which incorporates a settling velocity for each fraction. Within this model, two of the ten fractions have been specified as smaller than 0.063mm and as such have a settling velocity defined. These two fractions define the most prominent sizes for the inflow sediment distribution. The result of the relatively slow settling velocities for these fractions may mean that the sediment takes longer to drop out of suspension leading to the phenomenon that can be observed in Fig. 5. 21 and Fig. 5. 22. This build up, just upstream of the barrage is similar to what is actually being observed on the Tees itself, according to the sediment cores taken in the impoundment.

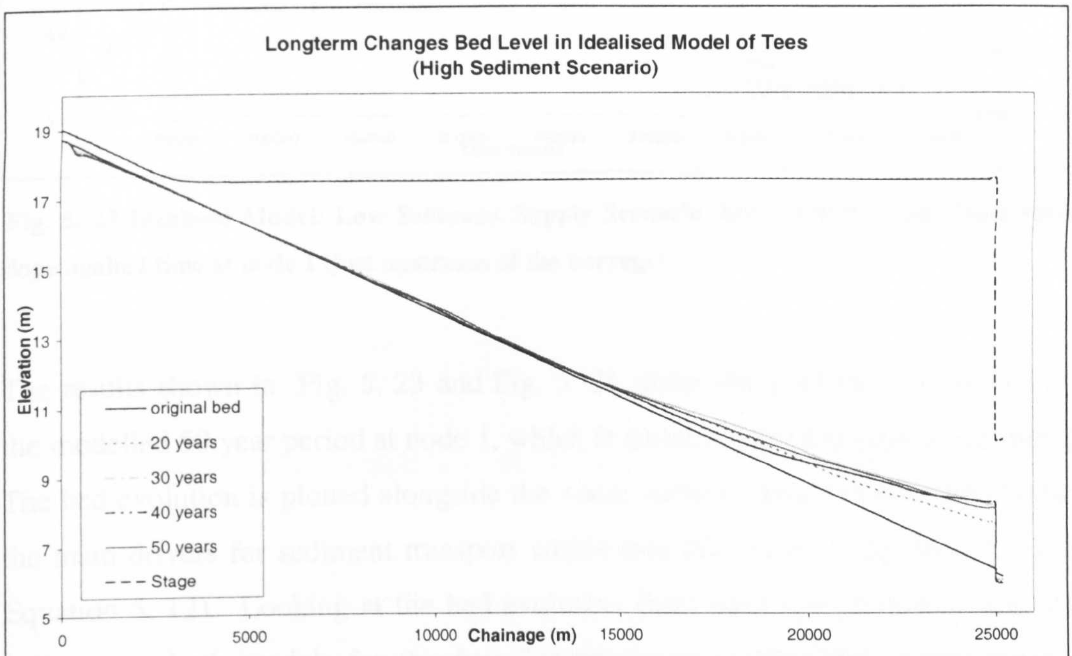


Fig. 5. 22 Long-term idealised model: High Sediment Supply Scenario, long section through the reach showing relative areas of deposition and erosion

From these idealised models, what has been observed is the gradual build up of sediment in the impoundment just upstream of the barrage. The amount of sediment being fed in at the upstream end seems to dictate the overall amount of sediment trapped in the impoundment. Therefore, the high sediment scenario is predicting a much more extreme sedimentation pattern over the course of the fifty years. What is interesting to note however, is that some type of dynamic equilibrium in the channel is being reached over this 50 year period. Although this can be observed in the long sections through the river it is more clearly seen if the bed evolution from one cross section is plotted against time.

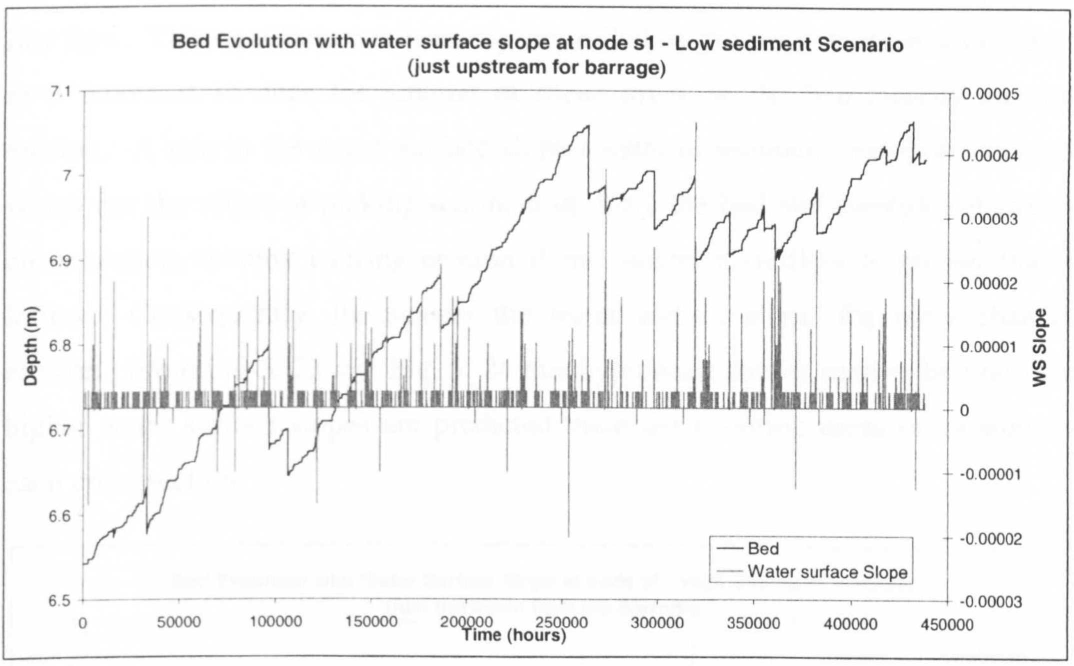


Fig. 5. 23 Idealised Model: Low Sediment Supply Scenario, bed evolution and water surface slope against time at node 1 (just upstream of the barrage)

The results shown in Fig. 5. 23 and Fig. 5. 24, show the evolution of the bed over the modelled 50 year period at node 1, which is situated just upstream of the barrage. The bed evolution is plotted alongside the water surface slope because this is one of the main drivers for sediment transport within this ISIS model (Equation 5. 14 and Equation 5. 12). Looking at the bed evolution first, what can be seen is a gradual build up in both models for the first 250000 hours or 28 years, where upon the dynamics of the system change. From this point on the channel appears to have reached a dynamic equilibrium, whereby the deposition levels out. The amount of deposition, in this case, is linked to the amount of sediment arriving into the section. This can be observed in the results shown; the high scenario shows a 1.8m increase whereas over the same period of time the low scenario shows a 0.6m increase. Therefore, the amount of sediment reaching the impoundment does not significantly affect the time at which this dynamic equilibrium is reached, however it does affect the rate of the deposition before the equilibrium is reached.

The water surface slope has been plotted on these graphs to indicate why the channel reaches equilibrium. Using the knowledge obtained from the previous models, each cross-section is attempting to return to its ideal shape, whereby the overall rate of erosion and deposition is in equilibrium, this is harder to achieve in this model as the upstream flow boundary fluctuates with time, modelling storms as well as periods of low flow. This equilibrium is partially controlled by the water surface slope because as it increases so does the amount of shear stress on the bed thereby increasing erosion. A rise in the water surface slope results in sediment transport increasing, which has the effect of picking sediment up from the bed and sweeping it from the cross section, thereby causing erosion if the sediment outflow is greater than the inflow. Consequently, the steeper the water surface slope, the more chance of erosion. From Fig 5. 23 and Fig. 5. 24 this hypothesis can be seen to be true; where higher water surface slopes are predicted there are resulting areas of erosion from each cross section.

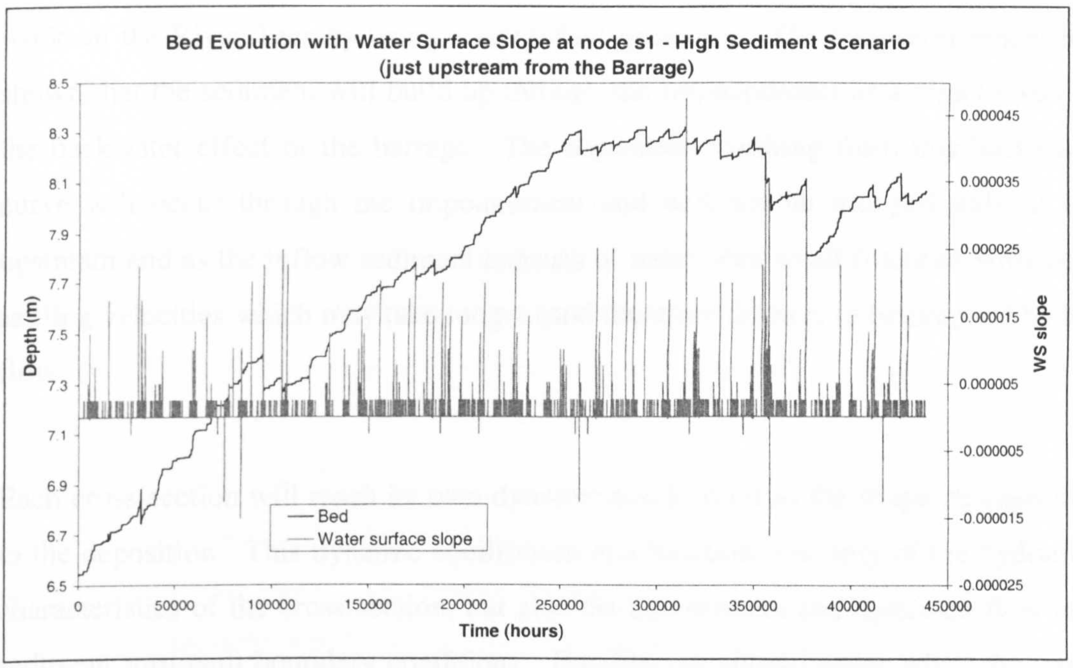


Fig. 5. 24 Idealised Model: High Sediment Supply Scenario, bed evolution and water surface slope against time at node 1 (just upstream of the barrage)

These areas of erosion become more common after the 28 year mark in this run, where sediment starts to be eroded as a result of the smaller values of water surface slope. This is because, as the sediment builds up it changes the shape of the cross section to a point where the new hydraulic characteristics of the cross section are such that, erosion is being predicted for a larger percentage of the time than at the start of the run where the predominant sediment prediction was deposition. This point is partially controlled by the section itself, so each cross section may take a slightly different amount of time to reach equilibrium, this will be more evident when analysing the results of the real Tees model as each cross section is differently shaped. However, it is also controlled by the water surface slope, which is linked inexorably to the weir and the flow prediction at the upstream end and the sediment inflow conditions. Obviously if there is more sediment flowing in at the upstream end then more sediment must be picked up from the bed to balance the deposition occurring, therefore reaching equilibrium. This explains why the high sediment scenario predicts more deposition, as the channel must undergo more change to obtain its equilibrium.

5.7.5 Long-term Idealised Model Conclusions

From these tests it is possible to understand some of the sedimentation processes at work on the River Tees by using a simplified geometry. The long-term model has shown that the sediment will build up through the impoundment as a direct result of the backwater effect of the barrage. The deposition resulting from this backwater curve will occur through the impoundment and will not be dropped only at the upstream end as the inflow sediment consists of some very small fractions with slow settling velocities which may take longer (and therefore further) to be dropped by the flow.

Each cross-section will reach its own dynamic equilibrium as the shape changes due to the deposition. This dynamic equilibrium is a function, not only of the hydraulic characteristics of the cross-section, but also the downstream and upstream flow and sediment upstream boundary conditions. Equilibrium should occur when the cross section has reached a point where erosion and deposition are balanced, thereby stabilising the geometry and holding the overall deposition to a particular depth.

The concentration of sediment being fed in at the upstream boundary affects the sediment regime by dictating the amount of sedimentation at each cross section. This does not affect the time to equilibrium for each cross-section, but it does affect the depth at which equilibrium is found. This is because if there is more deposition occurring, the hydraulic conditions of the channel (i.e. the water depth and water surface slope) have to change more dramatically to balance the amount of sediment being deposited and eroded.

This idealised model should help to explain the sedimentation processes at work on the River Tees and aid in analysing the long-term predictions resulting from the real Tees model.

5.8 Summary

The aim of this chapter was to explain the construction of the ISIS model for the River Tees. The construction of the model was completed using the data collected during the survey of the river in the summer of 2000, details of the bridges obtained from the councils involved and information on barrage operations from the Barrage Manager. The model incorporates the bridges and the barrage as a weir using the hydraulic unit sections available within ISIS.

Once the model was created, it was possible to calibrate it using the calibration data collected from the Tees on the 31st of August and the 6th of December 2000. These dates gave a good comparison of flow values with a particularly low and high flow event. However, an out-of-bank event was never collected and as a result the model was not calibrated to this. The calibration achieved was considered reasonable despite the fact an over-bank event was omitted. Sedimentation calibration was difficult. The calibration was completed using the results for both a 350m^3/s and a 100m^3/s hydrographs contained in the HR Wallingford Report (1992). The trapping efficiency was matched from the model predictions to the values given in the report. To gain further confidence in these results, the model was run for 8 years using the recorded flow values from Low Moor. This gave a predicted amount of sediment just upstream of the barrage. This value was matched to the amount of sedimentation observed from the core samples collected by The University of Durham to achieve more confidence in the sedimentation results.

After the Tees model was calibrated, a sensitivity test was devised to investigate the effect of using flows averaged over 24 hours. This was an issue because a long record of 24 hr averaged flows was available from the National River Flow Archive, which was very useful for this project, but had the disadvantage of being rather coarsely measured data rather than 15-minute data recorded for 2 years during this project. This study showed that the 24hr flows over predicted the amount of sedimentation in the impoundment and as such these results should be considered when analysing the long-term predictions for the impoundment.

Following on from this sensitivity study some simple tests were completed to investigate the sedimentation processes at work in the Tees. A simplified model was constructed to test the use of the gated weir function in ISIS, which resulted in a satisfactory outcome. The weir module predicts the same amount of sedimentation to the amount predicted by using a bump in the topography, although the downstream prediction may be distorted according to the way ISIS predicts sedimentation. The simplified Tees model allowed the deposition processes to be studied and understood, the outcome of which showed that deposition should occur where the backwater curve effect starts in the impoundment. However, due to the fine grain size of the suspended sediment deposition may occur downstream from this point and closer to the barrage as the suspended sediment will take some time to drop out of suspension.

The construction of the model is now completed, with it being calibrated not only for the hydraulics but for the sedimentation predictions as well. The sensitivity tests and the results from the simplified model have made the sedimentation processes at work in the Tees impoundment clearer. Now it is possible to gather all the information gained from this work and apply it to the long-term predictions for the impoundment.

Chapter 6: Long-term Sedimentation Results: River Tees

6.0 Introduction

To assess morphological sustainability of the Tees impoundment it is necessary to predict changes to the estuary over an extended period of time. These predictions have been produced using the one-dimensional hydrodynamic and sediment transport modelling package ISIS. The construction of the model for the Tees Impoundment is described in depth in chapter 5. The flow boundary for the upstream end has been extended for 50 years under present and future climate conditions using a Markov Chain method, which has been described in some detail in chapter 4. Each simulation has been repeated twice using a different flow boundary to check the sedimentation predictions are reasonable, however, the results must be recognised as representative scenarios of the possible future outcomes of the model. For each case the run with higher results is presented, although only minor differences have been recorded between runs. The sediment upstream boundary has been analysed from data collected in the field, the details of which can be found in chapter 3. This chapter aims to present the results of the long-term sedimentation simulations undertaken for the Tees.

Firstly, this chapter will set out and discuss the results of the runs completed using the flow boundary constructed under the present climate conditions using the three different sediment supply scenarios. Next the results will be presented and analysed for the flow boundaries altered to account for climate change, both under the medium/low and medium/high emissions scenarios.

6.1 Results of Long-term Predictions Under Present Climate Conditions

The results that will be presented in this section have been produced from the ISIS model of the Tees impoundment using the flow boundary created using the Markov chain method, from the historically recorded flow data for the Tees (described in detail in chapter 4). There are three separate scenarios regarding sediment inflow into the impoundment that have been investigated. Firstly, the results from the low sediment supply scenario will be presented. The low sediment input to the river is dictated by the sediment rating curve which was calibrated to the present or normal conditions on the river Tees since the opening of the barrage in 1994 (this calibration procedure is described further in section 5.5.3). These results will be followed by the medium and high sediment supply scenarios, which are dictated by the sediment rating curves derived from the post-October 2000 data. The medium sediment supply inflow relates to the normal curve which was fitted to this data, and the sediment inflow characteristics dictated by the upper 95% of this curve are termed the high sediment supply scenario. Therefore, the results will predict differing extremes of sedimentation depending on the sediment inflow curve used for the simulations.

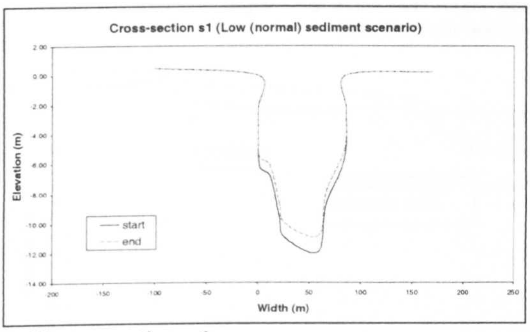
For each sediment scenario the same information in graphical format will be presented showing the varying amounts of deposition predicted by each different sediment input. Firstly selected cross-sections are presented from the lower 2km of the model, which is just upstream from the barrage. These cross-sections are chosen as they represent areas of high and low deposition in this area. The cross-sections displayed are nodes s1, s4, s6, s8, s10 and s13. Cross-section s1, s4 and s10 show large amounts of deposition, which is spread evenly over the area of the cross-section as dictated by ISIS. Node s1 is situated just 100m upstream of the barrage while node s4 is 300m further up the impoundment. Node s10, however, is situated 1.4km upstream of the barrage but is also just upstream of Victoria Bridge. Conversely, cross-sections s6, s8 and s13 show much less deposition, which can be explained partly by their size, shape and situation in the impoundment. This will be analysed further in the discussion section. Node 6 is situated 0.9km upstream of the barrage, with nodes s8 and s13 located 200m and 1.1km further upstream respectively.

After the cross-sections are displayed a detailed long-section of the whole, modelled impoundment is shown. This graph plots the lowest point in each cross-section against the nodes' distance downstream. This gives a good representation of where the sediment is predicted to build up through the impoundment. To represent the river more fully a 'typical' water level is plotted on the long-section, so that the depth of water existing in the impoundment can be appreciated. The next three graphs are detailed versions of this long-section. The first graph shows the upper 10km of the river in more detail, while the second graph shows the middle 10km. The last graph shows the 5km just upstream of the barrage in more detail. Each of these graphs highlights important areas of deposition or erosion through the impoundment and indicates landmarks where appropriate.

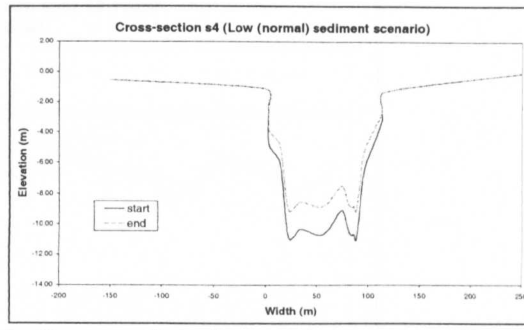
The final two graphs that were selected show the evolution of the bed deposits over the 50 year simulation plotted with the water surface slope at a particular node. The water surface slope was added to the graph as it is an important control on sediment transport and, as such, was calculated by finding the water surface level at the nodes upstream and downstream of the cross-section in question. Then the difference in water surface level was divided by the distance between the nodes. Node s4 and s10 were chosen as both nodes demonstrate high deposition values; therefore, they show the bed deposition, and how it varies with water surface slope, over the 50 year run.

6.1.1 Results of Long-term Predictions (Low Sediment Supply Scenario)

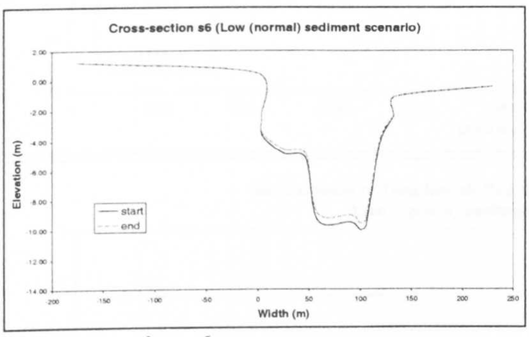
A fifty year simulation was completed using the low sediment rating curve, which had been calibrated to sediment cores in the impoundment and as such should be considered to represent the normal sediment conditions in the river. The flow boundary was constructed using the Markov chain technique, and is the same boundary condition that is used for the high and medium sediment scenarios under present climate conditions. The results are shown graphically in figures 6.1-6.3. It is important to give a value for the deposition at each cross-section. Taking the highly deposited nodes first, the deposition is in the order of a metre depth for cross-section s1, 1.856m from s4 and 2.133m for s10. However for the nodes with less deposition, the sedimentation depth is in the order of half a metre for node s6, 0.282m for node s8 and similarly 0.288m for node s13.



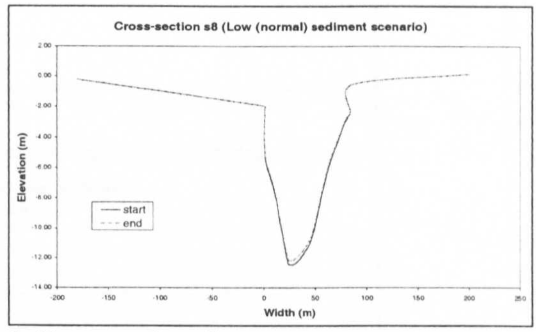
a. Cross-section s1



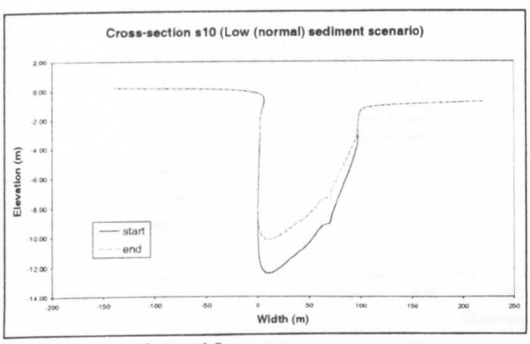
b. Cross-section s4



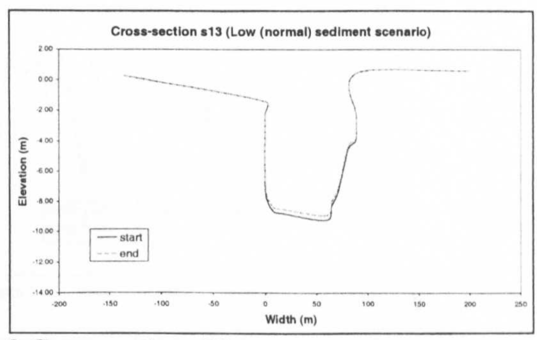
c. Cross-section s6



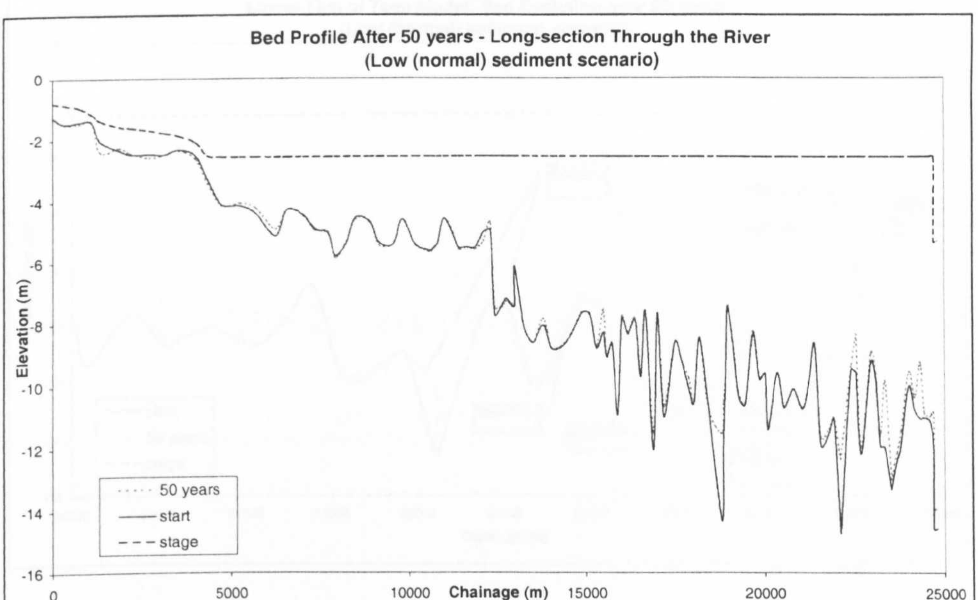
d. Cross-section s8



e. Cross-section s10



f. Cross-section s13



g.

Fig. 6. 1 (a-f) Cross-sections of lower 2km & (g) detailed long-section of River Tees following 50 year simulation (Low sediment supply scenario)

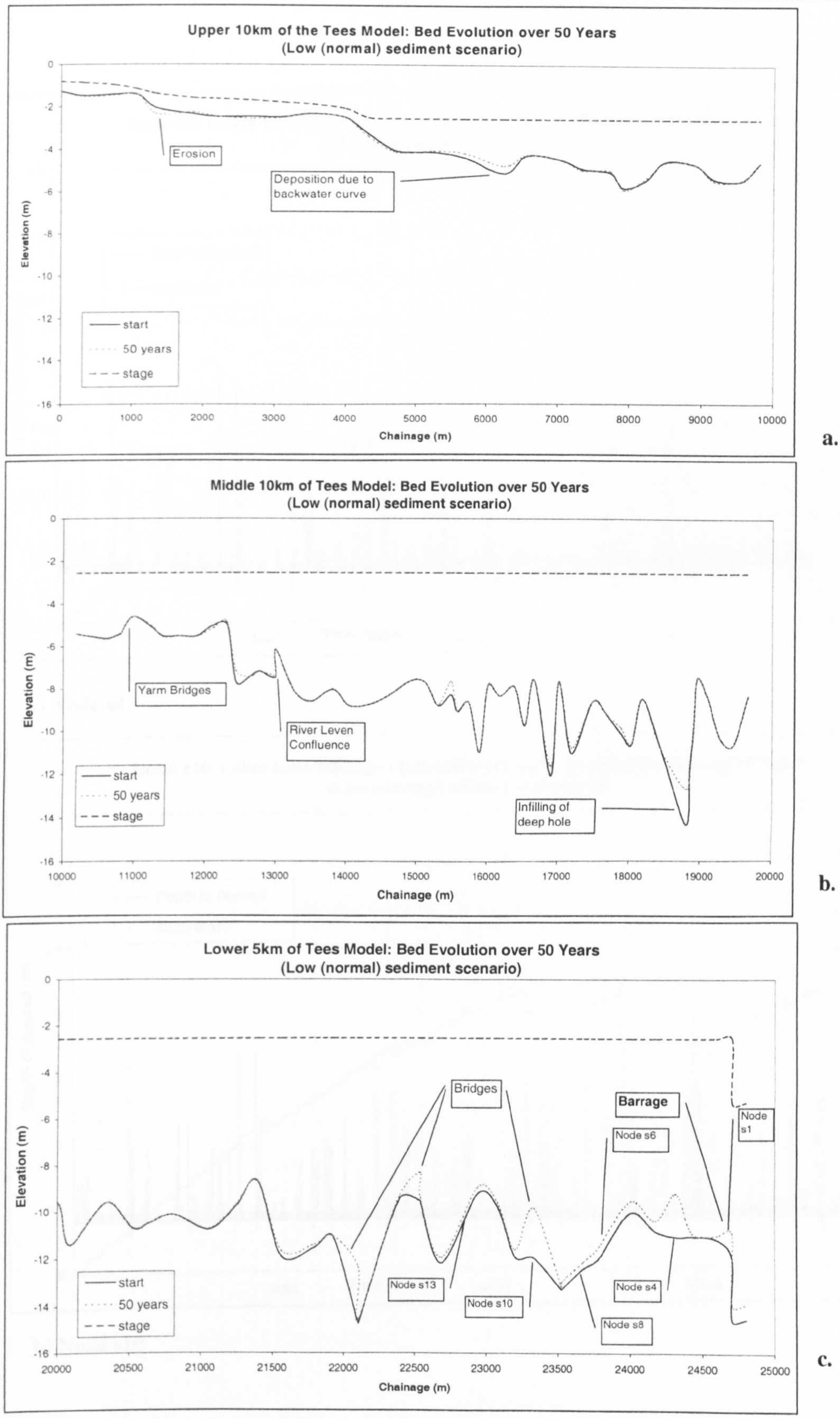
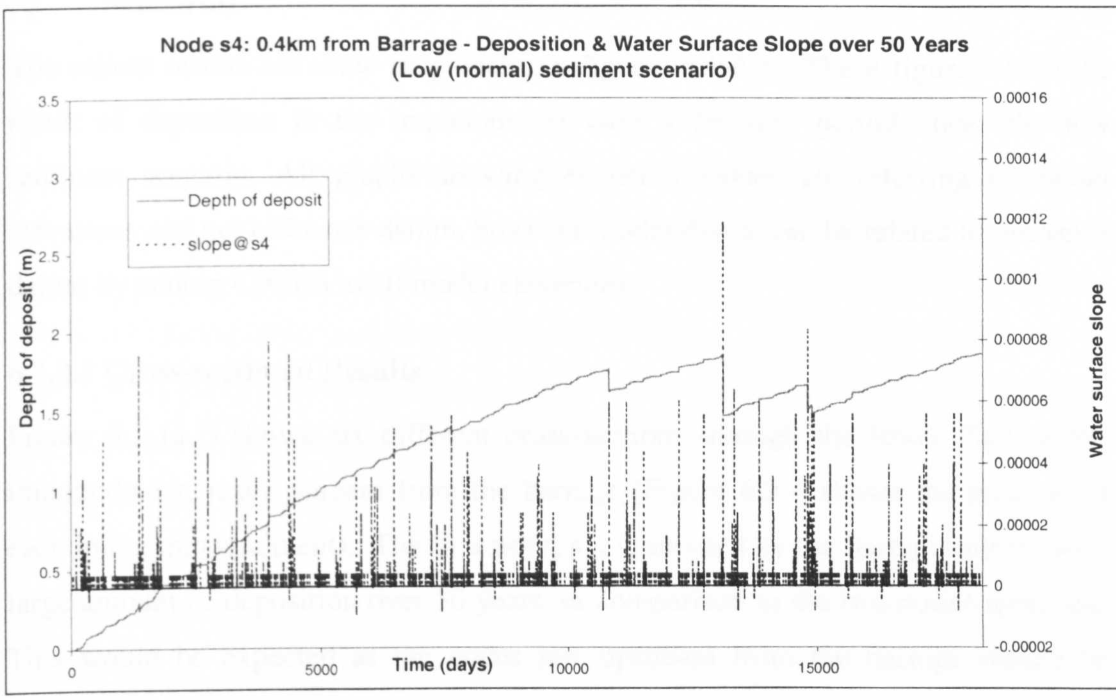
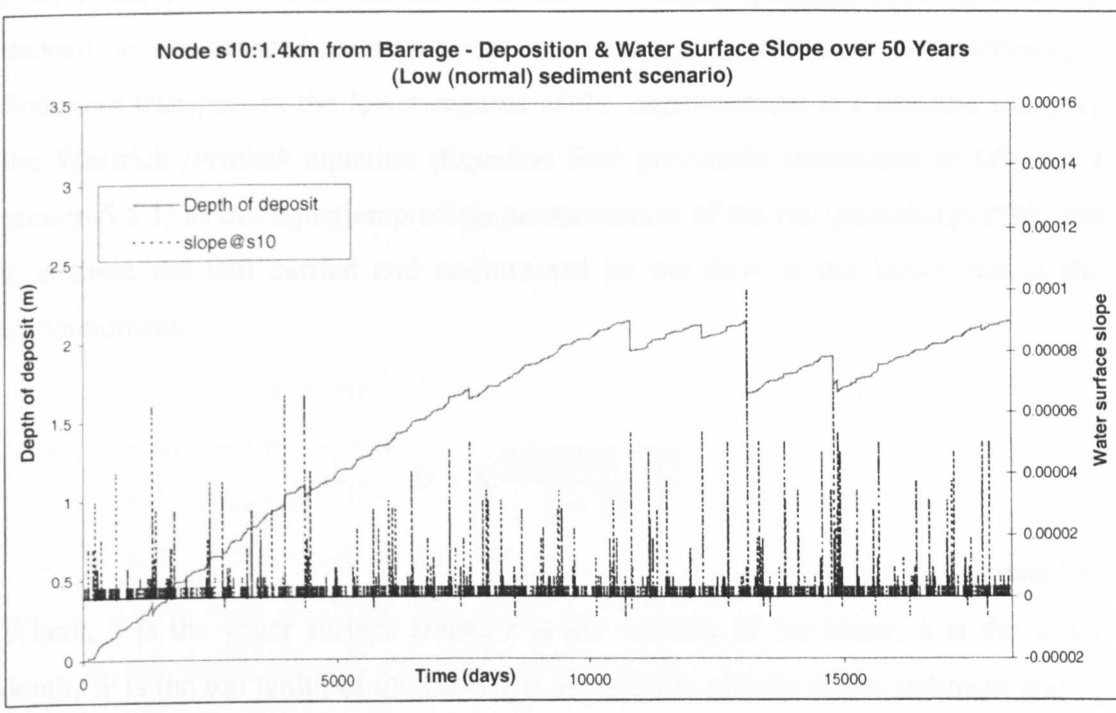


Fig. 6. 2 Detailed long-sections through the impoundment showing a) the upper 10km, b) the middle 10km and c) the lower 5km of the impoundment (showing the positions of the cross-sections) – demonstrating areas of deposition (Low sediment supply scenario)



a) Node s4



b) Node s10

Fig. 6. 3 Deposition and water surface slope over 50 Years at a) node s4 and b) node s10 showing the equilibrium reached by the channel (Low sediment supply scenario)

6.1.2 Discussion of the Long-term Predictions (Low Sediment Supply Scenario)

The salient results are show graphically in figures 6.1-6.3. These figures show the result of deposition in the impoundment over a 50 year period under the low sediment scenario. All graphs showing elevation values are referring to model elevations and not ordnance datum, however model datum can be related to ordnance datum by adding 4.951m to all model elevations.

6.1.2.1 Cross-sectional Results

Figure 6.1 (a-f) shows six different cross-sections through the lower 2km of the impoundment, just upstream from the barrage (Figure 6.2 c shows the position of each in the impoundment). The first node, s1, is situated by the barrage and shows a large amount of deposition over 50 years, in comparison to the two nodes upstream. This would be expected as the nodes just upstream from the barrage should be influenced strongly by the ponding effect of the barrage and as such should attract sedimentation. However, the fact that the two nodes upstream show 10% of the deposition experienced at node s1 it is necessary to investigate the difference. Sediment transport in the lower regions of the impoundment is computed using by the Westrich-Jurashek equation (Equation 5.14 previously introduced in Chapter 5 section 5.5.1) as this equation predicts the movement of the fine particles in ISIS, and it is these are still carried and re-entrained by the flow at the lower end of the impoundment.

$$G = K\frac{0.0018SV^2Wh}{(s-1)V_s}$$

Equation 5.14

Where, S is the water surface slope, V is the velocity of the water, h is the water depth, W is the top width of the flow, s is the specific gravity of the sediment and V_s is the settling velocity of the particle.

Investigating this equation it is obvious that the sediment transport is being controlled by: the velocity of the water, the water surface slope, the depth of the water, the top width of the water and the sediment settling velocity at each cross-section. The settling velocity of the particles is held constant throughout the run, thus the large amount of deposition observed at cross-section must be due to the cross-section geometry, the velocity of the river and the water surface slope. Firstly, the water surface slope has a large amount of influence on the cross-section's behaviour, as node 1 is just upstream of the weir. Therefore the varying gate heights effect the water surface slope at this position resulting in negative water surface slopes which can lead to more deposition. The influence of water surface slope is discussed further when analysing figures 6.3 a. and b. The velocity of the water at each node is partly controlled by the shape of the cross-section, this is especially true as the model utilised is a one-dimensional model and thus the flow equations are area-averaged. Consequently, when analysing the amount of deposition predicted at each node it is important to remember that this is dictated, largely, by the shape of the cross-section itself.

In the case of node s1, it is clear from Figure 6.1a that the cross-section is narrow and deep. Due to the fact it is narrow it would be fair to expect a small amount of deposition as there is less space for the water to flow in, however because it is almost a metre deeper than the two nodes upstream the velocity reduces through this section. If this is then considered in conjunction with the water surface slope being influenced heavily by the proximity of the barrage, it becomes obvious why a large amount of deposition is encountered at node s1.

Node s4 reports a large amount of deposition for a different reason. The node is situated around 400m from the barrage and as such is not affected as drastically by the barrage movements. Figure 6.1b demonstrates the reason why ISIS predicts a large amount of deposition at this point, as it is clear from the graph that the cross-section is very wide and quite deep in comparison to the two nodes upstream. As a result of this larger cross-section, the velocity of the water is predicted to decrease, which results in sediment being dropped out of suspension at node s4.

Figure 6.1c shows the predicted amount of deposition at node s6 and while it appears that there is only a small amount of deposition in metres, in terms of tonnes the amount of deposition is similar to that predicted at node s1. The apparent difference in terms of depositional depth is a function the sediment transport facility in ISIS.

ISIS calculates the amount of sediment being deposited at any one timestep as the difference between the out flowing sediment and the in flowing sediment at each cross-section. If the difference is positive then the cross-section is eroded, however if the difference is negative then deposition occurs. The deposition or erosion is calculated as a weight first, and then it is transferred into a depth by spreading the tonnage evenly over the whole node. This means that if there is a large distance between cross-sections the amount of deposition appears to be smaller when the depth is investigated, rather than the overall tonnage. The cross-section is shallow and wide in comparison to those upstream, which means that it should attract some deposition. Due to the change in channel geometry from the cross-sections upstream, the velocity drops quite considerably in cross-section s6 and this is the reason that deposition occurs.

In contrast, node s8 (Figure 6.1d) only predicts a small amount of deposition in terms of both depth of deposit and tonnage. The cross-section occurs in a relatively deep section of the river. The nodes downstream are all around one and a half metres higher (apart from node s1) whereas those immediately upstream are almost a metre deeper and affected by a bridge. This deeper part of the river is also narrower by approximately 45m, which in itself is justification for a bridge. However, it terms of sediment transport it means that the velocity is higher in these cross-section as the flow is confined to a very narrow, deep, channelised cross-section and as such minimal deposition occurs.

Cross-section s10, Figure 6.1e, shows a large amount of deposition. This node occurs just upstream from a bridge, which is situated at node s9 and is 200m downstream of node s10. ISIS models the effect of bridges, and consequently reproduces the backwater effect produced by bridge piers in a river. Therefore, this means that the sediment transport at node s10 will be affected by the backwater effect of the bridge as this influences the water surface slope at this node. This results in a flatter water surface slope, thus more sedimentation. In addition to this, cross-section s10 is of a similar depth to those upstream but 30m wider. Consequently the water suddenly has more room in which to flow and this results in a drop of velocity. This in turn means that sediment is dropped out of suspension and deposited. The tonnage of deposition reinforces the fact that a large amount of deposition occurs at this cross-section, unlike at cross-section s6, as the distance between cross-sections is similar to that of the surrounding cross-sections.

Unlike node s10, cross-section s13, shown in Figure 6.1f, only demonstrates a small amount of deposition in terms of depth, however investigating the tonnage shows that node s13 has double the depth of deposition found at node s8. The distance between cross-sections here is 260m, whereas the average distance between nodes through the lower section of the model is 160m. This results in a small depth of deposition being reported on a cross-section graph, however the true amount of deposition will become clearer on the long-sectional graphs of the impoundment. Cross-section s13 is sufficiently far from the bridge at node s9 to be unaffected by the backwater effect on the water surface slope. Consequently the channel geometry must be investigated as a means to explain the behaviour of velocity through the node. The velocity is relatively fast through this node, because the channel is shallow but not very wide therefore the flow is confined to flowing through a smaller area than just upstream resulting in a medium amount of deposition.

The cross-sectional graphs were presented to show how the amount of deposition, after 50 years, changes at particular cross-sections depending on how much sediment is fed in at the upstream end. This will be discussed further when all three sediment scenarios are compared in section 6.1.7. In addition to this it is also important to demonstrate how ISIS models sedimentation through the impoundment. ISIS is one-dimensional package and as such averages the flow equations over the area of the cross-section, resulting in only one value for the water height and velocity at each node. This information is then required to run the sediment package, but with only one value for each variable per cross-section, it means that only one volume of deposition or erosion can be calculated for each cross-section per timestep. Consequently, a volume of erosion or deposition is calculated for each node and then the sediment is distributed over the whole cross-section area, which is defined by the area of cross-section underwater multiplied by the distance between cross-sections. Within ISIS there are 3 different methods for distributing the sediment over the cross-section, the first involves raising or lowering the whole cross-section and is the method which results in the quickest run times, while the second method updates the regions of the section that are under water only. The third method uses a function to spread the deposition which is related to the local depths of flow. Method 3 was used for the River Tees, so that sediment was deposited in the body of the cross-section and at the edges of the river. From the cross-sectional graphs it is obvious that deposition is occurring over the whole cross-section. In comparison to a two or three-dimensional model the distribution of sediment by ISIS is not as accurate, however the runs took no longer than one day to complete and as such made ISIS a viable model to use.

For each set of results presented these cross-sectional graphs will be shown, however although the amounts of deposition will change, the overall processes will remain the same. A discussion each time would be repetitive, so there will only be a small discussion of the cross-sectional results for other sediment supply scenarios.

6.1.2.2 Longitudinal-sectional Results

Figure 6.1g shows the full long-section through the River Tees model, starting from Low Moor at chainage 0m at the top end, down to the barrage at the lower end of the model. The deepest points of each cross-section are plotted on the graph to give an idea of the amount and position of erosion and deposition occurring through the impoundment. A snapshot of the water surface at one particular timestep is included in the graph and shows the depth of water through the impoundment at one particular time. The water level for the snapshot is held at -2.55m at the barrage, which is well within the bandwidth allowed, although does indicate it is a low flow situation. The water heights allowed in the model are between –2.1m and –2.6m which translates to between 2.35m and 2.85m AOD (which is allowed by British Waterways on the Tees itself). The purpose of including the water level on the long-section is firstly to show how far upstream the backwater effect of the barrage is felt. Additionally, it shows the depth of water that is held in the impoundment, which is especially important for the lower reaches. This depth of water explains why the bed is not smoothed entirely over the fifty year simulation period. The original surveyed cross-sections, when plotted as a long-section using the lowest points of the channel against the chainage, show a large variability in depth through the impoundment. It would be expected in a river that over a period of time the lumps in the riverbed would eventually become smoothed out over a period of time, as the sediment in the shallow sections would become eroded and then deposited into the deeper cross-sections. However this does not happen in the case of the Tees as the water level is held too high to make any impact on the variability of the channel depths, although deep holes are filled in over a period of time. This shows that deposition occurs where velocity drops considerably.

Figures 6.2 a-c show the overall long section divided into three different graphs; where fig 6.2 a shows the upper 10km, fig 6.2 b shows the middle 10km and figure 6.2 c shows the lower 5km of the River Tees model in more detail. These figures highlight important areas of erosion or deposition through the impoundment. Figure 6.2 a, details the top 10km of the model. For the first 4km of the model, the water surface level is unaffected by the barrage 20km further downstream. This results in areas of erosion being identified over the 50 year simulation. However, 4km downstream from Low Moor the water surface becomes influenced by the effect of the barrage. The backwater effect of the barrage changes the water level, keeping the water surface artificially high. Where this change in water surface level occurs, sedimentation begins to happen. An idealised test model was constructed for the river Tees to investigate the possible processes at work. This identified the possibility of the progression of a fan or delta of deposition moving downstream over time occurring just downstream of the end of the backwater effect from the weir (discussed further in section 5.7.2). The area of deposition found at 6km downstream from Low Moor can be attributed to this phenomenon. The coarser sediment is dropped out of suspension in this area of the model. The flow can no longer carry the heavier sediments due to the lower velocity that occurs as the depth of water deepens towards the barrage.

Figure 6.2 b shows the details of the sedimentation patterns through the middle 10km of the impoundment. This graph highlights the area around the Yarm Bridges, which appears to remain unaffected by sediment deposition, according to the prediction. This will mean that previously predicted flood levels in this area should remain unaffected, however the flood levels may still be affected by the sedimentation occurring downstream towards the barrage. The Environment Agency continually monitors and investigates water levels at Yarm, as this area has been prone to flooding. The River Leven confluence is highlighted on the graph at chainage

1300m and causes very little immediate effect on the behaviour of sediment in the river. No appreciable areas of deposition are experienced immediately upstream or downstream of the confluence. However there is an area of sedimentation that occurs at chainage 15500m. The deposition occurs as the velocity slows at this particular cross-section, which is a result of the sudden widening of the river by 30m at this cross-section. The river then returns to a similar width to the cross-sections upstream, from this point. In addition to this, at chainage 18900m there is a large dip in the topography, where a hole in the riverbed can be observed. The bed falls from -9m to -14.5m in 600m, and then rises back to -8.5m in 400m. This hole in the topography causes a significant reduction in velocity through this cross-section, which results in a large amount of deposition occurring in this area. Over a period of time, this hole will be filled in with sediment until the cross-section reaches the size and shape that results in it reaching regime. This means that every cross-section through the river will keep being eroded or deposited until the cross-section reaches the desired shape, whereby most sediment remains in suspension as it travels through the impoundment and the sediment that is deposited or eroded, is replaced in times of heavy flood or drought.

Similarly, figure 6.2 c shows the bed evolution over 50 years of the lower 5km of the impoundment, which is directly upstream from the barrage. In this area, three bridges are modelled at chainage 22100m, 22500m and 23300m. A large amount of deposition can be observed at each of these points. This is a function of the ISIS sediment package. As has been previously mentioned, ISIS does not model scouring around bridge piers because it is a one-dimensional package and this is outwith its capability. To model local scour round the bridges it would be necessary to calculate more than one velocity component of the flow at this point by solving more than one momentum equation, this is not completed by the hydrodynamic package of ISIS and as a result this information can not be fed into the sediment package to calculate details. However, the modelling of bridges in ISIS means that the backwater effect caused by the bridge is modelled. This backwater effect influences the water slope making it flatter around these points, which in turn influences the amount of sediment transport that can calculated at these points. Thus, the sediment is dropped out of suspension around these bridges, and can over-predict the amount of deposition occurring. To investigate each bridge further it is necessary to analyse the shape of each cross-section. The first bridge, situated at chainage 22100m, is built in a particularly deep section of the river. The velocity of the water drops at this point as the water has more area in which to flow; this results in sediment dropping out of suspension and becoming deposited. So some sedimentation would occur here even if the bridge was either; not modelled, or modelled more realistically, allowing for local scour. Conversely, the bridge situated at chainage 22500m is constructed in a shallow area of the river, although the width of the node is 20m larger than those nodes upstream and downstream. The amount of deposition predicted around this bridge may be over-predicted because the scour is not being accounted for around the bridge despite the fact the water surface slope is being modelled realistically. The water surface level in this area of the impoundment is so high that it does not affect the variability in the bed level. The riverbed is not levelled out by the water surface level, which means that deposition can occur even in shallow areas. The bridge that is closest to the barrage is situated at chainage 23300m. This bridge has been built in a relatively deep, narrow area of the river and as such the velocity slows in this section and causes deposition, however it affects the node upstream more drastically than at the bridge itself. Node s10 was discussed when analysing the cross-sectional graphs. The deposition pattern here occurs because the river is wider and shallower upstream than at the bridge itself, and with the water surface slope being affected by the bridge, it means deposition occurs. Investigating the shape of node s10 shows why deposition occurs, the node has a large amount of cross-sectional area in comparison the node at the bridge and thus it attracts more sedimentation. Again if local scour around the bridge was modelled, less deposition would be observed, however as long as this is remembered when analysing the results it is possible to account for it.

6.1.2.3 Bed Evolution and Water Surface Slope Results

Figures 6.3 a and b show the evolution of the depth of deposit and the water surface slope over 50 years at two different nodes, s4 and s10 which have a similarly large amount of sediment being deposited. These graphs show the equilibrium that is occurring in the system over the 50 year period.

Figure 6.3 a shows the predicted deposition and water surface level occurring at node s4 over the 50 year simulation. Water surface level was plotted alongside the deposition rate, as it is one of the major controls on sedimentation in the impoundment. What is interesting to note is that after a period of 11000 days the deposition at this node starts to reach a dynamic equilibrium. Before this point high water surface slopes have very little influence on the rate of deposition that can be seen to rise gradually with time. However, once this depth of deposition has occurred the water surface slope starts to have an increased influence on the behaviour and speed of the deposition. Flatter water surface slopes start to erode some of the previously deposited sediments in conjunction with the steeper water surface slopes eroding more sediment than before. This has the effect of creating a type of dynamic equilibrium at this node because while deposition continues to occur the increased influence of the water surface slope results in the limiting of the deposition rate. This equilibrium can be observed at other nodes too, which can then be interpreted to mean that the system is reaching a dynamic equilibrium, or reaching regime.

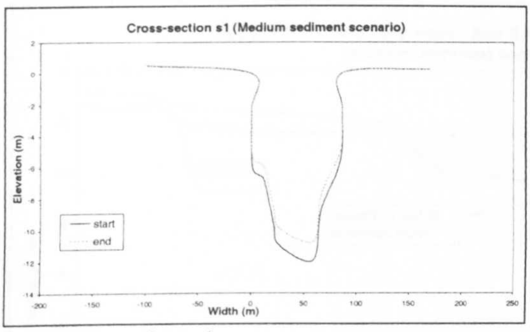
Figure 6.3 b shows the same information for node s10. This graph indicates that the same dynamic equilibrium is being reached at node s10. While the water surface is generally flatter at this node because it is further from the barrage and just upstream from a bridge, a similar trend can be observed. Initially the deposition accrues steadily, with very little erosion, until 11000 days into the simulation. Whereupon, the water surface slope begins to influence the behaviour of the sedimentation process more strongly. Again flatter water surface slopes are beginning to control the erosion of sediment in conjunction with the steeper water surface slopes eroding a larger depth of sediment than before this point. A dynamic equilibrium can be observed, in terms of the sedimentation, at both nodes s4 and s10. This dynamic equilibrium can be observed to occur through the impoundment, at a similar point in the simulation. However the depth of deposition at which this occurs depends on the sediment inflow to the impoundment and the particular situation and geometry of each cross-section. Therefore each cross-section, while showing a similar trend, will have different characteristics and report differing initial deposition rates and overall depth of deposition. The graphs displayed in figure 6.3 a and b show that the impoundment is reaching an equilibrium after 11000 days, which is equivalent to 30 years. The fact that this equilibrium can be observed within the simulated period shows that after 30 years the impoundment is beginning to settle down into a new regime, which includes the barrage. New sediment regimes can take many years to establish, however it appears that under existing climate scenarios and with low sediment input the impoundment, a new regime should be reached 30 years in the future.

These are the results of the low or normal sediment scenario runs under existing climate conditions. They show that over 50 years there is sediment being deposited in the impoundment and where it is being dropped. The areas in which sedimentation is being predicted have been analysed to ensure the model is providing realistic results. While the amount of deposition predicted in the impoundment is important, perhaps the most interesting point from this investigation is the discovery of a dynamic equilibrium in terms of sediment in the impoundment. If this is repeated with other simulations, it can be concluded that the impoundment reaches regime in around 30 years.

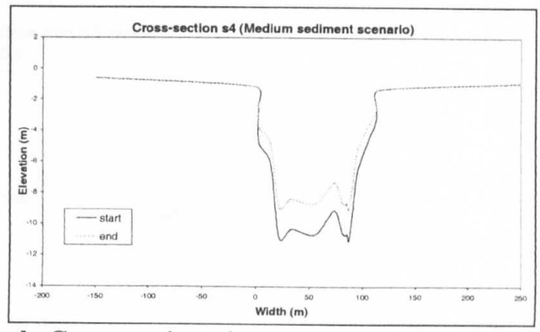
6.1.3 Results of Long-term Predictions (Medium Sediment Supply Scenario)

Another fifty year simulation was carried out using the same upstream flow boundary as for the low, or normal sediment supply scenario run. However this time a rating curve formed from the medium sediment supply scenario was used as the upstream sediment supply boundary condition. This means that while the flow of water into the model is held constant, the sediment input is increased in line with the medium sediment supply scenario. The results are shown graphically in figures 6.4-6.6.

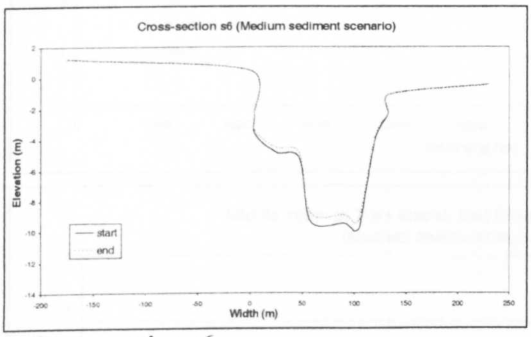
As a comparison to the low sediment scenario results the depths of deposition are presented for each of the cross-sectional nodes displayed in figure 6.4. Node s1, just upstream from the barrage, reports a deposition of 1.175m, which is approximately 20% more than for the low scenario. Similarly, node s4 and s10 both predict more deposition than for the previous simulation, recording a depth of deposition of 2.032m and 2.244m respectively. The nodes with a predicted lower overall deposition also record an increased of sedimentation after the 50 year simulation. Node s6 shows a deposition of 0.574m, while both node s8 and s13 report a predicted depth of 0.388m and 0.385m, respectively. These values are all considerably higher than those predicted for the normal or low sediment scenario.



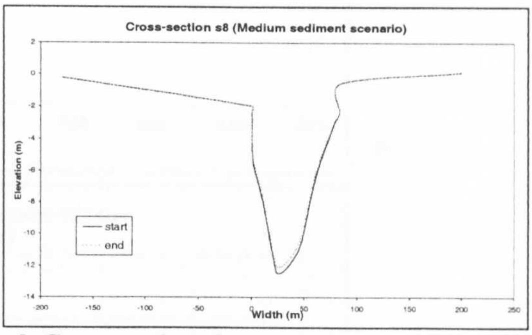
a. Cross-section s1



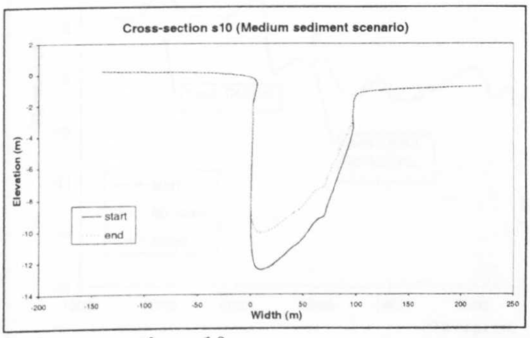
b. Cross-section s4



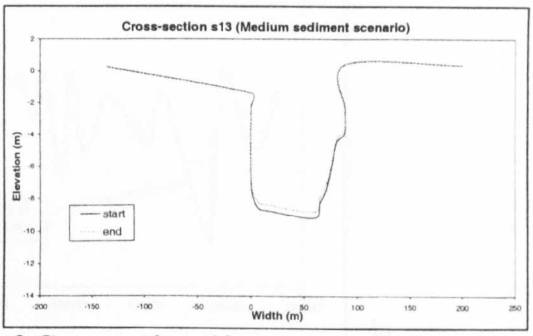
c. Cross-section s6



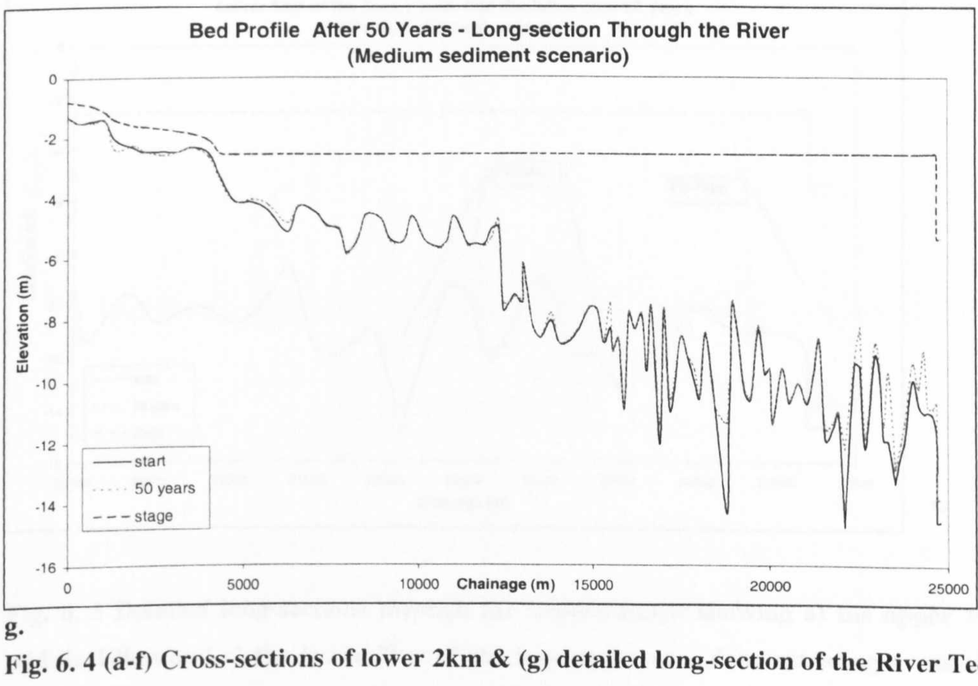
d. Cross-section s8



e. Cross-section s10

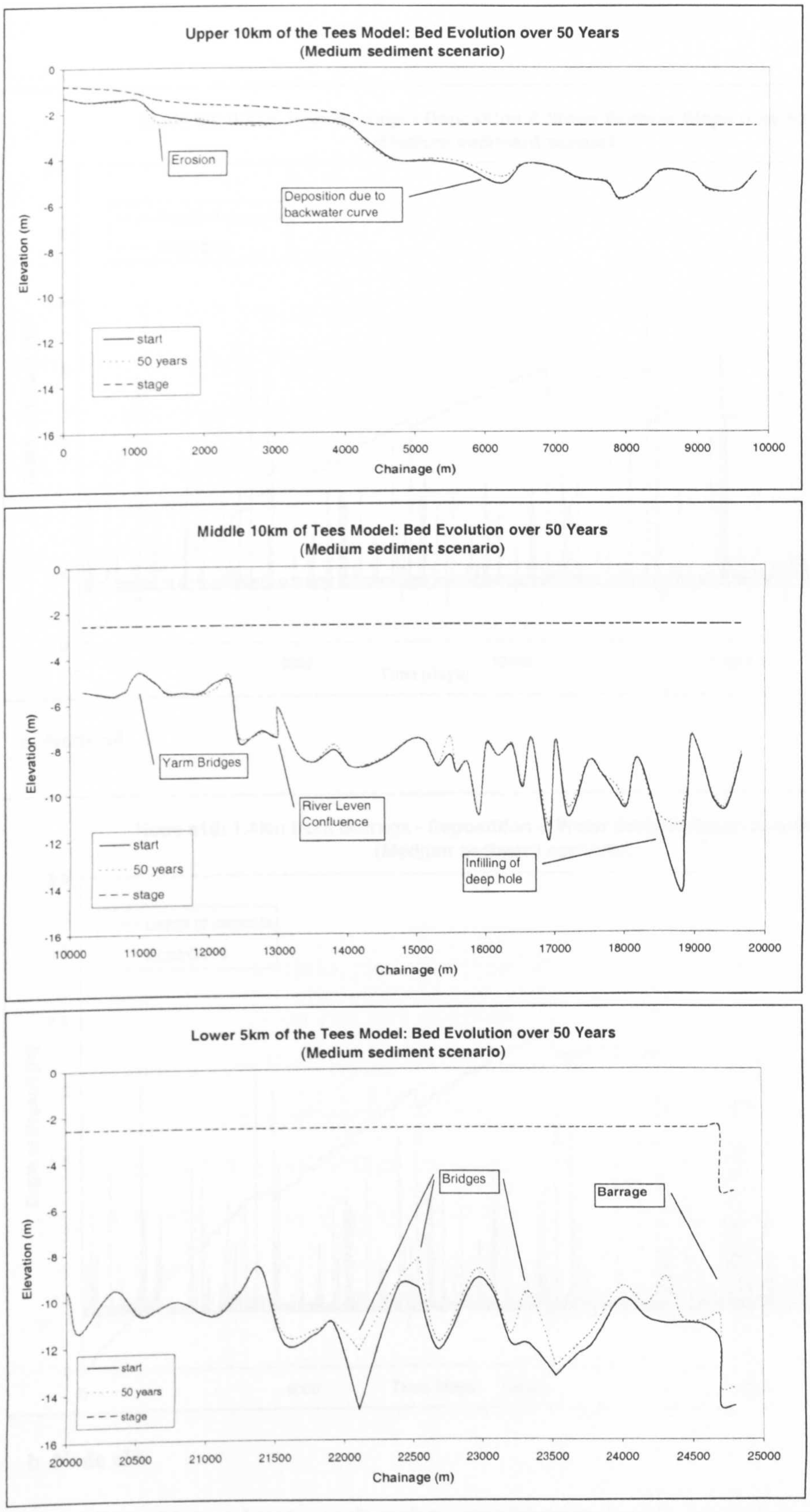


f. Cross-section s13



g.

Fig. 6. 4 (a-f) Cross-sections of lower 2km & (g) detailed long-section of the River Tees following 50 year simulation (Medium sediment supply scenario)

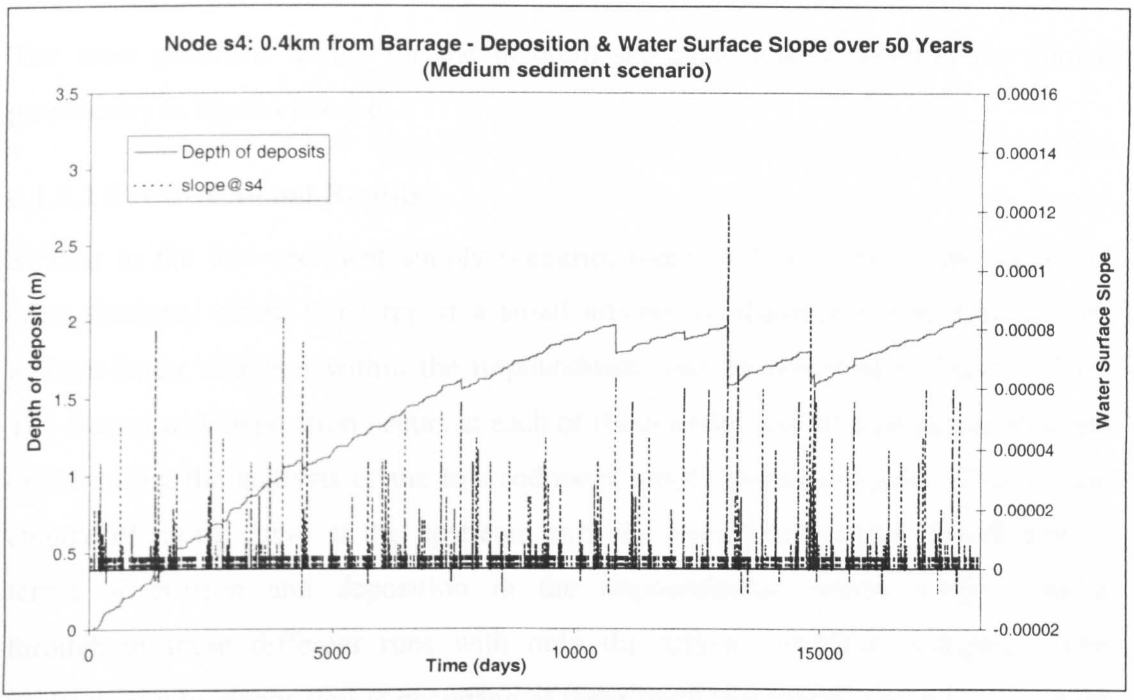


a.

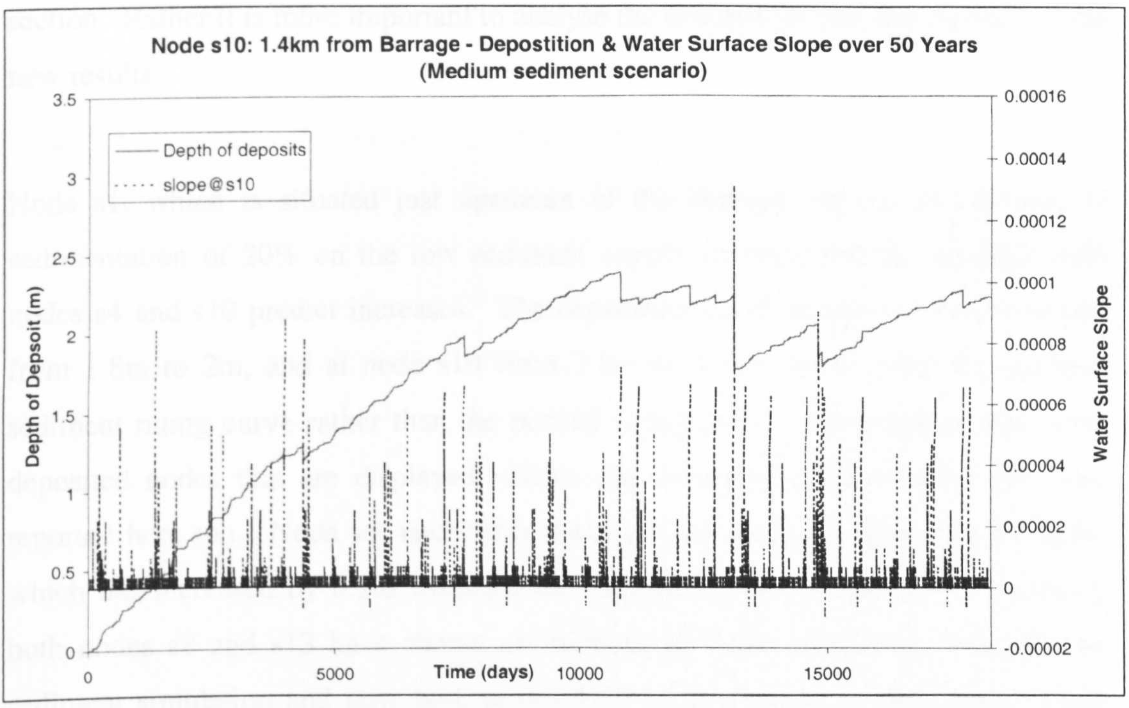
b.

c.

Fig. 6. 5 Detailed long-sections through the impoundment showing a) the upper 10km, b) the middle 10km and c) the lower 5km of the impoundment – demonstrating areas of deposition (Medium sediment supply scenario)



a. Node s4



b. Node s10

Fig. 6. 6 Deposition and water surface slope over 50 years at a) node s4 and b) node s10 showing the equilibrium being reached by the channel (Medium sediment supply scenario)

6.1.4 Discussion of Long-term Predictions (Medium Sediment Supply Scenario)

The most pertinent results for the medium sediment supply scenario are shown graphically in figures 6.4-6.6.

6.1.4.1 Cross-sectional Results

Similar to the low sediment supply scenario, figure 6.4 (a-f) shows the same six cross-sections, where three report a small amount of deposition and three a high amount (their situation within the impoundment can be observed in figure 6.2 c). The reason why deposition occurs at each of these nodes has been discussed in some detail during the analysis of the low sediment supply scenario results. Despite the change of rating curve at the upstream end, the overall behaviour of sediment in terms of erosion and deposition in the impoundment should remain similar throughout these different runs with only the inflow sediment changing. The analysis of why deposition is occurring at these particular points has been discussed and is considered realistic, thus it is not necessary to re-discuss these details in this section. Rather it is more important to analyse the differences and significance of the new results.

Node s1, which is situated just upstream of the barrage, reports an increase of sedimentation of 20% on the low sediment supply scenario results, similarly both nodes s4 and s10 predict increases. The deposition depth at node s4 has increased from 1.8m to 2m, and at node s10 from 2.1m to 2.25m when using the medium sediment rating curve rather than the normal rating curve. Investigating the lower deposited nodes that are displayed, shows that increased sedimentation has been reported here too. Node s6, under this scenario, has shown a deposition of 0.6m, which has increased by 0.1m from the low sediment supply simulation. Similarly both nodes s8 and s13 have shown an increase of 0.1m deposition from the low sediment simulation and now both report 0.4m of deposition at each node. From these results it is clear that under a higher sediment inflow prediction, the impoundment traps more sediment, although whether it is a greater percentage of the inflow sediment will be investigated further when all three sediment scenarios are analysed in section 6.1.7. Thus, if the sediment concentration is higher, more deposition occurs through the impoundment, but this deposition appears to occur in similar places to predictions under a lower sediment concentration.

6.1.4.2 Longitudinal-sectional Results

Figure 6.4 g shows the full long-section through the River Tees model, starting from Low Moor at chainage 0m, down to the barrage at the lower end of the model. Similar to figure 6.1 g, a snapshot of a typical water depth during the simulation has been included to emphasise the depth of water in the impoundment. This is important as it helps explain why the topography of the riverbed undulates widely and is not predicted to be smoothed over the passage of time according to the simulation. This is partly because the water is rather deep and the gradient too flat to cause erosion in the lower part of the river. Instead the morphology of the river is changing in relation to the cross-section geometry and local hydraulic conditions at each point. The full long-section shows that although more deposition is reported for this scenario, rather than the normal scenario, the shape and distribution of the deposition remains largely unchanged. Similar cross-sections are experiencing erosion or deposition, however the magnitude of the depth of deposition is altered.

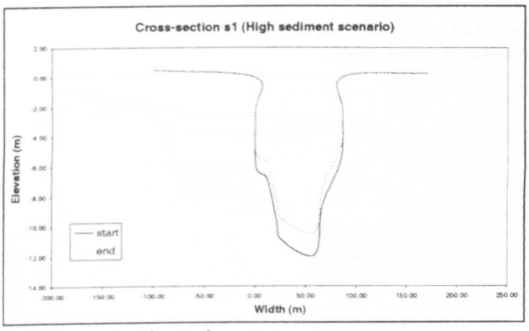
Figures 6.5 a-c show the overall long-section split into three separate graphs. Figure 6.5 a shows the upper 10km of the impoundment, from Low Moor downstream. Figure 6.5 b represents the middle 10km of the Tees while figure 6.5 c details the lowest 5km of the impoundment, just upstream of the barrage. These three figures again highlight the important areas of sedimentation or re-sedimentation through the impoundment.

Figure 6.5 a shows areas of deposition, which are a direct result of the backwater curve from the barrage. It is in this area that the effect of the barrage ceases to be felt by the river. Upstream of chainage 4000m the river flows unchecked, no ponding effect on the water from the barrage can be seen. Erosion occurs upstream of this point, and downstream as the water slows due to the effect of ponding, sediment is deposited. The amount deposited here is again larger than that predicted under the low sediment scenario. However, similar to the low sediment scenario, figure 6.5 b shows no appreciable deposition around Yarm bridges and the River Leven confluence but it does indicate that there is a larger amount of deposition at chainage 18900m. This deep hole acts as a sediment trap, and logically if there is more sediment in the system then more deposition will occur in this area. What is interesting to note is that just upstream of this hole, some of the deeper sections are beginning to attract increased deposition, which is less evident for the low sediment scenario. This is a direct result of feeding more sediment into the same system at the upstream end. Figure 6.5 c details the lower 5km of the impoundment, where the model predicts most sedimentation under any scenario. Increased sedimentation is evident around the bridges, which indicates that the increased sediment at the upstream end is finding its way to the lower end of the model over the fifty year simulation. Deposition is building up in the lower 5km of the model, and it is at this point in the model that the increased sedimentation is most obvious

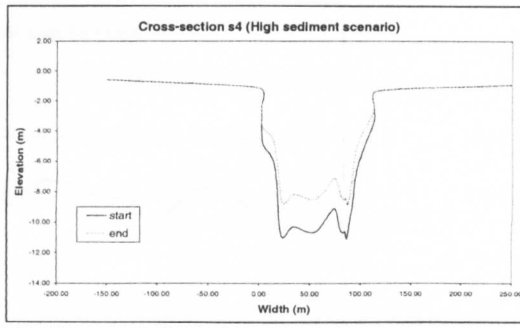
6.1.4.3 Bed Evolution and Water Surface Slope Results

Figures 6.6 a and b show the evolution of the deposition over the fifty year simulation, along with the water surface slope over the same period. If these graphs are compared to figures 6.3 a and b from the low sediment scenario results, the increase in deposition can be observed over the simulation. What is striking about these results is that a dynamic equilibrium is occurring at a similar point in time for both medium and low simulations. This may be partly due to the fact that both simulations use the same hydraulic upstream boundary and the ordering of storms controls the bed this way. Although increased deposition in the river will effect the behaviour of the water surface slope over a period of time, which will result in pushing the water surface slopes to a higher gradient than before. However, it seems more likely that the river is reaching a dynamic equilibrium, which is controlled by both the amount of inflowing sediment and the hydraulic conditions rather than simply the hydraulic conditions. The behaviour of node s4 and s10 shows that after a period of continual accretion the bed starts to respond to the hydraulic conditions more voraciously. The water surface slope begins to influence the behaviour of the sediments and flatter water surface slopes start to erode previously deposited sediments maintaining a particular depth of sedimentation. This depth appears to be linked to the amount of sediment flowing into the system. Practically this means that the river will experience a different sediment regime, depending on the amount of sediment reaching the impoundment each year. This seems sensible as the new regime of a river is dictated by both the flow and sediment inflow to the river each year. This phenomenon will be discussed further after the results of the high sediment scenario have been presented and all three set of results can be compared.

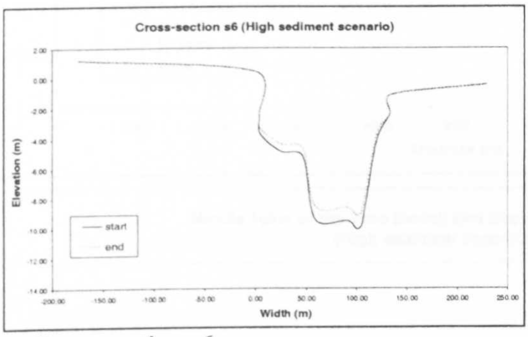
The results of the medium sediment scenario have been presented and they show that the pattern of distribution is largely the same as that predicted for the low sediment scenario. However, there have been some notable differences. Firstly some areas of appreciable deposition can be observed after the medium simulation that showed either, minimal or, no deposition after the low sediment scenario. This is due to the increased sediment inflow for this run, which affects the concentration of suspended sediments in the water and causes sediment to drop out of suspension in new areas. Overall more deposition, throughout the impoundment, was observed after the medium sediment scenario run, which is a direct result of increasing the sediment load to the system. Finally, evidence points towards a dynamic equilibrium being reached by the impoundment at the same point in time as predicted during the low sediment simulation. While the point in the simulation at which this occurs is maintained, the predicted depth of deposition is increased in the medium simulation. This shows that the new sediment regime for the river is heavily dependent on the sediment inflow at the upstream end.



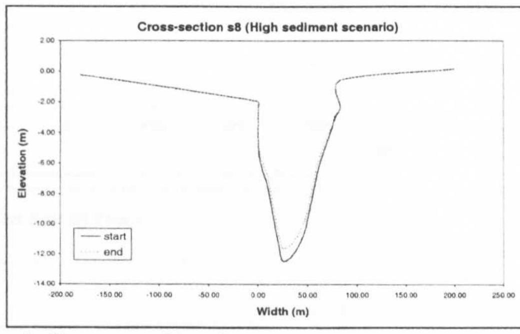
a. Cross-section s1



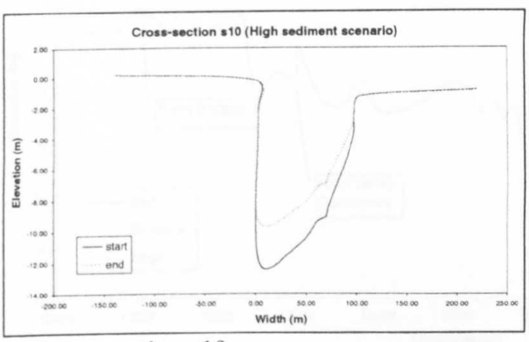
b. Cross-section s4



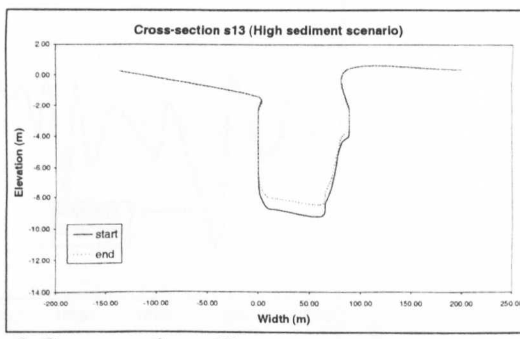
c. Cross-section s6



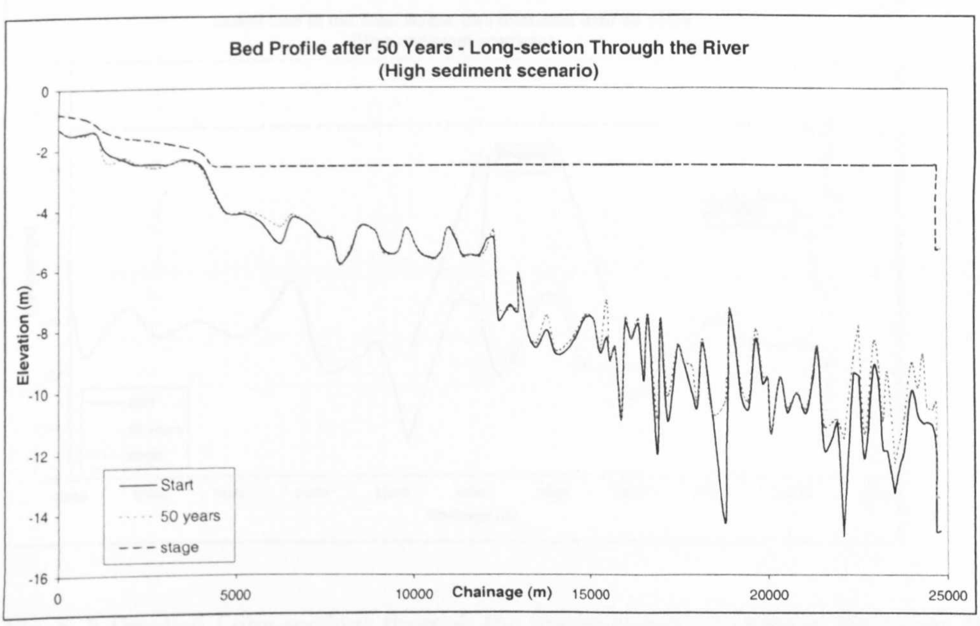
d. Cross-section s8



e. Cross-section s10



f. Cross-section s13



g.

Fig. 6. 7 (a-f) Cross-sections of lower 2km & (g) detailed long-section of River Tees following 50 year simulation (High sediment supply scenario)

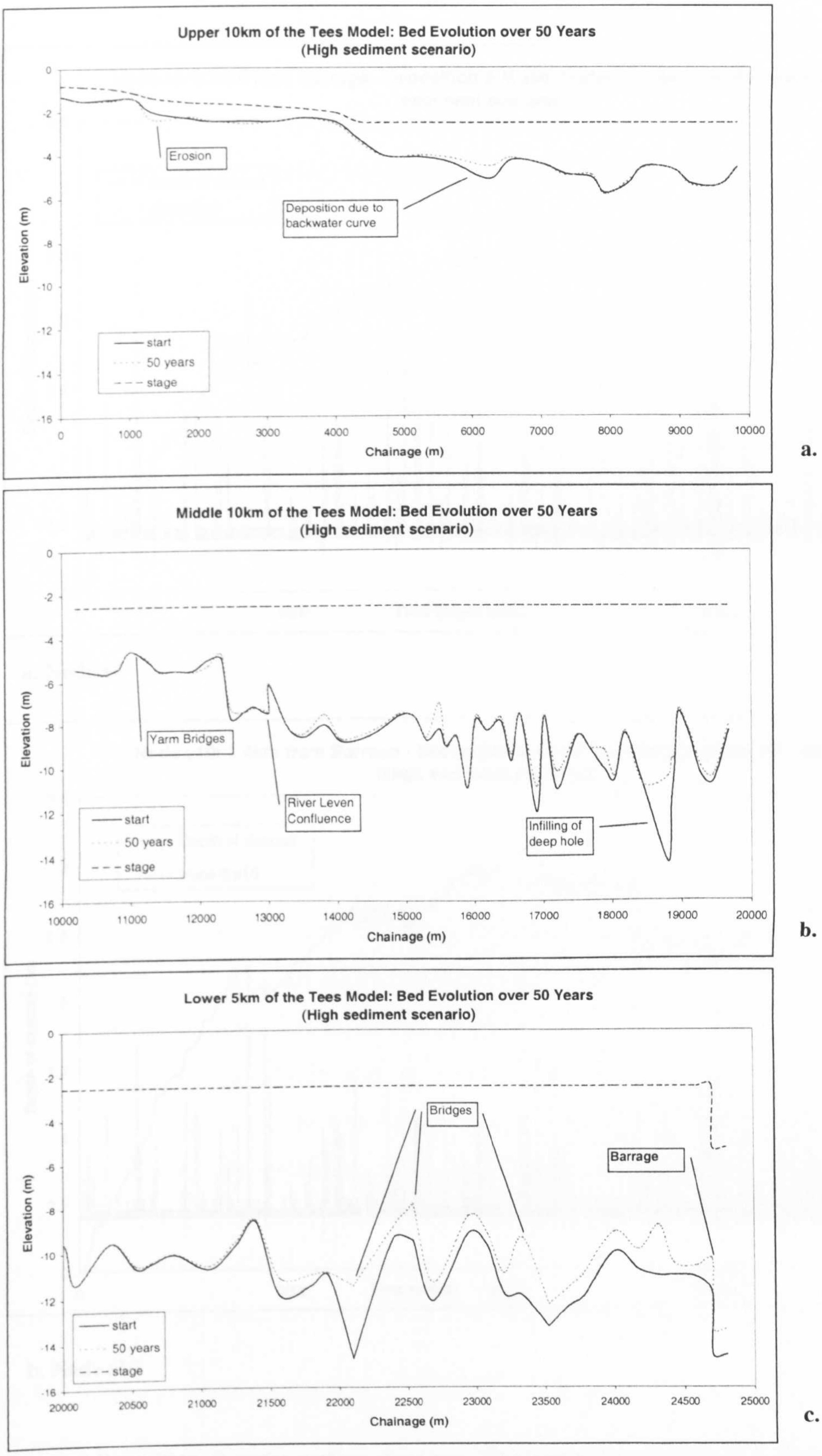
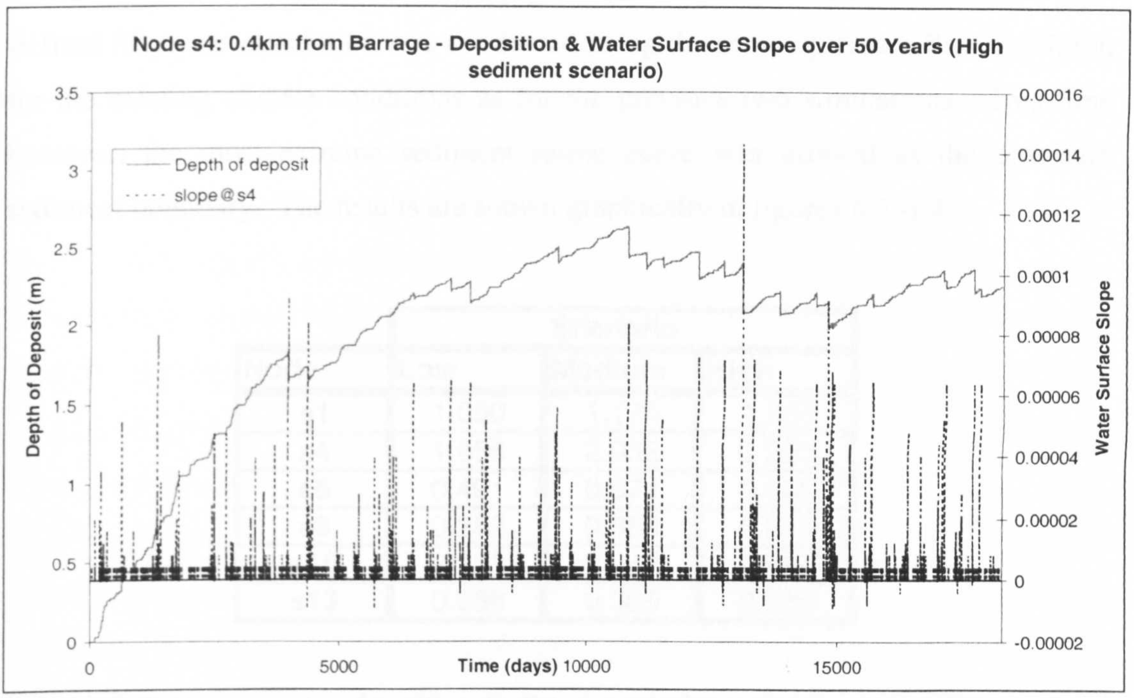
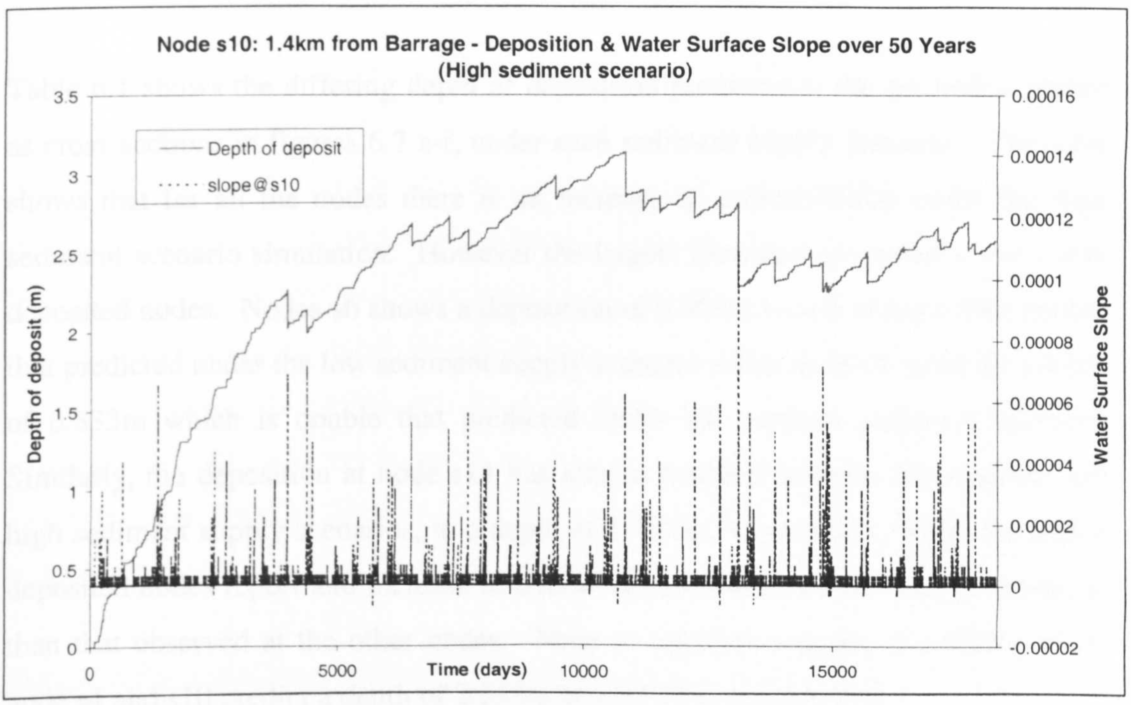


Fig. 6. 8 Detailed Long-sections through the impoundment showing a) the upper 10km, b) the middle 10km and c) the lower 5km of the impoundment - demonstrating areas of deposition (High sediment supply scenario)



a. Node s4



b. Node s10

Fig. 6. 9 Deposition & water surface slope over 50 years at a) node s4 and b) node s10 showing the equilibrium being reached in the channel (High sediment supply scenario)

6.1.5 Results of Long-term Predictions (High Sediment Supply Scenario)

A final fifty year simulation was conducted using the same upstream flow condition for the existing climate conditions as for the previous two simulations. This time however, the most extreme sediment rating curve was utilised as the upstream sediment boundary. The results are shown graphically in figures 6.7-6.9.

	Scenario		
Node	Low	Medium	High
s1	1.060	1.175	1.528
s4	1.856	2.032	2.255
s6	0.491	0.574	0.908
s8	0.282	0.388	0.833
s10	2.133	2.244	2.577
s13	0.288	0.385	0.780

Table 6. 1 Table comparing deposition depths at particular nodes for each sediment supply scenario

Table 6.1 shows the differing depth of deposition predicted at the six nodes, shown as cross-sections in figures 6.7 a-f, under each sediment supply scenario. The table shows that for all the nodes there is an increase of sedimentation under the high sediment scenario simulation. However the largest increases are noted at the lower deposited nodes. Nodes s6 shows a deposition of 0.908m which is more than double that predicted under the low sediment supply scenario while node s8 predicts a depth of 0.833m which is double that predicted under the medium sediment scenario. Similarly, the deposition at node s13 has almost doubled between the medium and high sediment supply scenarios, to a depth of 0.780m. Conversely, while the highly deposited nodes report and increase in overall deposition it is much less pronounced than that observed at the other nodes. Node s1 predicts a depth of 1.528m, while node s4 and s10 predict a depth of 2.255m and 2.577m, respectively.

6.1.6 Discussion of Long-term Predictions (High Sediment Supply Scenario)

All the salient graphical results for the simulation under the high sediment supply scenario can be found in figures 6.7-6.9

6.1.6.1 Cross-sectional Results

Similar to the two previous sediment scenarios, figures 6.7 (a-f) show the same six cross-sections from the lower 2.5km of the impoundment (Figure 6.2 shows where the cross-sections are situated within the impoundment). The mechanics of the deposition was discussed in section 6.1.2 during the analysis of the low sediment scenario results and were deemed sensible. This need not be repeated as the reasons for deposition at each node stay the same with only the amount of sediment at the upstream end being changed. What is interesting to note from figures 6.7 (a-f) is that under the high sediment supply scenario, increased sedimentation is observed at each node displayed. This reinforces the hypothesis noted in section 6.1.4 that under higher sediment inflows the impoundment traps more sediment. Thus if the sediment concentration is higher, more deposition occurs through the impoundment, but this deposition appears to occur in similar places to the predictions under both the low and medium sediment scenarios.

6.1.6.2 Longitudinal-sectional Results

This hypothesis is further reinforced by figure 6.7 g, which shows the full long-section through the River Tees model. This shows the relative areas of erosion and deposition through the impoundment. From the graph, it can be seen that although more deposition is being predicted over the 50 years, the positions in which it is building up are predominantly the same as in the previous scenarios. Some new areas are beginning to attract deposition, where in other scenarios there have been none. This is due to the fact that the flow is carrying increased sediment for each scenario while the transport power of the flow remains similar through each scenario. Therefore new areas of sedimentation form progressively for each scenario, as the sediment must be deposited through the impoundment.

Figures 6.8 a-c show the long-section through the impoundment split into three more detailed graphs, with the first showing the upper 10km of the impoundment, the second showing the middle 10km and last detailing the lower 5km. Figure 6.8 a highlights the sediment movement at the top of the modelled impoundment, where the effect of the barrage on the water surface level first becomes evident. The effect of the backwater curve from the barrage on deposition is increased under the high sediment scenario with the predicted deposition, occurring at 6000m, almost doubling from the medium sediment scenario. Conversely, the erosion reported at the upstream end of the model, between chainage 0 and 4000m, shows very little change between all three sediment scenarios. Figure 6.8 b details the sediment behaviour through the middle 10km of the impoundment, which includes the area around the Yarm bridges and the Leven confluence. Similar to the previous scenario results, virtually no sedimentation is predicted around the Yarm bridges and the Leven confluence. However downstream from this point increased sedimentation begins to occur, which is a direct result of the increased concentration of sediment being carried in the river for this scenario. Around chainage 17000m deposition in deep areas can be observed. This deposition has almost doubled from the amount predicted by either the low or medium scenarios. In addition to this more sedimentation can be observed around the deep hole at chainage 18900m. Figure 6.8 c shows the lower 5km of the Tees impoundment. Here it is very evident that there is an increased amount of sedimentation. The first 2km of figure 6.8c shows that little or no deposition is occurring, which is similar to the previous two sediment scenarios. However, downstream from this section, an increased amount of sedimentation occurs, where nodes with a small amount of deposition from previous scenario simulations, show a marked increase in deposition, sometimes up to double the previous estimate. Conversely, those nodes previously recording high deposition rates under the earlier scenarios display a more muted response to the increased sediment load. This may be partly because the heavily deposited nodes are reaching regime under even the low sediment scenario and as a result increased sedimentation at the upstream end only influences the amount of sediment deposited slightly.

6.1.6.3 Bed Evolution and Water Surface Slope Results

Figures 6.9 a and b show the evolution of the deposition over 50 years, along with the water surface slope at two different nodes. If these results are compared to those presented in figures 6.3 a and b and 6.6 a and b, it is obvious that more sedimentation is being reported at both nodes than under the previous two scenarios. What is interesting to note from these results is that the point at which the channel settles down to regime is the same as for both of the previous two scenarios. Similar to the medium sediment scenario results it is clear that continual accretion occurs for the first 10000 days of the simulation. After that the channel can be said to be self stabilising, where the water surface slope begins to influence the behaviour of the sediments. Flatter water surface slopes start to sweep sediments away, where before they did not and water surface slopes, which already eroded, sweep more sediment out each time. This has the effect of counter balancing the continual sedimentation at each node, and brings a dynamic equilibrium to the system. However, while this regime appears in the channel after a similar amount of time for each scenario, the amount of sedimentation predicted at each node is increased depending on the sediment scenario used, which lends weight to the hypothesis that the position of the regime is linked to the inflowing sediment as well as hydraulic conditions. Practically, this means that the river will experience a different sediment regime, depending on the amount of sediment reaching the impoundment each year. This seems to be a sensible conclusion, as the sediment regime in the impoundment is controlled by both the flow and sediment inputs to the system.

The results for the high sediment scenario have been presented, and show that overall they follow the same pattern as those presented for the low and medium scenarios with increased sedimentation being evident in many areas. Some areas show deposition where previously, in the other scenario predictions, there had been none, but this is directly linked to the inflowing concentration of suspended sediments. The channel's sediment transport capacity will remain similar throughout each run, irrespective of the sediment concentration, therefore if more sediment is reaching the impoundment it make sense that more is dropped. Conversely, with more sediment being dropped out of suspension during low flow periods, it means that there is more sediment in the system to be swept out in periods of floods. This can be seen in the final two graphs, which show that the impoundment reaches regime even during the high sediment scenario.

6.1.7 Comparison of Long-term Predictions Under Present Climate Conditions

Since the results for each sediment scenario have been presented separately it is important to compare some of the salient results against each other to show the effect of large sediment loads reaching the impoundment.

The results presented in table 6.2 give an overview of the amount of sedimentation predicted in the impoundment under the three differing sediment scenarios. As more sediment is allowed to flow into the impoundment, more is permitted to deposit, although the overall percentage of the inflow sediment that remains retained by the impoundment drops as the inflowing sediment concentration increases. The low sediment scenario allows an average of 33000 tonnes of sediment into the impoundment every year, while the medium scenario permits an average of 44000 tonnes per year. The high sediment scenario allows an average of 92000 tonnes of sediment to reach the impoundment every year. If these figures are compared to the information provided in table 3.1 in chapter 3, it is simple to see how these values compare to the measured average annual sediment estimates on the Tees. The low sediment scenario is comparable to the HR Wallingford 1992 estimate for the average annual sediment yield, which is 35630 tonnes per year. Conversely, the high sediment scenario seems to be an extreme scenario reporting an average of 92000 tonnes per year reaching the impoundment. If this is directly compared to the sediment yield calculated by Durham University for the year February 2000 to January 2001 it can be seen that this predicted annual sediment yield is in fact not so extreme. The calculated value is 85598 tonnes, which in comparison to 92000 tonnes is relatively similar, however the 92000 tonnes is an average value for a year and is fed in every year for 50 years. The year 2000/2001 can be thought of as a unique or irregular extreme event (under present climate and catchment conditions) with the high sediment input being partially linked to the extreme runoff conditions in the catchment and may not necessarily become more frequent. Thus the high sediment scenario should still be thought of as the upper bound of possibility for the evolution of the channel in the future.

Supply Scenario	Inflow (tonnes)	Outflow (tonnes)	Deposited (tonnes)	Retained %
Low	1675636 (33000 tonnes/yr)	1533057	142579	8.51% (8.12%)
Medium	2225787 (44000 tonnes/yr)	2065253	160534	7.21% (6.99%)
High	4618494 (92000 tonnes/yr)	4377618	240876	5.22% (4.87%)

Table 6. 2 Summary of sedimentation results under existing climate conditions – retention rates for the second run are in brackets

Table 6.2 also details the sediment retention percentages as predicted by the second run to show that the sediment predictions shown here are reasonable. Each run is only one representative possible outcome for the morphological sustainability of the Tees, and a discussion on this can be found in chapter 4, section 4.2.2.

Figure 6.10 shows a comparison of the bed evolution at node s4 over the 50 year simulation with the three different sediment scenarios. The graph shows the depth of deposit against the time, thus comparing the prediction of depositional history for the same cross-section over 50 years. What is interesting to note is that, depending on the sediment concentration fed in at the upstream end, the depositional patterns are different. For all three sediment scenarios the deposition is predicted to accrete for the first 30 years, with only a few occasions where erosion occurs due to storms (which is especially evident in the high sediment scenario). However, each sediment

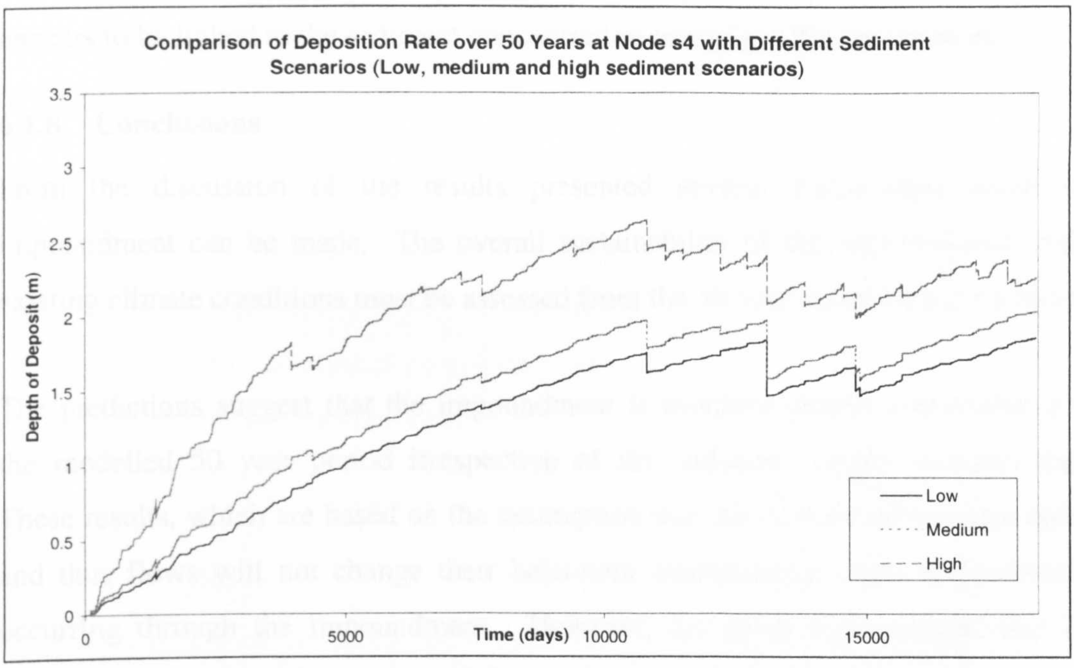


Fig. 6. 10 Comparison of deposition rate over 50 years at node s4 with three different sediment scenarios (low, medium and high) under existing climate conditions

scenario reports a different sedimentation rate over these initial years, with the high scenario showing the steepest gradient on the graph, thus indicating a faster accretion rate than the other scenarios. At the same point in time, each of the scenarios change behaviour, and appear to reach a type of dynamic equilibrium where the water surface slope starts to have a dominant influence on the deposition. The highest sediment scenario is most affected by the water surface slope throughout the simulation and reports several periods of large erosion, however it does show the change between constant accretion and dynamic equilibrium clearly. Smaller magnitudes of water surface slope start to have an increased effect on the sedimentation pattern and as such maintain the dynamic equilibrium of the channel. Accretion continues to take place between the occurrences of the new critical water surface slope, for all the scenarios, then the sediment is re-entrained during periods of high flows and the channel is considered to be in dynamic equilibrium. Towards the end of the simulation all three sediment scenarios appear to be tending to a similar value, although without extending the length of the simulation there is no way of telling whether the cross-section would attract the same amount of sedimentation irrespective of the input sediment. From the fifty year simulation it is only possible to interpret the predictions as they are presented, which point towards a dynamic equilibrium becoming established in the impoundment and that equilibrium appears to be linked to the sediment concentration arriving at the upstream end.

6.1.8 Conclusions

From the discussion of the results presented several conclusions about the impoundment can be made. The overall sustainability of the impoundment under existing climate conditions must be assessed from the 50 year simulation predictions.

The predictions suggest that the impoundment is morphologically sustainable over the modelled 50 year period irrespective of the sediment supply scenario used. These results, which are based on the assumption that the climate will remain stable and thus flows will not change their behaviour dramatically, show sedimentation occurring through the impoundment. However, the predictions suggest that the impoundment is reaching a type of dynamic equilibrium after 30 years with each cross-section becoming self stabilising, and this equilibrium does not appear to cause the impoundment to silt up. No one cross-section reports sufficient deposition to create unsightly mudflats. Therefore it is sensible to say that the impoundment is sustainable in terms of sediments for the next 50 years and seems to reach regime after 30 years. This regime is a function of the upstream sediment concentration reaching the impoundment. These results have been presented in a paper (Beevers et al. 2003), and some earlier findings were presented in Beevers & Pender 2001.

In addition, the early work on the Tees model must be remembered from Chapter 5 section 5.6. The sensitivity study showed that by averaging flows over 24 hour time periods rather than using 1 hour averaged flows, the prediction of retained sediment within the impoundment was over-estimated. Therefore, the long-term results can be considered to be conservative, thus adding weight to the hypothesis that in the medium to long-term the impoundment morphology will reach equilibrium.

The impacts on flooding, for the riparian landowners, of the sedimentation predicted has not been investigated in this study. Thus it is impossible to make a statement of the sustainability of the impoundment with respect to flooding. Further investigations requiring a more detailed model would be necessary. The survey and the resulting ISIS model were concentrated on reproducing the river channel in detail and did not include an assessment of the floodplains and banklines of the river. This was sufficient for investigating the sedimentation processes with regard to fluctuating flows over 50 years, however it is probably not suitably detailed to predict flood levels at particular points along the impoundment.

In conclusion, under the present climate conditions, using the different sediment supply scenarios, it is sensible to say that the Tees impoundment is sustainable with regard to sedimentation and shows no immediate signs of silting up. However it is not possible, with the present model, to make a statement regarding the long-term flooding prospects for the catchment

6.2 Results of Long-term Predictions Under Future Climate Conditions

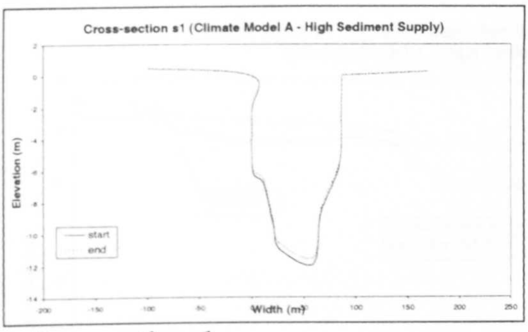
Chapter 4 describes in detail the creation of a multinomial logit model to link precipitation and temperature in the catchment to the flows in the River Tees. This allowed climate change predictions for temperature and precipitation from the Hadley Centre's RCM (for the period 2070-2100) to be used to predict flow in the River Tees under climate change. The period 2070-2100 was used as these were the only climate change predictions available, however the simulations were completed for 50 years similar to the previous simulations as this is considered an appropriate design life for the barrage. The temperature and precipitation data was then used to create two different flow boundaries for medium/high emissions and medium/low emissions. The flow boundary for the medium/high emissions has been used to give sedimentation results which are referred to as Climate Model A, while the medium/low emissions sedimentation results are known as Climate Model B. For more information on the climate change modelling work please turn to Chapter 4 section 4.3.1. Similar to the sedimentation predictions under no climate change, these predictions have been repeated twice to ensure their validity, however it must be remembered that these results are representative scenarios of the possible future outcomes for the impoundment. The sea level is assumed to be unchanged.

Firstly the results for Climate Model A will be presented. This climate scenario is the most extreme scenario and assumes the most change from present climate conditions. The results from Climate Model B will then be shown, which are a less extreme realisation of the possible future climate, however it still assumes that the climate will change. In each case only the results of the high sediment supply scenario are shown. Initially it was thought that climate change would increase the sediment retained in the impoundment due to the increased amount of sediment arriving in the impoundment, however analysis of the results showed that in fact the opposite was true. Therefore it is sensible to show only the most extreme sediment supply results as they give a conservative estimate of the amount of sedimentation building up in the impoundment when the flows have been adjusted to account for climate change.

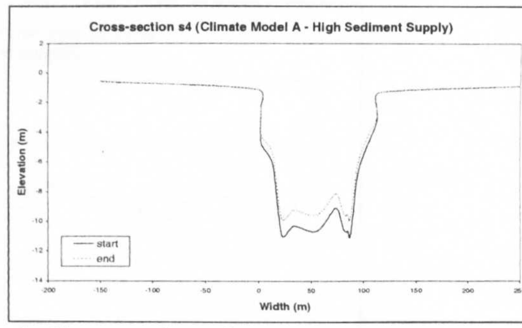
6.2.1 Climate Model A – Long-term Results (High Sediment Supply)

Climate Model A is used to describe the ISIS model which has the upstream flow boundary calculated using the precipitation and temperature predictions assuming medium/high emissions over the next 70-100 years (see chapter 4 for details). The model has been run three times using the high, medium and low sediment rating curves for the morphological input for the model. Only the results using the high sediment rating curve are presented here.

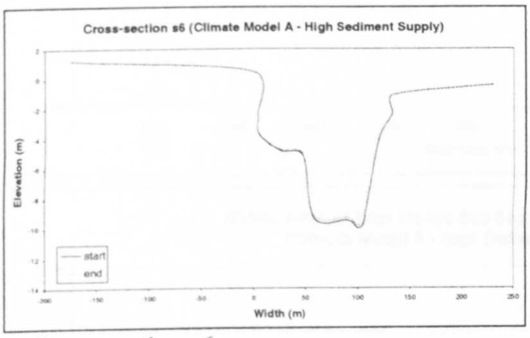
The results and the discussion are split into cross-sectional results from the lower 2km of the impoundment, longitudinal bed level changes for the impoundment, and the bed evolution and water surface slope at two particular nodes at the downstream end of the model.



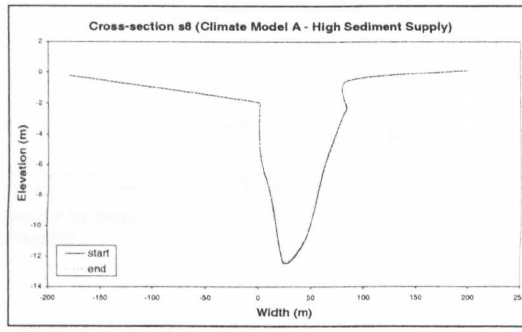
a. Cross-section s1



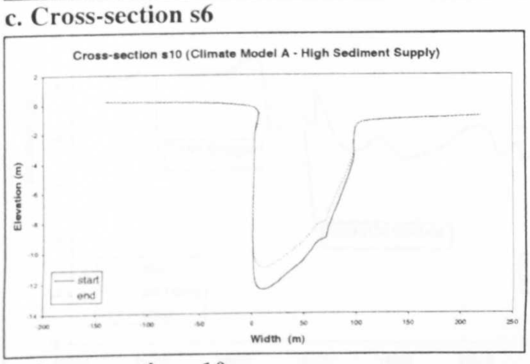
b. Cross-section s4



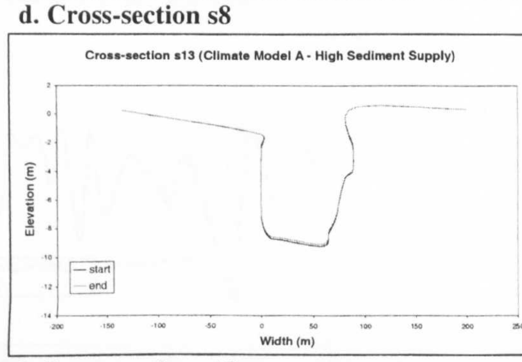
c. Cross-section s6



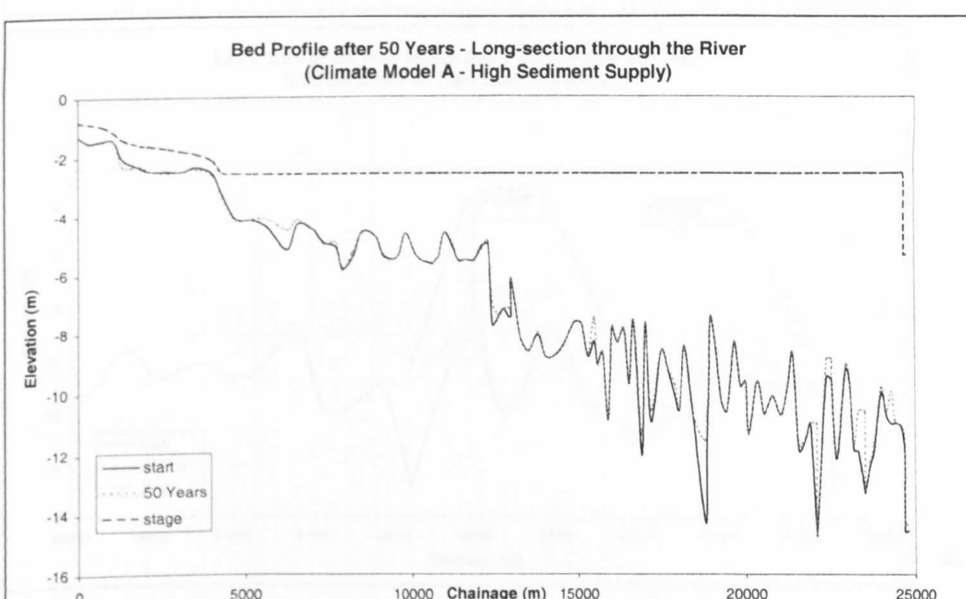
d. Cross-section s8



e. Cross-section s10

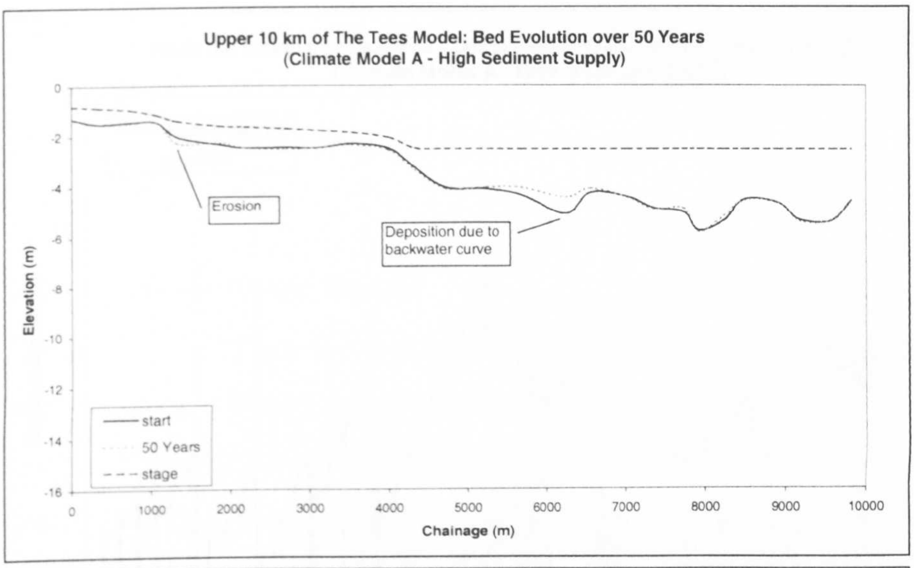


f. Cross-section s13

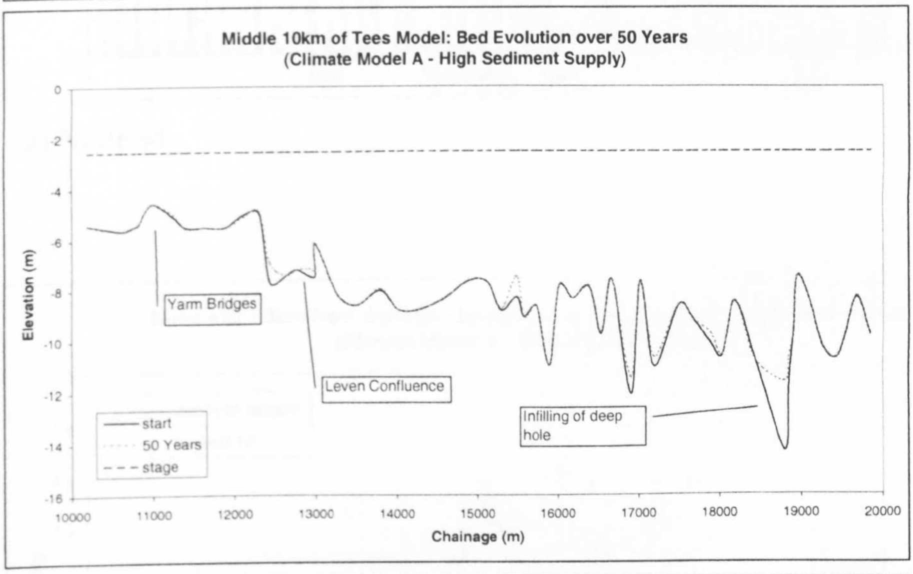


g.

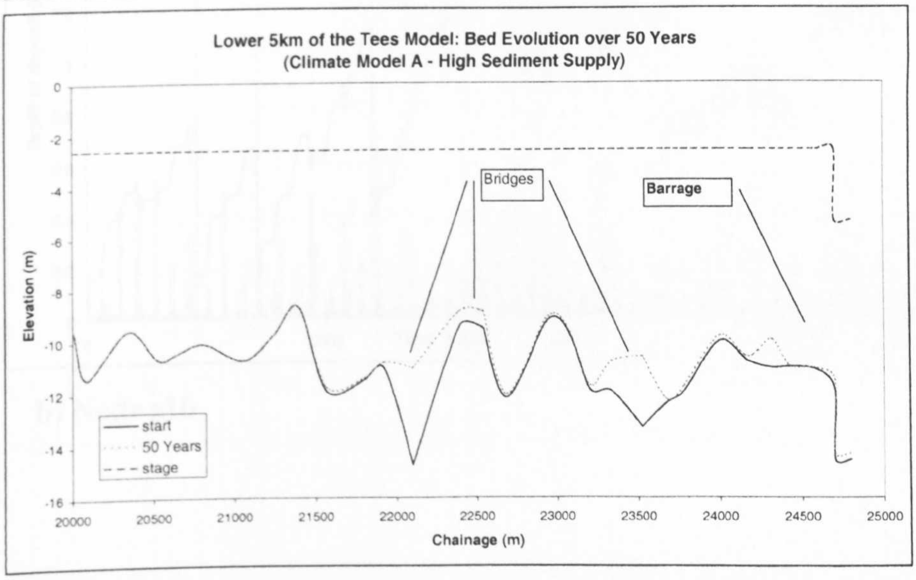
Fig. 6. 11 (a-f) Cross-sections of lower 2km & (g) detailed long-section of River Tees following 50 year simulation (Climate Model A - High Sediment Supply)



a.

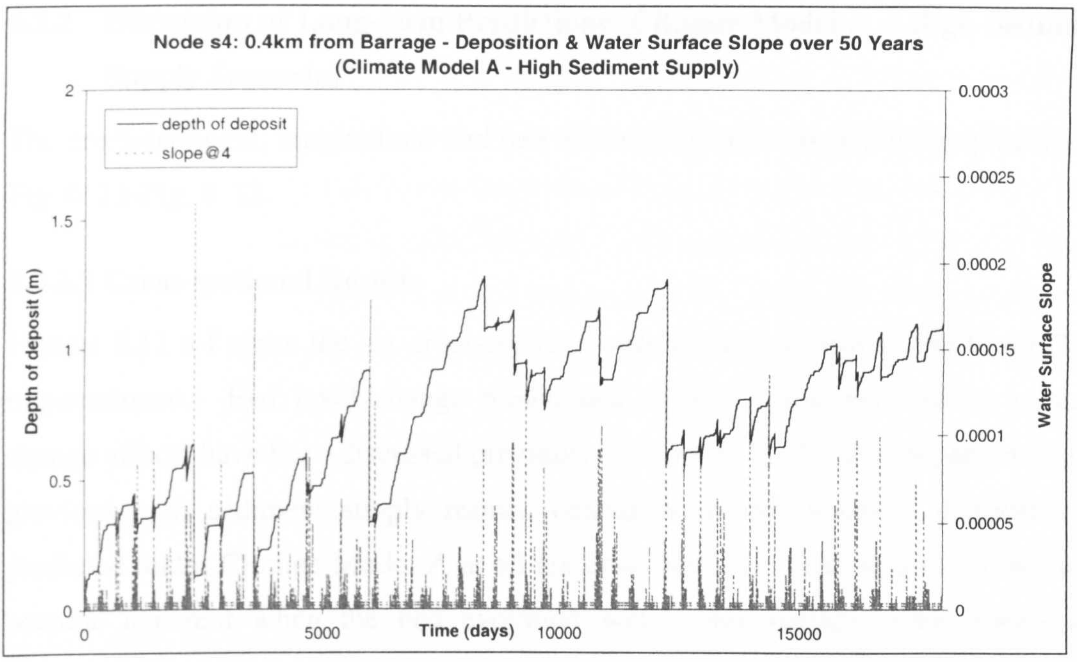


b.

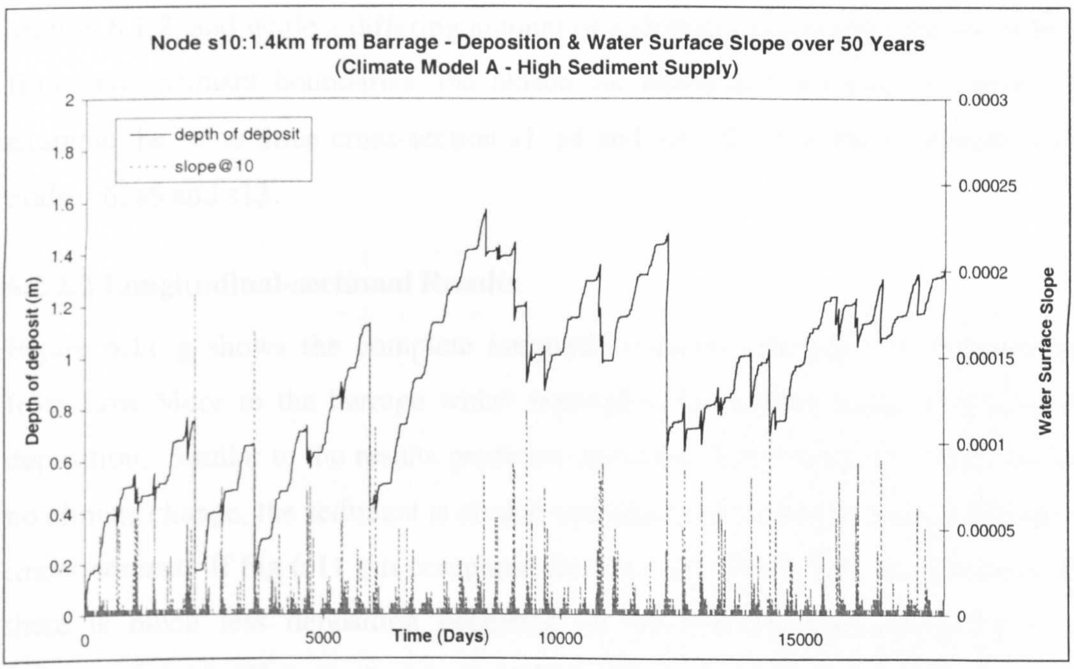


c.

Fig. 6. 12 Detailed long-sections through the impoundment showing a) the upper 10km, b) the middle 10km and c) the lower 5km of the impoundment (Climate Model A - High Sediment Supply)



a) Node s4



b) Node s10

Fig. 6. 13 Deposition and water surface slope over 50 Years at a) node s4 and b) node s10 showing the equilibrium reached by the channel (Climate Model A - High Sediment Supply)

6.2.2 Discussion of Long-term Predictions (Climate Model A – High Sediment Supply Scenario)

The cross-sectional, longitudinal and bed evolution results are shown graphically in Fig. 6. 11-Fig. 6. 13.

6.2.2.1 Cross-sectional Results

Figures 6.11 a-f show the six cross-sections over the lower 2km of the River Tees impoundment. Bed level change predictions at these locations without climate change affects have been discussed previously in section 6.1.2. In comparison to the previous high sediment supply results, considerably less sediment deposition is predicted under Climate Model A at all six cross-sections. The reason for this will become apparent when the bed evolution with water surface slope graphs are discussed.

The mechanics of the deposition for each of these cross-sections was described in section 6.1.2, and while a differing amount of sedimentation is recorded for different flow and sediment boundaries, the reason for deposition remains the same. For example the same three cross-section s1, s4 and s10 all show more deposition than nodes s6, s8 and s13.

6.2.2.2 Longitudinal-sectional Results

Figure 6.11 g shows the complete longitudinal-section through the impoundment from Low Moor to the barrage which highlights the relative areas of erosion and deposition. Similar to the results predicted using the flow boundary, which assumes no climate change, the sediment is eroded and deposited in similar places through the impoundment. If Fig 6.11 g is compared directly with Fig 6.7 g it is plain to see that there is much less deposition occurring in the impoundment according to the computer model. This results in a hypothesis that states the effect of climate change on flows has a direct impact on the morphological regime of the impoundment.

Figures 6.12 a-c show the upper 10km, middle 10km and lower 5km of the impoundment, respectively. These graphs allow a more detailed assessment of the sediment distribution within the impoundment. If figure 6.12 a-c are compared with figures 6.8 a-c it can be seen that the upper 10km of the river shows a very similar distribution pattern to that predicted without climate change. The erosion reported between chainage 0-4000m shows very little change; conversely the amount of deposition attributed to the coarser fractions settling out due to the backwater curve at chainage 6000m shows a small increase. This can be explained by the larger number of low flows reported with climate change. The sediment entering the impoundment during periods of low flows tends to be dropped out of suspension immediately as the river has minimal transporting power when the flows are low. This mechanism will be discussed in detail when comparing the climate change results with those that assume no climate change (Section 6.2.5)

Investigating the middle 10km of the impoundment (Figure 6.12 b) reveals that while less deposition is occurring through this section, similar areas are attracting deposition compared to Figure 6.8 b. For example the deep areas at chainage 17000m and especially 18900m exhibit considerable deposition. However, less deposition is reported here than for the high sediment supply scenario under climate change. Through this section of the impoundment no deposition is predicted at the Yarm bridges and very little at the Leven confluence. This is similar to the results predicted under the medium and low sediment supply scenarios with no climate change but for this simulation the sediment supply was high. The reason for less deposition occurring through this section must therefore be a direct result of climate change on the river flows. This will be investigated further when analysing the bed evolution results in section 6.2.2.3 and when a comparison is made between the climate change results and those predicted assuming no climate change (section 6.2.5).

Finally, looking at the lower 5km of the impoundment, Figure 6.12 c shows that less deposition is reported in this area in comparison to the results predicted under no climate change. The high sediment supply scenario that is shown here indicates that while the sediment concentration entering the impoundment is a factor in determining the amount of deposition in the channel, deposition is also controlled by the river discharge. The sedimentation extent in the lower 5km is evident in similar areas to those predicted in previous simulations. In particular, sedimentation is evident around the bridges in this area of the catchment at chainage 22100m, 22500m and 23300m. This is partially because the bridges superimpose a further backwater onto the one already dictated by the barrage in this region, thus the sediment is dropped out of suspension due to a flattening of the water surface slope. Additionally, ISIS does not possess the capability to predict sediment scour round bridge piers which means the package may have a tendency to overestimate the deposition occurring around bridges.

6.2.2.3 Bed Evolution and Water Surface Slope Results

Figures 6.13 a and b show the evolution of deposition over 50 years along with the water surface slope at node s4 and node s10 in the impoundment. From these results it is obvious that less sedimentation is deposited at these nodes using the climate change predictions. For example figures 6.9 a and b show 2.5 to 3m deposition, whereas, for the climate change predictions the depth of sediment depositing is between 1.2 and 1.6m. The reason why becomes obvious when the water surface slopes are investigated. High water surface slopes are partly responsible for scouring sediment out of the impoundment and these tend to be linked to periods of high flows in the river. Under climate change an increased number of high flows are predicted in the Tees (section 4.3.1.5), which directly influences the water surface slope recorded on the river. As the frequency and magnitude of extreme water surface slopes increases so does the amount of sediment scoured from the impoundment. Therefore, under climate change less sediment is allowed to deposit as the frequency of high flows that cause high water surface slopes has increased. Additionally, the magnitude of these water surface slopes has increased, this can be seen by comparing Fig. 6.9a with Fig. 6.13a. Under climate change, the water surface slope is recorded at a magnitude of over 0.001 on more than 11 occasions whereas under no climate change this occurs only once through the duration of the simulation.

While the amount of deposition varies when climate change is accounted for in the simulations, the overall behaviour of the impoundment with regard to regime is similar. The impoundment appears to reach regime after a few decades. Over the first 25 years of the simulation, sedimentation increases steadily in the impoundment despite the periods of high flows, which scour sediment. However, after around 25 years the impoundment reaches a dynamic equilibrium in a similar way to previously described. If this is considered in conjunction with more sediment being scoured during periods where sediment was already eroded then it is sensible to say that these two factors combine to create a dynamic equilibrium within the impoundment. The main difference between the non-climate change simulations and the climate change simulations is that the dynamic equilibrium appears to occur slightly earlier. However this may be due to the fact that each simulation is only one possible realisation of the future of the impoundment, thus slight variations between predictions should be expected.

As a check that this dynamic equilibrium was expected to continue after 50 years according to the computer model, an 80-year simulation was carried out. This used flows predicted by Climate Model A and a sediment inflow using the high sediment supply rating curve. A period of 80 years was chosen as the amount of data points for input restricted any longer simulations and the high sediment scenario was chosen as the most conservative option. The results of the bed evolution are shown in figure 6.14.

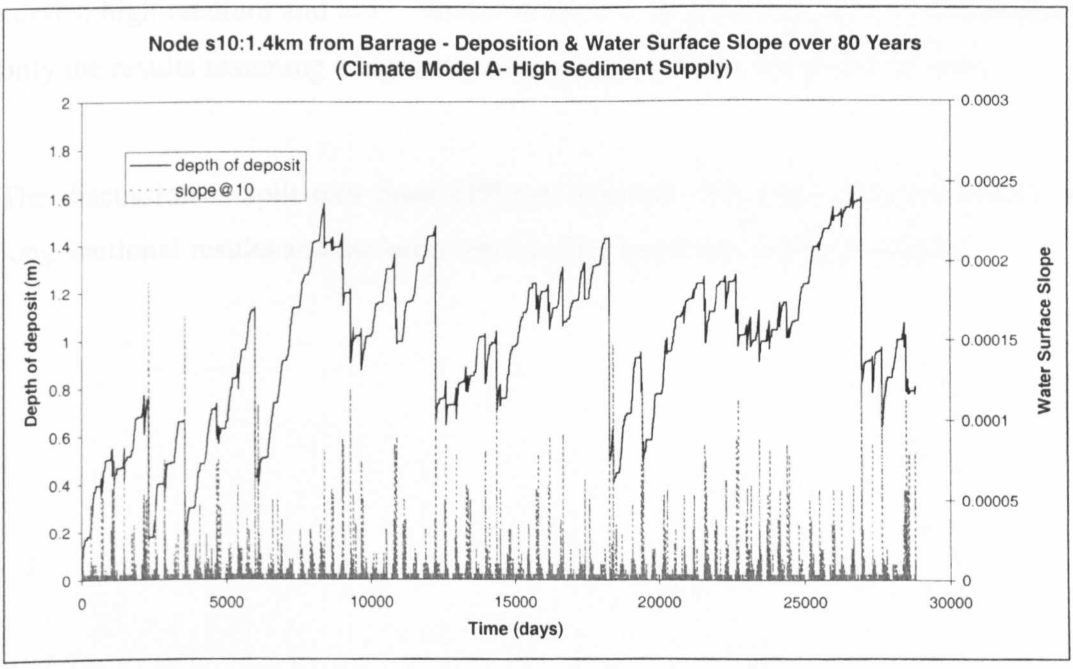


Fig. 6. 14 Deposition and water surface slope over 80 years at node s10 (Climate Model A - High Sediment Supply)

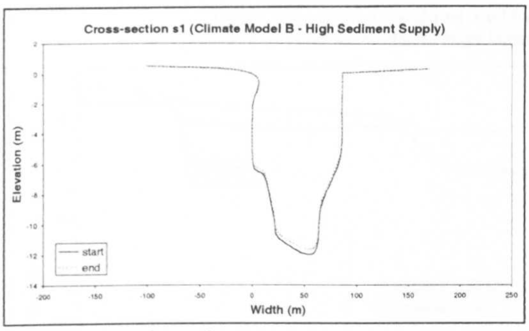
Figure 6.14 shows that over 80 years the impoundment is still maintaining the predicted equilibrium, that was estimated during the 50 year simulation.

The predictions for climate model A (medium/high emissions) have been presented and analysed. They show that less deposition is predicted through the impoundment under climate change, although it is deposited in similar places to those predicted with no climate change. The predictions also show that the impoundment reaches a dynamic equilibrium after approximately 25 years, which reinforces the hypothesis stated in the discussion of the non-climate change results that the impoundment will reach regime over a period of years irrespective of the sediment supply scenario.

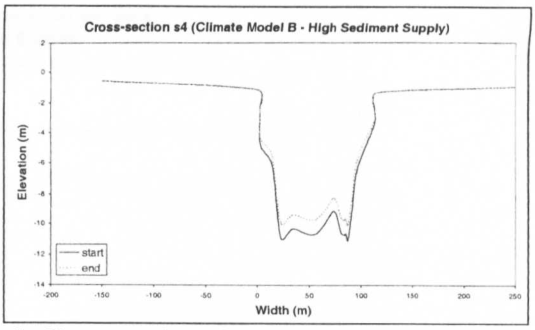
6.2.3 Climate Model B – Long-term Results (High Sediment Supply)

The results of these simulations have used a flow boundary constructed using the multinomial logit model (described in chapter 4) for the River Tees. The temperature and precipitation predictions were taken from the Regional Climate Models that were set up assuming a medium/low emissions scenario for the next 70-100 years. The predicted flows were then taken as the upstream flow boundary for the ISIS model and sediment was modeled using the three different sediment rating curves; high medium and low. Similar to the results presented for Climate Model A, only the results assuming a high sediment supply scenario are presented here.

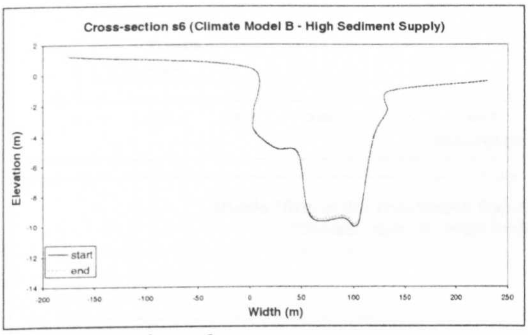
The discussion is split into three different sections; the cross-sectional results, the long-sectional results and the bed evolution and water surface slope results.



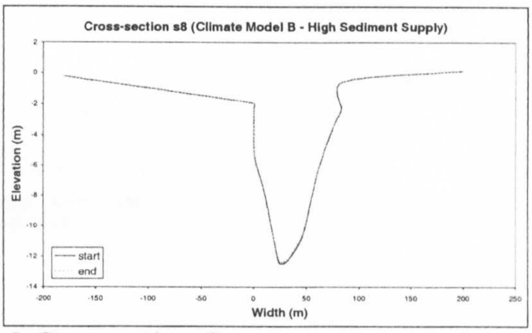
a. Cross-section s1



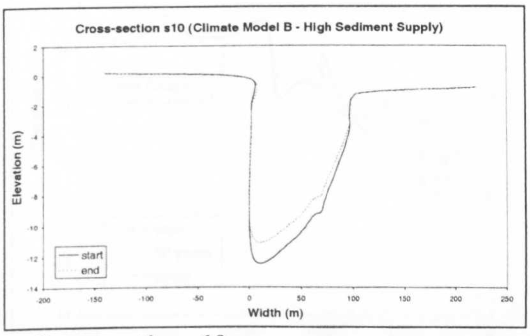
b. Cross-section s4



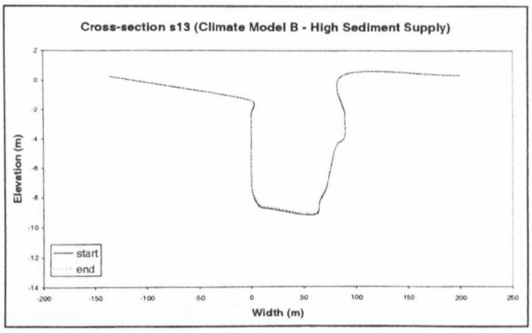
c. Cross-section s6



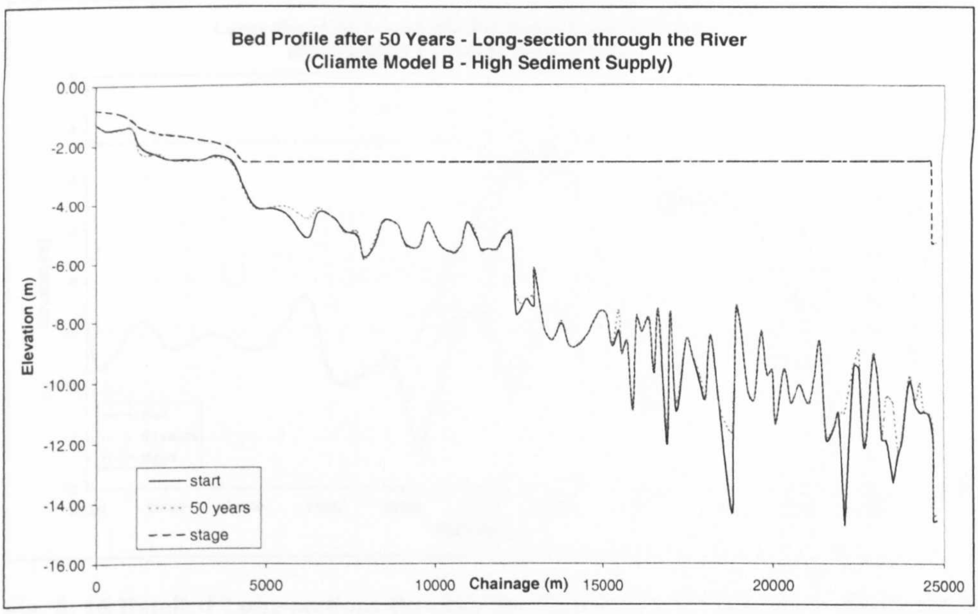
d. Cross-section s8



e. Cross-section s10



f. Cross-section s13



g.

Fig. 6. 15 (a-f) Cross-sections of the lower 2km & (g) detailed long-section of the River Tees following a 50 year simulation (Climate Model B - High Sediment Supply)

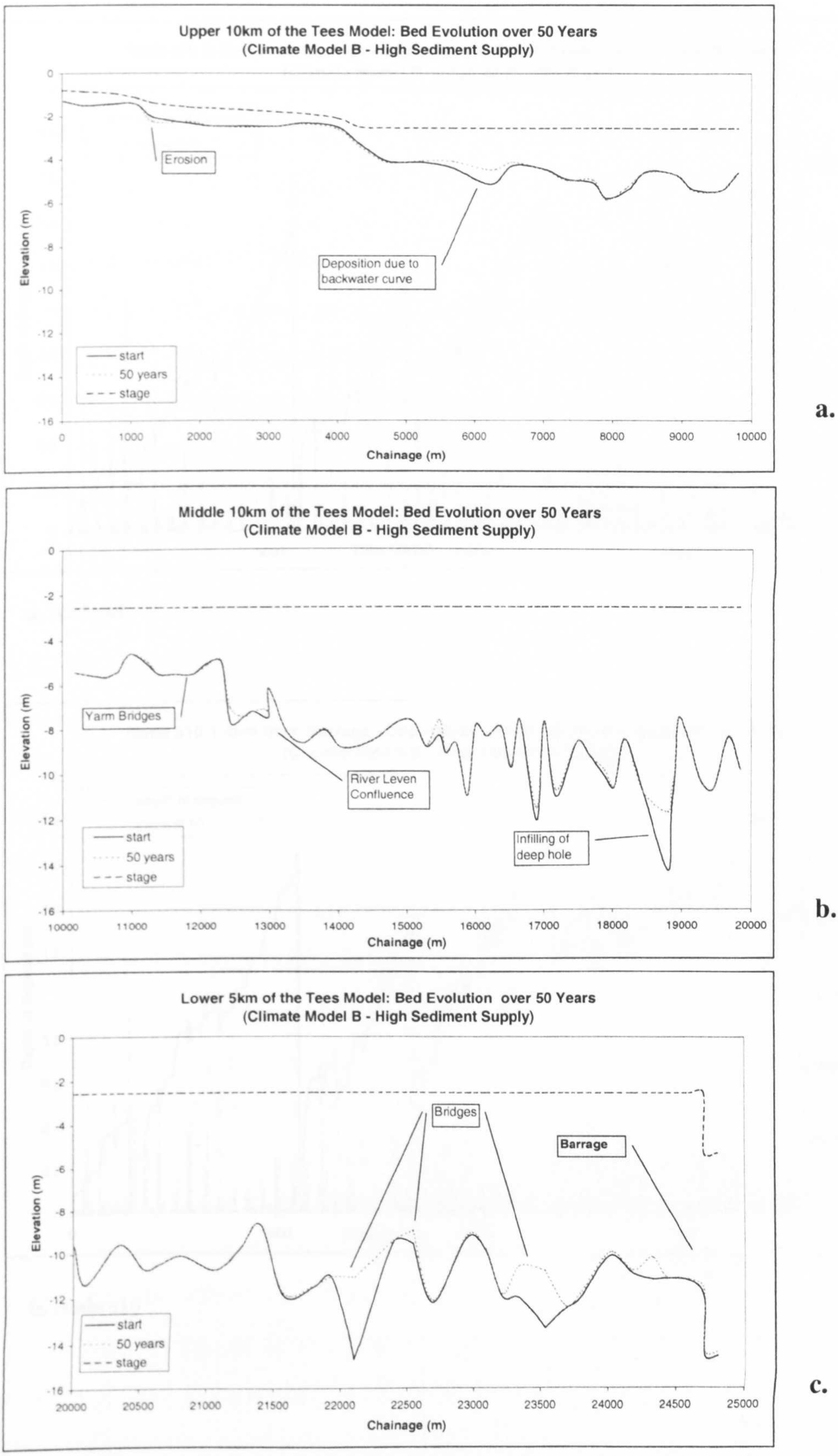
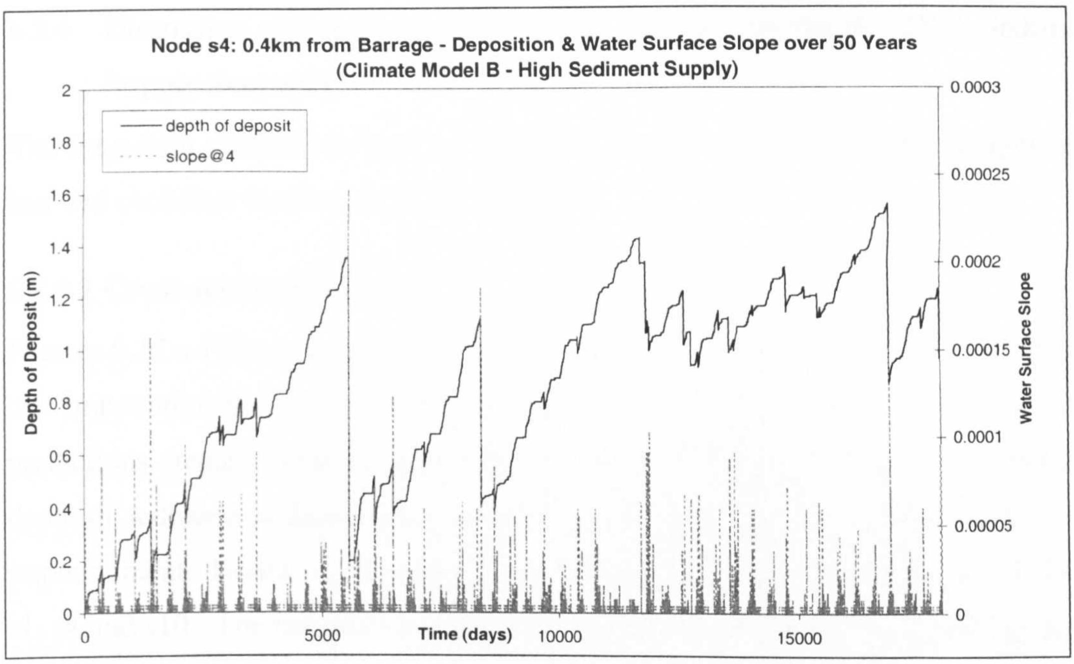
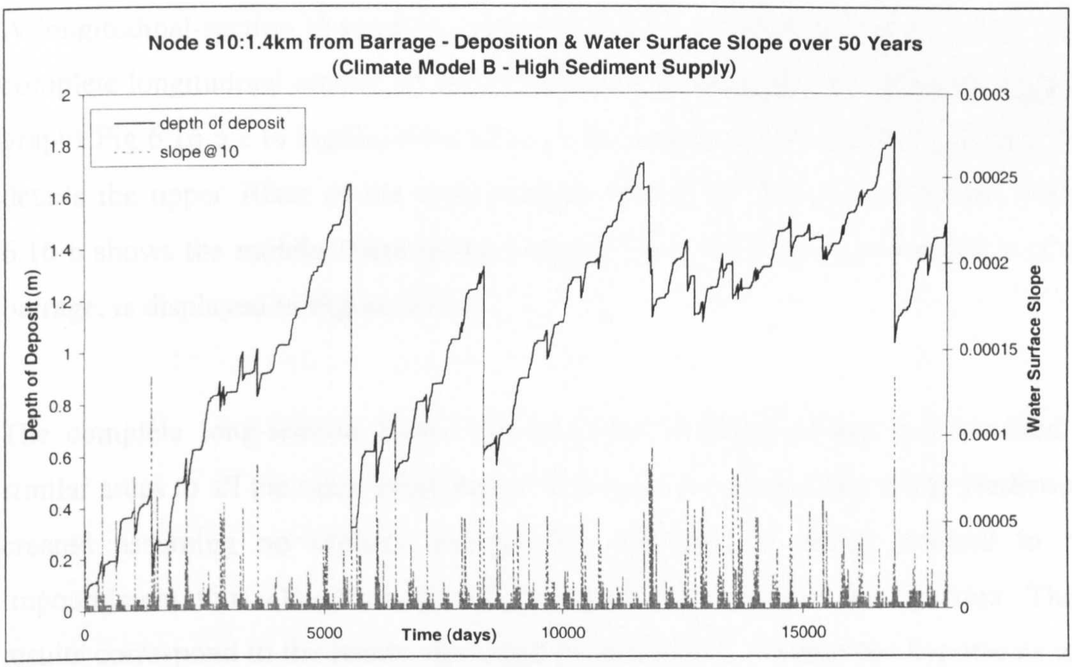


Fig. 6. 16 Detailed Long-sections through the impoundment showing a) the upper 10km, b) the middle 10km and c) the lower 5km of the impoundment - demonstrating areas of deposition (Climate Model B - High Sediment Supply)



a. Node s4



b. Node s10

Fig. 6. 17 Deposition & water surface slope over 50 years at a) node s4 and b) node s10 showing the equilibrium being reached in the channel (Climate Model B - High Sediment Supply)

6.2.4 Discussion of Long-term Predictions (Climate Model B – High Sediment Supply Scenario)

The long-term predictions after 50 years are shown in cross-sectional, longitudinal and bed evolution form in Fig 6.15 – Fig 6.17.

6.2.4.1 Cross-sectional Results

Figures 6.15 a-f show cross-section s1, s4, s6, s8, s10 and s13 from the lower 2km of the impoundment. The pattern reported by the model is very similar to the predictions created when using Climate Model A discharge results. A comparative depth of sediment is deposited at each of the nodes through the lower section of the impoundment. Nodes s6, s8 and s13 show considerably less deposition than at nodes s1, s4 and s10. The reasons for increased deposition in some areas rather than others is discussed in detail in section 6.1.2.

6.2.4.2 Longitudinal-sectional Results

A longitudinal-section through the impoundment is shown in Figure 6.15 g. This complete longitudinal-section of the impoundment is then split up into three separate graphs Fig 6.16 a-c to highlight the areas of deposition in more detail. Figure 6.16 a details the upper 10km of the impoundment from Low Moor downstream, Figure 6.16 b shows the middle 10km of the river and the lower 5km, just upstream of the barrage, is displayed in Figure 6.16 c.

The complete long-section shows that sediment is being eroded and accreted in similar areas to all the other simulations. However, in comparison to the predictions created assuming no climate change, less sediment is being retained in the impoundment, thus a lower amount of deposition is occurring in any one area. These results correspond to the results discussed in section 6.2.2 where the hypothesis was stated that the effect of climate change on flows has a direct impact on the morphological regime of the impoundment. The predictions from both Climate Models A and B show less sedimentation through the impoundment than those predicted assuming no climate change on the flow regime.

Figure 6.16 a shows an area of erosion over the upper section of the river, which has been repeated in each set of results. Erosion occurs in this area of the river as during periods of low discharge the water is allowed to flow freely at this point and is not affected by the barrage. Further downstream at chainage 6000m a large area of deposition can be found. Again this is repeated for each simulation, however for both the climate change simulations this area of deposition is deeper than for those assuming no climate change. This is because with climate change there is an increase in the number of low flows reaching the impoundment. During low flows the sediment is dropped out of suspension by the river in the upper reaches, as the transporting capacity of the channel is very small in these circumstances.

The middle section of the river is shown in Fig 6.16 b. If this figure is compared directly with Fig 6.12 b and Fig 6.8 b it can be seen that a similar amount of deposition is occurring to the results of Climate Model A but the deposition for both of these is considerably less than predicted using no climate change. The sediment is depositing in similar places through impoundment as would be expected, for example the infilling of the deep holes at chainage 17000, and 18900m. Again little or no deposition is being predicted at Yarm bridges and the Leven confluence.

Finally, investigating the lower 5km of the impoundment (Fig 6.16 c) shows that the model is predicting a similar amount of deposition as for Climate Model A (Fig 6.12 c). Again the sediment is deposited around the bridges located at chainage 22100m, 22500m and 23300m. Overall less sediment is deposited through the lower section of the impoundment under climate change (either model A or B) than if no climate change is assumed to affect the flows. While the amount of sediment flowing in at the upstream end is kept constant by means of using the same rating curve, the creation of the flow boundary has changed for each simulation. Therefore it is sensible to suggest that the effect of climate change on the flows has a direct impact on the amount of sediment accruing in the Tees impoundment.

6.2.4.3 Bed Evolution and Water Surface Slope Results

Figures 6.17 a and b show the bed evolution over 50 years at nodes s4 and s10 in the lower section of the impoundment. From these results it is plain to see that the dynamic equilibrium, which has been identified in each simulation so far, is again evident. The point at which this equilibrium becomes obvious is around 18 years into the simulation. This is earlier than each of the previous simulations, however as previously discussed this is dependent on the order of flows that are fed in from the upstream end of the model and as such each simulation is only one possible realization of the future for the impoundment. Despite this, the fact that the river still *finds a dynamic equilibrium* suggests that the river will reach regime over a period of years irrespective of the sediment supply.

If the depth of deposition is now considered it is can be seen that in comparison with Figures 6.9 a and b the climate change results show much less deposition than the original simulations. As discussed in section 6.2.2.3 this is a direct result of an increase in the number of extreme flows. More high water surface slopes are generated, which cause the sediment to be swept out of the impoundment. Again investigating the amount of water surface slopes predicted over 0.001, show that a greater number are predicted after climate change is accounted for in the flows. These larger water surface slopes keep the deposition in check through the course of the simulation.

Both node s4 and s10 for Climate Model B show marginally more deposition than for Climate Model A. The sediment in the case of Climate Model B is shown to accrete in a similar way to all the other simulations. If Figures 6.17 a and b are compared to Figure 6.13 a and b it can be seen that Climate Model B reports a deposition depth of 1.6m for node s4 and 1.8m for node s10, which is 0.2m higher than for Climate Model A. The difference here is minimal and a closer inspection will be completed when comparing all three flow scenarios; No Climate Change, Climate Model A and Climate Model B in section 6.2.5.

The cross-section, long-sectional and bed evolution results have been presented and discussed for Climate Model B (medium/low emissions) used in conjunction with the high sediment supply scenario. What is important to note from these results is that:

- Deposition is predicted through the impoundment in a similar pattern to the previous simulations under climate change and no climate change,
- Less deposition overall is predicted using an upstream flow boundary which takes account of climate change,
- The impoundment reaches a dynamic equilibrium after a certain period of years, which is irrespective of the sediment supply inflow, but dependent on the inflowing water.

6.2.5 Comparison of Long-term Sedimentation Predictions Assuming No Climate Change or Climate Change – Model A or Model B

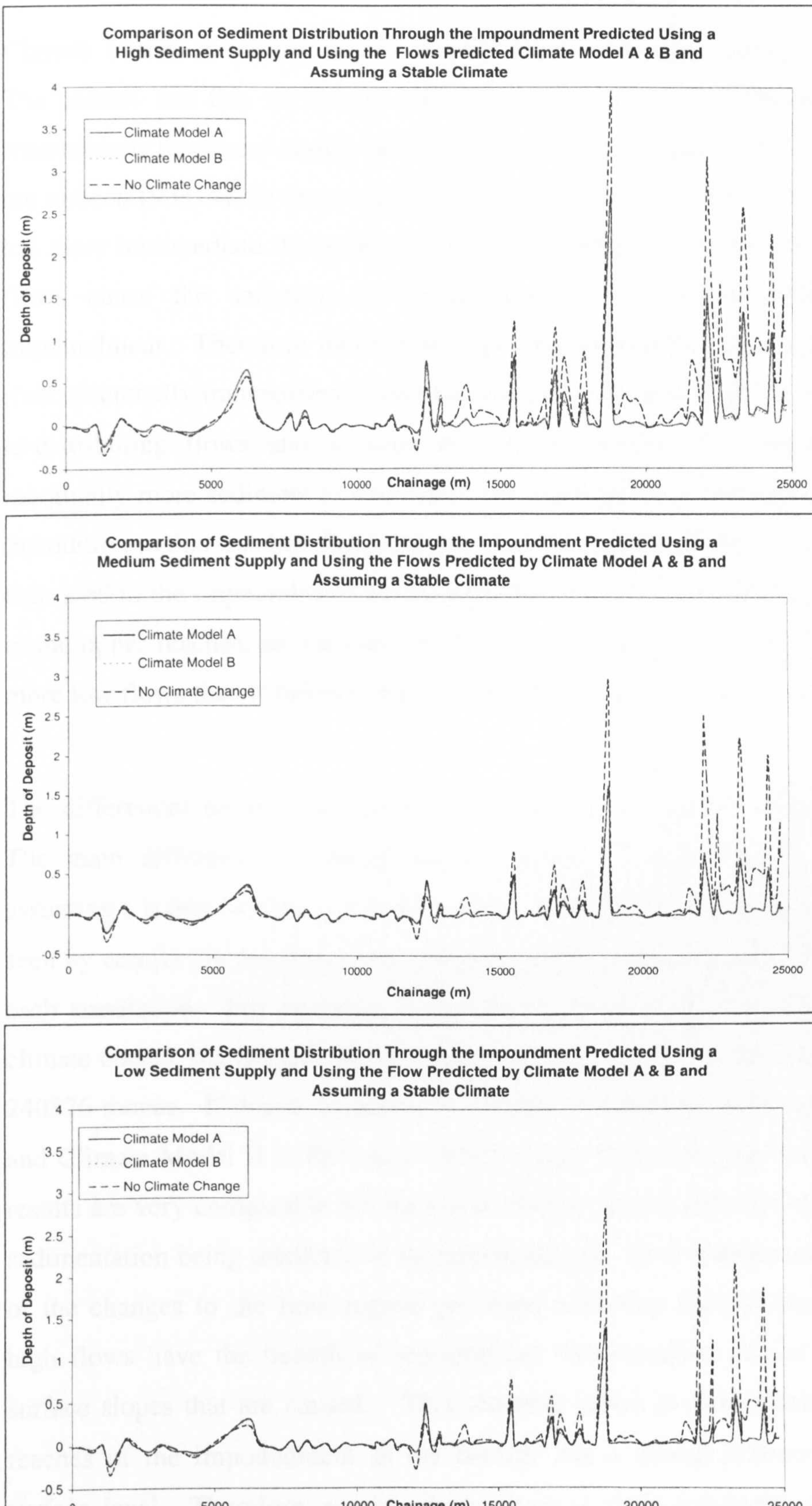
A comparison between all three different simulations has been compiled. For each set of flow boundaries created using either the Markov Chain method or the Multinomial Logit model, the model has been run using three different sediment rating curves to show low medium and high sediment supply into the impoundment. Each of the nine different simulations has been repeated to show that the results are valid as each set of generated flows are only one representation of the possible future for the river under each scenario – climate change or no climate change.

	Sediment Supply	Inflow (tonnes)	Outflow (tonnes	Deposition (tonnes)	Retained (%)
No Climate Change	High	4618494	4377618	240876	5.22%(4.87%)
	Medium	2225787	2065253	160534	7.21%(6.99%)
	Low	1675636	1533057	142579	8.51%(8.12%)
Climate Model A	High	4320401	4224229	96172	2.26%(2.05%)
	Medium	2089700	2037458	52242	2.50%(2.26%)
	Low	1578571	1534939	43632	2.76%(2.70%)
Climate Model B	High	4361739	4289114	72624	1.66%(1.49%)
	Medium	2125937	2084199	41738	1.96%(1.79%)
	Low	1621657	158796	33681	2.08%(1.80%)

Table 6. 3 Sediment retention results for all 9 simulations -Climate Model A, B & no climate change with high, medium and low sediment supply (Second run results in brackets)

Table 6.3 shows the results for each different simulation; assuming no climate change and climate change with medium/high emissions (Climate Model A) and medium/low emissions (Climate Model B). What is interesting to note is that all the simulations completed assuming climate change (either emissions scenario) show a much lower retention of sediment in the impoundment than for the results predicted assuming no climate change. The reason for this has already been discussed in the bed evolution results discussion (sections 6.2.2.3 and 6.2.4.3) but is directly related to the increased number of extreme flows predicted when assuming climate change. For the sake of this investigation high flows are termed as state 7 flows (130m^3/s and above) as these are known to cause a large amount of scouring). A product of extreme flows is high water surface slopes in the impoundment, which in turn results in sediment being swept out of the impoundment in a scouring motion. If more of these occur, as predicted when assuming climate change, then it is sensible to expect more sediment to be scoured out of the impoundment over time.

Table 6.3 also shows the result of more low flows reaching the impoundment. For the sake of this investigation low flows are described as state 1 and 2 (flows between 0-15m^3/s) as these are known to cause no transport through the impoundment. The results of each of the six different climate change runs (using both emissions scenarios) show much less sediment reaching the impoundment in the first place. For example, for the high sediment supply simulations 4.6 million tones of sediment is predicted to reach the impoundment over 50 years assuming a stable climate, however under both climate change scenarios this has dropped to around 4.3 million tones. This is a direct result of increased low flows on the river. One of the results of climate change is a flattening of the distribution of flows on the river, with more flows being predicted at both extremes (section 4.3.1). Low flows carry less sediment therefore if more low flows are predicted for the Tees, less sediment will arrive in the impoundment. Additionally, sediment will be dropped out of suspension quickly as the transport capacity of the river is minimal during low flows. Therefore more sedimentation will occur in the upstream reaches under climate change as the sediment will be dropped out of suspension and not re-distributed.



a.

b.

c.

Fig. 6. 18 A comparison of sediment distribution, showing erosion and deposition through the impoundment, predicted using Climate Model A, B and assuming a stable climate; using a. high sediment supply, b. medium sediment supply and c. low sediment supply

Climate Model A reports slightly higher retention results than Climate Model B. The reason for this is due to the distribution of flows, although it must be remembered that these results are actually very similar and only minor differences are noticed (this can be seen when investigating figures 6.18 a-c). Climate Model B has more intermediate flows (states 3-6) than Climate Model A. These intermediate flows cause the sediment to be re-entrained and re-distributed through the impoundment. Therefore these flows pick the sediment up and move it down the river, eventually transporting it over the barrage. Climate Model A has less of these re-distributing flows and as such less is moved over the barrage. Therefore marginally more sediment is retained in the impoundment during these simulations. In addition to this less low flows are reported for Climate Model B. All the sediment delivered to the impoundment during periods of low flows (state 1 & 2) is deposited in the upper reaches, as discussed earlier; consequently if Climate Model A reports more low flows then it follows that an increased retention percentage is reported.

The differences between the predictions that assume climate change are minimal. The main difference in sedimentation patterns is observed between the results assuming a stable climate and those predicted assuming climate change. This can be seen by comparing the amount of sediment actually retained in the impoundment for each simulation. For example, if the high sediment supply is considered, for no climate change the amount of sediment retained is 5.22% of the inflow sediment or 240876 tonnes. If this is compared to Climate Model A (2.26% and 96172 tonnes) and Climate Model B (1.66% and 72624 tonnes) it is clear that the climate change results are very comparable but the stable climate results show a marked increase of sedimentation being predicted in the impoundment. Less sedimentation is a product of the changes to the flow regime predicted assuming climate change. Increased high flows have the benefit of scouring out sedimentation due to the high water surface slopes that are caused. This scouring action is more evident in the lower reaches of the impoundment as the barrage has a strong influence on the water surface level. Therefore, scoring downstream is more common under the climate change predictions. This can be seen from Fig 6.18 a-c, where the model assuming a stable climate shows a much larger amount of deposition at the downstream end than the climate change models.

Figures 6.18 a-c show the distribution of sedimentation through the impoundment. Deposition is shown as positive and erosion as negative along the river. Erosion is evident at the upstream end only, whereas deposition occurs along the length of the river. These graphs show that there is very little difference between the two simulations that were completed assuming climate change, especially for the medium and low sediment supply scenarios where the difference is almost indecipherable. However, there is a large difference between the climate change results and those predicted assuming no climate change. The latter shows more deposition is retained in the impoundment and the deposition is concentrated towards the downstream end of the impoundment. There are two main reasons this is happening. Firstly, as discussed, the increased frequency of extreme high flows causes more scouring, which results in less sediment being retained in the impoundment. The scouring impacts on the sediments concentrated in the downstream section of the impoundment, where the water surface slopes are the most sensitive. Secondly, the flow series that was created assuming no climate change has a different distribution than those created assuming climate change. The former distribution has a higher density of intermediate flows (states 3-6) and less low (states 1 & 2) and extreme high (states 7) flows. Therefore there is more intermediate flows that bring in sediments and re-distribute the, through the impoundment, hence the build-up of sediment concentrated towards the downstream end of the impoundment.

6.3 Conclusions

From the results presented it is necessary to make an assessment of the overall sustainability of the impoundment over the next 50-100 years. From the previous summary in section 6.1.8, it was stated that the impoundment was deemed morphologically sustainable because the impoundment was predicted to become self-stabilising over a period of years. The point at which the dynamic equilibrium occurred showed that insufficient sediment had been deposited to silt-up the impoundment. Additionally, the simulations were proved to be conservative during a sensitivity study in Chapter 5 section 5.6, adding weight to this statement. However this study did not investigate the effects of the increased sedimentation on flooding and flood levels.

If the results of the climate change simulations are now considered there are several additional conclusions;

- Firstly, less deposition is predicted through the impoundment under both climate change scenarios (medium/high and medium/low emissions).
- This is a direct result of changed flows reaching the impoundment due to climate change.
- More extreme (state 7) flows cause more scouring of the impoundment, especially at the downstream extent of the impoundment as they give rise to an increased number of high water surface slopes.
- More low flows cause less sediment to arrive in the impoundment in the first place.
- These low flows change the distribution of the sediment through the impoundment, concentrating the deposition in the upper reaches as fewer intermediate flows mean that the sediment fails to be distributed along the length of the river
- The impoundment still reaches a dynamic equilibrium during the simulations, which is irrespective of the sediment supply scenario. However the time at which the impoundment reaches equilibrium is dependent on the flows reaching the impoundment.
- Finally, the equilibrium that is reached shows that the impoundment will not silt up over the course of the 50 year simulation, and infact a longer simulation of 80 years showed that the dynamic equilibrium would be continued past 50 years, meaning that the impoundment has reached regime.

The conclusions from the climate change simulations show that the impoundment is infact morphologically sustainable over the next 50 years. However, the modelling undertaken does not allow an assessment of the sustainability regarding flooding over the same period. In this case it has been shown that climate change has a positive influence on the sedimentation through the impoundment, demonstrating that the increased high flows allow less sediment to be deposited.

Chapter 7: Conclusions and Suggested Further Work

7.0 Introduction

The purpose of this thesis was to assess the morphological sustainability of the River Tees impoundment. This final chapter presents a review of the work. The main body of work is summarised and the salient conclusions stated. This is followed by some suggestions for further work in this area. For simplicity the work has been split into four different sections; the Markov Chain Modelling work, the Multinomial Logit Model for climate change predictions, the results of the long-term predictions assuming a stable climate and the results of the long-term predictions under climate change. The final two sections of this summary chapter detail the applicability of the overall method presented in this thesis for other long-term feasibility studies, and the long-term sustainability of the Tees impoundment.

7.1 Markov Chain Modelling

7.1.1 Summary of Work

Markov chains are a generic modelling technique that can be used to forward predict existing data sets based on their statistical properties. This section of the work used Markov Chains to extend the recorded flow series at Low Moor on the River Tees for the purpose of creating a realistic long-term upstream flow boundary for the ISIS model of the impoundment. Previously used methods of extending flow boundaries were reviewed, however this method aimed to present a relatively simple approach, while retaining the statistical properties and the structure of the historical series. A Markov Chain was proposed as it uses categorical data thus allowing the extreme state to be dealt with separately using extreme value theory. Both a first order and second order transition matrix were created and the resulting series were tested statistically against a period of historical flows recorded at Low Moor gauging station between 1970-1980.

7.1.2 Conclusions

A different approach to extending flow series for the purpose of long-term sedimentation modelling is proposed. This approach uses the generic technique Markov Chain and applies it to flow series. The method was tested by creating a long-term flow series for Low Moor on the River Tees of 50 years. Several conclusions were reached during the course of this work:

- Using the POT value for the highest flow state allowed extreme value theory to be used when re-assigning the states. A large amount of research exists on extreme value theory and as such this allows the high flows to be modelled realistically.
- The method uses categorical data and calculates transition probabilities of moving between states. To retain the integrity of the transitions the data was split seasonally (winter and summer), which improved the prediction capacity of the matrix.
- First order and second order series were created to compare with the historical series.
- A chi square goodness of fit test was completed on the binned data. This showed that the result was statistically significantly different. It was decided that there was insufficient evidence to categorically dismiss the statistical hypothesis solely on the basis of the chi squared test. Therefore further tests were completed to investigate the hypothesis further.

- Comparison of the descriptive statistics and distribution of the series showed that the Markov Chain method produced a series with a comparable spread of flows.
- Comparison of the autocorrelation function showed the created series reproduced the structure of the historical series well.
- Despite the second order matrix incorporating more of the history of the flow series into the matrix the first order matrix was found to be just as effective for prediction as the second order matrix.
- An eight year series was created and used as an upstream boundary for the ISIS model. When the results were compared to the simulation completed using the recorded flow series it was shown that the sedimentation pattern predicted was reproduced reasonably.
- The Markov Chain method produces a series of states that re-produce the historical statistics of the series well. However it is important to note that each series created is only one possible representative realisation of the possible future outcome for flows in the impoundment.
- The proposed Markov Chain method is a simple, robust method for extending flow series for the purpose of long-term sedimentation modelling but takes no account of the possible effect of climate change on these flows.

7.1.3 Further Work

Further investigation for the Markov Chain modelling would be interesting in several areas. Firstly, it would be interesting to divide the series up into four seasons; spring, summer, autumn and winter and investigate whether this would improve the predictive capability of the method. However, this would require a very large dataset to avoid the possible problem of non-intercommunication between states. Secondly, it would be interesting to investigate the benefit of using higher order transition matrices for flow problems. This would require a large dataset which had a small flow range so only a few states would be required therefore keeping the matrices small enough to be workable. Finally, splitting the flow record into more states

7.2 Multinomial Logit Model – Climate Change Modelling

7.2.1 Summary of work

With the increasing interest in the effect of climate change on water resources it was considered beneficial to try and incorporate these effects into the flow series, thereby creating a long-term flow boundary that would allow the investigation of the influence of climate change on sedimentation. This section of the work was completed in collaboration with Dr. Nicole Augustin from the Department of Statistics, University of Glasgow.

The method uses a multinomial logit model to link catchment precipitation and temperature data to the flows recorded in the River Tees. The model was created and then validated using a K-fold cross-validation technique. Then climate change predictions were received from the Hadley Centre's Regional Climate Model for the Tees catchment under both a medium/high and medium/low emissions scenario. Once these predictions had been corrected, they were then used to predict 50 year flow series for the River Tees that took account of climate change under both emission scenarios.

7.2.2 Conclusions

A method for extending flow series, that is capable of accounting for the influence of climate change on the flows, is proposed. This approach uses a Markov model fitted in the framework of a multinomial logit model to link precipitation and temperature data to the flows in the Tees. The conclusions from this work are:

- Using catchment temperature and precipitation data as explanatory variables improves the prediction capacity of the method over a straight Markov Chain method.
- Statistical tests completed, comparing the autocorrelation function and the empirical cumulative density function showed that the model has good prediction capability.

- Without any climate change data the model is set up to work as a short-term forecasting model, which it can do if the catchment 30 day mean temperature and the previous days precipitation is known.
- An investigation of the transition probabilities shows that the effect of increasing temperature in the catchment results in a change of transition probabilities. Similarly, increasing precipitation within the catchment also influences the transition probabilities.
- The flow series predicted using both the medium/high emissions and the medium/low emissions show a change to the flow series. Both record a flattening of the flow distribution.
- More extreme high flows (state 7) are recorded for both climate change series. This is more pronounced for the medium/high emissions scenario. These results agree with recent research.
- An increased amount of low flows (state 1 and 2) are recorded for both climate change series, again this is more evident for the medium/high emissions scenario and the results follow recent consensus.
- The climate control temperature and precipitation data from the Hadley Centre (1961-1990) was used to predict a flow series, which took no account of climate change. This was used as an upstream boundary for the ISIS model, simulated for 50 years and the results compared with the Markov Chain predictions. The results showed reasonable agreement, showing that the multinomial logit model produces series with similar properties as the Markov Chain which results in repeatability of the long-term morphological predictions
- In a similar way to the Markov Chain modelling it is important to acknowledge that each flow series created is only one possible realisation of the possible future outcome for flows in the River Tees.
- The proposed method provides a robust, relatively simple technique for forward predicting flow series which are modified to account for the possibility of climate change

7.2.3 Future Work

This section of work details a proposed method for forward predicting flow series, which are modified to account for climate change. There are several possibilities for extending this work in the future. Firstly, the model's prediction power would be increased if more catchment parameters were used to build the model, for example specific humidity, maximum/minimum temperature and catchment wind speed. These explanatory variables are available as outputs of the RCM and therefore would be ideal to build into the model, however the initial dataset required for the investigated catchment would be large and difficult to collect. An investigation into which parameters would provide the most significant improvements to the method would be very useful.

Secondly, the discrete flow data has been modified to account for climate change through the multinomial logit model, however the same extreme value distribution has been used to re-assign the flows to complete the new series. New research by Fowler & Kilsby (2002) has shown that new return period estimates under climate change may be required for precipitation estimates, along with increased values for annual maximums. It would follow that this would then affect return periods and maximums within rivers. Thus, new amended distributions should be used to sample from when re-assigning flows for the extreme state (state 7).

Finally, in a similar way to the Markov Chain future work, an investigation into the improvements experienced when using more state divisions would improve knowledge on the application of the Multinomial Logit methods.

7.3 Long-term Predictions for the Tees Impoundment Assuming No Climate Change

7.3.1 Summary of Work

Using the results from the Markov Chain method 50 year flow series were used as upstream flow boundaries for the 1-D ISIS model that was constructed for the impoundment. Three different sediment rating curves were used to simulate differing levels of sediment supply; high, medium and low. These rating curves were constructed using a relatively short data set of suspended sediment concentrations measured on the river at Low Moor. The different rating curves were a consequence of an observed change to the sediment regime that was noticed during the period of sediment monitoring. Each simulation was repeated with a different flow boundary to ensure the validity of the morphological prediction, resulting in six simulations.

7.3.2 Conclusions

The long-term simulations were completed to make assessment of the overall morphological sustainability of the impoundment over 50 years assuming a stable climate. Several conclusions were drawn from the results:

- The analysis of the measured sediment inflow into the impoundment indicated that a change in the dominant sediment source occurred during the measurement period. This change was triggered by the high flows that occurred during October/November 2000. It is unclear without more monitoring on the river whether the sediment supply to the lower Tees will return to its previous levels over time or if the higher levels are a consequence of greater flows, which are a result of climate change.
- Within the modelling section of the Tees this uncertainty was handled by using three different sediment rating curves for the upstream sediment boundary representing low, medium and high sediment supply scenarios.
- All six simulations show deposition predicted through the impoundment in a similar pattern with deeper deposits produced by the higher sediment supplies.
- Deposition is concentrated at the downstream end of the impoundment, as the finer sediments, which have been carried downstream in the flow, finally settle out.
- The modelling suggests the impoundment reaches a state of dynamic equilibrium after about 30 years, irrespective of the sediment supply. This occurs because after a certain amount of sediment has been deposited (between 1.5m and 3m depending on the sediment inflow rate), subsequent floods generate sufficiently steep water surface slopes to re-entrain deposited sediments and partially flush the system.

- The impoundment reaches equilibrium during all six simulations completed, however the equilibrium point is found at a different point in time for each different flow boundary used. This is because the main difference in the created flow series is that different times between peaks will be predicted. While this means that the overall sediment retention in the impoundment will be similar with each simulation (because no time-dependent processes are present in the ISIS model), it does mean that the time it takes for the impoundment to reach equilibrium will vary marginally.
- Using the flow boundary predicted by the Markov Chain method means that the sediment simulation predictions are also only one possible realisation for the future of the impoundment assuming no climate change.
- A sensitivity study that was completed for the impoundment, which showed that by using daily flows, rather than hourly flows the sediment retention in the impoundment was being over-predicted. This results in the long-term simulations being conservative with regard to depth of deposition.
- The Tees impoundment is morphologically sustainable, assuming a stable climate, according the computer simulations. Sediment build up is predicted but this is not sufficient to cause the impoundment to become unusable for the purposes for which it was built.
- No assessment was made on the sustainability of the impoundment with regards to flooding.

7.3.3 Further Work

The results from the computer simulations show that the River Tees impoundment is sustainable over the next 50 years. However, as previously stated the results show only one possible outcome for the future of the impoundment with regards to sedimentation. Despite the fact that a second run showed very little difference in terms of overall sediment retention and distribution within the impoundment, some investigation into the effect of different times between extreme flows would be beneficial to address this uncertainty. To develop this method further, a Monte Carlo approach to the sedimentation modelling could be investigated. Many different flow boundaries, with the same statistical parameters, should be created and then each should be run through the ISIS model to investigate the range of sediment retention and distribution predicted.

To investigate the sustainability of the impoundment with regard to flooding some further surveying would be required with special attention being paid to the floodplains. It would be advantageous at this point to try and link the long-term simulations with a 2D package. This would have the effect of investigating the spatial distribution of the sediment through the impoundment and look at the potential inundation of the river. This is dependent on whether a 2D code could be found that enabled long-term simulations without being too computationally intensive.

7.4 Long-term Predictions for the Tees Impoundment Under Climate Change

7.4.1 Summary of Work

Long-term simulations of the Tees impoundment were completed that used the flow series created using the multinomial logit model. Both the medium/high and medium/low emissions scenarios were simulated; therefore twelve different runs were completed. Each emissions scenario was used to create a flow series, which was then used as the upstream boundary for the ISIS model. The sediment supply was varied using the three different rating curves; low, medium and high. This was repeated twice for each emissions scenario. Additionally, the control climate scenario was used to create a flow series, which was then used to predict the sediment distribution through the system to check that the predicted distribution was the same as predicted using the Markov Chain method. Sea level was assumed to remain unaffected by climate change and the work only considered potential changes to the fluvial flows.

7.4.2 Conclusions

After the completion of the long-term simulations some interesting conclusion were reached:

- The flows created using the control climate scenario show a very similar depositional pattern and comparative retention rates to those predicted using the Markov Chain method. The outcome of this test was used to check the validity of the corrected climate change predictions.

- Both of the flow boundaries created for each emission scenario show very similar results with regards to sediment distribution, retention and depositional depth.
- All twelve results show that the effect of climate change on flows had a beneficial influence on the build-up of sediments in the Tees impoundment. Much less deposition was predicted using the climate adjusted flow series. This was noticed in the retention rates and the depth of sediment predicted at particular nodes.
- The reason less sediment is retained in the impoundment is because of the increase of extreme flows arriving in the impoundment (state 7). These cause an increased frequency of high water surface slopes to be observed which re-entrain sediments and scour the impoundment.
- Sediment deposition was distributed slightly differently. More sedimentation was concentrated at the upstream end. This was due to more low flows reaching the impoundment (state 1 and 2). These states do not transport sediment thus it is dropped at the upstream end.
- Less sediment is deposited at the downstream end. This is partly because of the scouring action of the high water surface slopes. Additionally, under climate change less intermediate flows (states 3 - 6) are reported for both scenarios. These intermediate flows distribute the sediment through the impoundment, thus less sediment movement occurs from upstream to downstream.
- The impoundment was predicted to reach a dynamic equilibrium over the period of simulation, which is irrespective of the sediment supply. Similar to non-climate change results the river becomes partially self-cleaning during the course of simulation.
- This equilibrium is reported at different times through simulation depending on the flow boundary, between 19 and 25 years. Thus it is important to remember that each simulation represents only one possible outcome for the future of the impoundment.

- This equilibrium is predicted to be maintained past the simulated 50 years as indicated by an 80 year simulation undertaken.
- According to the computer modelling, climate change improves the morphological sustainability of the River Tees impoundment.

7.4.3 Further Work

For this section of work a similar progression is suggested for the future as was mentioned for the long-term predictions assuming no climate change. A Monte Carlo approach to the sediment modelling would be beneficial to investigate the range of possible future outcomes for the morphological sustainability of the Tees impoundment and the effect of the time dependency of flows. However, this may be difficult, as only a few climate change simulations have been completed. The multinomial logit model requires future temperature and precipitation predictions; therefore it may be harder to create more flow series than for the simpler Markov Chain method.

In a similar way to the long-term predictions completed assuming no climate change, widening the investigation by using a 2D code would be interesting. Again, with more survey data this could be included to investigate the sustainability of the impoundment with regard to flooding as well as providing more information on the spatial distribution of sedimentation. However this would require a non-computationally intensive code.

7.5 Future Use of Proposed Method for Long-term Impact Studies

While this procedure, proposed in this thesis, has only been applied to one study, the author believes that the overall method has applications beyond the River Tees. The method has been shown to be a relatively simple and robust method for investigating the long-term impact of structures on sediment regimes within the fluvial environment.

With the increased importance placed upon environmental sustainability in terms of construction within fluvial and estuarine locations; it is essential that the engineering community develop reasonable, time-efficient methods of assessing long-term impacts to habitats. The procedure set out in this thesis has applications for any major construction within natural water bodies, whether a simple forecasting or a more detailed analysis incorporating the effects of climate change is required. The method requires a similar amount of information routinely collected for fluvial and morphological studies completed in industry, and has been shown to incorporate the effect of climate change in a reasonable manor.

7.6 Statement on the Morphological Sustainability of the River Tees Impoundment

According the computer predictions presented and discussed in the course of this thesis, the River Tees Impoundment is morphologically sustainable over the next 50-80 years. These calculations have covered a stable climate and one, which is influenced by climate change. The investigations have also varied the sediment supply reaching the river to account for possible changes to sediment sourcing in the future. Despite all the possibilities modelled, the results all point to the fact that the impoundment will be morphologically sustainable for the future of the barrage.

However, as stated at the start of this thesis, while in investigating the sustainability of the system it is also necessary to consider whether the barrage has caused the Tees any irreparable damage. On this note, it is the author's opinion that due to the river's resilience, no irreparable damage has been done to the system. The river has adapted relatively quickly (around thirty years) to the repositioning of the tidal limit within the system by creating a new sediment regime. If the barrage was to be removed it is the author's belief that the sediment regime of the Tees river would return to its pre-barrage status over a period of time; with the river eroding the deposited sediments to return to a regime similar to it's pre-impoundment status.

References

1. Abbott, M. & Price, W. 1994, Coastal, Estuarial & Harbour Engineers' Reference Book. E & FN Spon (Chapman & Hall), London. ISBN 0-419-15430-2
2. Abrahart, R & See, L. 2000. Comparing neural network and autoregressive moving average techniques for the provision of continuous river flow forecasts in two contrasting catchments. Hydrological Processes. **14**. pp 2157-2172
3. Ackers, P & White, W. 1973. Sediment Transport: New Approach and Analysis. Journal of the Hydraulics Division. American Society Civil Engineers. **99**. pp 2041-2060.
4. Agresti, A. 1996. An Introduction to Categorical Data Analysis. John Wiley & Sons. New York. ISBN 0-471-11338-7
5. AIAA. 1998. Guide for the Verification and Validation of Computational Fluid Dynamics Simulations. American Institute of Aeronautics and Astronautics. Reston, VA, USA. ISBN 1-56347-285-6
6. Aksoy, H. & Bayazit, M. 2000. A model for daily flows of intermittent streams. Hydrological Processes. **14**. pp.1725-1744.
7. Annadale, G W. 1992. Modelling the uncertainty of sediment deposition upstream of flood control dams. In Water Resources and Reservoir Engineering. Ed. Parr, N. Charles, A. & Walker, S. Thomas Telford, London. ISBN0-7277-1602-1
8. Arnell, N. 1992. Factors controlling the effect of climate change on river flow regimes in a humid temperate environment. Jornal of Hydrology. **132**. pp 321-342
9. Arnell, N. 1996. Global Warming, River Flows and Water Resources. Wiley. Chichester. 224 pp.
10. Arnell, N. 1998. Climate Change and Water Resources in Britain. Climatic Change. **39**. pp 83-110
11. Arnell, N. 1999. Climate change and global water resources. Global Environmental Change. **9**. pp. s31-s49

12. Arnell, N. 2003. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain. Journal of Hydrology. **270**. pp. 195-213

13. Arnell, N. & Reynard, N. 1996. The effects of climate change due to global warming on river flows in Great Britain. Journal of Hydrology. **183**. pp. 397-424

14. Augustin, N. Cummins, R. & French, D. 2001. Exploring spatial vegetation dynamics using logistic regression and a multinomial logit model. Journal of Applied Ecology. **38**. pp. 991-1006

15. Bechteler, W. & Vetter M. 1989, The Computation of Total Sediment Transport in View of Changed Input Parameters. In Sediment Transport Modelling Proc. Int. Symp, New Orleans, Louisiana, Aug 14-18 1989. Ed. S. Y Wang. ASCE. New York. ISBN 0-87262-718-7.

16. ***Beevers, L.*** & Pender, G. 2001. Predicting Sedimentation in Estuarine Impoundments. 3rd International Symposium on Environmental Hydraulics, Tempe, Arizona, USA. December 5-8 2001.

17. ***Beevers, L.*** Pender, G. Sloan, W. White, S. & Worrall, F. 2003. Assessing the Morphological Sustainability of Estuarine Barrages: The Tees Barrage. *In Review:* Journal of River Basin Management.

18. Bernstein, A. & Cecconi, G. 1996. The Impacts on Water Quality of the Venice Tidal Barriers. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

19. Bettes,R & White, W. 1981. Mathematical simulation of sediment movement in streams. Proceedings of the Institution of Civil Engineers, Part 2 Research & Theory, **71**. pp 879-892

20. Bettes, R. 2001. Private Communication

21. Betty, N. Turner, A. Tyler, A. Falconer, R. & Millward, G. 1996. Modelling Contaminant Geochemistry in Estuaries. Water Research. Vol. **30**. No. 1. pp. 63-74

22. Beven, K. Kirkby M. 1979, Physically based, variable contributing area model of basin hydrology, Hydrol Sci Bull Sci Hydrol. Vol **24**. no.1. pp. 43-69

23. Black, A. & Burns. A. 2002. Re-assessing the flood risk in Scotland. The Science of the Total Environment. Vol. **294**. Issue 1/3. pp. 169-184.

24. Bowie, K. 1999. The analysis of selected habitat improvement measures in river alteration/engineering schemes in Scotland. Msc Thesis, University of Glasgow.

25. Box, G. Jenkins, G. 1976. Time Series Analysis: Forecasting and Control. Revised edition. Holden-Day, San Francisco. ISBN 0-8162-1104-3

26. Box, G. Jenkins, G. Reinsel, G 1994. Time Series Analysis: Forecasting and Control. Third edition. Prentice Hall. New Jersey. ISBN 0-13-060774-6

27. Bradley, J. Gardarsson, S & Grindeland, T. 1999. Geomorphological Study of the Upper Mississippi River. Proceedings XXVIII IAHR Congress, Hydraulic Engineering for Sustainable Water Resources Management at the Turn of the Century. Graz, Austria, 22-27 August 1999.

28. Brejck, H B. 1995. The North Sea continent and the pioneer settlement of Norway. In A. Fischer (ed.), 1995, pp. 131-44.

29. Burt, N. 2002. Cardiff Bay Barrage: overview of hydraulic studies. Proc. Instn. Civil Engrs. Water & Maritime Engineering. **154.** Issue 2. pp. 93-102

30. Burt, N. & Cruickshank, I. 1996. Tidal Barrages – Learning from Experience. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

31. Burt, N & Littlewood, M. 2002. Cardiff Bay Barrage: sedimentation aspects. Proc. Instn. Civil Engrs. Water & Maritime Engineering. **154**. Issue 2. pp. 103-107

32. Cameron, D. Beven, K. & Tawn, J. 2001. Modelling extreme rainfalls using a modified random pulse Barlett-Lewis stochastic rainfall model (with uncertainty). Advances in Water Resources, Vol. **24**, no.2, (nov) pp. 203-211.

33. Carvalho, N O. 1999. Reservoir sedimentation effects on hydropower generation – a case study. Proceedings XXVIII IAHR Congress, Hydraulic Engineering for Sustainable Water Resources Management at the Turn of the Century. Graz, Austria, 22-27 August 1999.

34. Castino, F. Festa, R. & Ratto, C.F. 1998. Stochastic modelling of wind velocities time series. Journal of Wind Engineering and Industrial Aerodynamics. **74-76**. pp. 141-151

35. Chanson, H. 1999. The Hydraulics of Open Channel Flow: An Introduction. First Edition. Arnold. Oxford, England. ISBN 0-340-74067-1

36. Chapman, T. 1997. Stochastic models for daily rainfall in the Western Pacific. Mathematics and Computers in Simulation. **43**. pp. 351-358

37. Chow, V.T. 1956. Open Channel Hydraulics. International Student Edition. McGraw & Hill. London. ISBN 0-07-Y85906-X

38. Chow, V.T. 1978. Evolution of Stochastic Hydrology. In Applications of Kalman Filter to Hydrology, Hydraulics and Water Resources. Ed. Chui, C. Stochastic Hydraulics Program, Pittsburgh, USA.

39. Coles , B J. 1998. Doggerland: a Speculative Survey. Proceedings of the Prehistoric Society **64.** pp 45-81

40. Conlan, K. & Rudd, T. 2000. Sustainable Estuarine Development? Cumulative Impact Study of the Humber. Journal of the Chartered Instn. Of Water and Environmental Management. **14**. pp 313-317

41. Copeland, R. 1989, Simulating Long-Term Sedimentation Trends on the Lower Mississippi River In Sediment Transport Modelling Proc. Int. Symp, New Orleans, Louisiana, Aug 14-18 1989. Ed. S. Y Wang. ASCE. New York. ISBN 0-87262-718-7.

42. Copperwait, P. O'Connell, P. Metcalfe, A. & Mawdsley, J. 1996. Stochastic point process modelling of rainfall. II. Regionalisation and diaggregation. Journal of Hydrology. **175**. pp. 47-65

43. Corti, S. & Pennati, V. 2000. A 3-D hydrodynamic model of river flow in a delta region. Hydrological Processes. **14** pp. 2301-2309.

44. Craig, R.F. 1992. Soil Mechanics. Fifth Edition. Chapman & Hall. London. ISBN 0-412-39590-8

45. Crookall, D. & Bradford, W. 2002. Impact of climate change on water resources planning. Proc. of Instn. Civil Engrs. Civil Engineering. **138**. Special Issue 2. pp. 44-48

46. Cunge, J. Holly, F & Verwey, A. 1980. Practical Aspects of Computational River Hydraulics. Pitman Publishing Limited. London. ISBN 0-273-08442-9

47. Davis, J. 1986. Statistics and Data Analysis in Geology. John Wiley & Sons, New York. ISBN 0-471-83743-1

48. Davison, A. & Hinkley, D. 1997. Bootstrap Methods and their Application. Cambridge University Press. Cambridge. ISBN 0-5121-73912

49. Dennis, J M. Spearman, J R. Dearnley, M P. 2000. The Development of a Regime Model for Prediction of the Long-Term Effects of Civil Engineering Activities on Estuaries. Phys. Chem. Earth (B). Vol **25.** no. 1. pp 45-50

50. Fahrmeir, L & Tutz, G. 2001. Multivariate Statistical Modelling Based on Generalised Linear Models. Springer-Verlag. New York. ISBN 0-3879-51873

51. Falconer, R. & Riddell, J. 1992. The Clyde dredging study. Proc. Instn. Civil Engrs Water, Maritime & Energy. **96**. pp. 81-94

52. Falconer, R. & Lin, B. 1997. Three-Dimensional Modelling of Water Quality in the Humber Estuary. Water Research. Vol. **31.** No. 5. pp. 1092-1102.

53. Forbes, G. 2000. The Practical Application of an Enhanced Conveyance Calculation in Flood Prediction. Unpublished Ph.D. Thesis, University of Glasgow, 194pp.

54. Fowler, H.J. 2000. The impacts of climatic change and variability on water resources in Yorkshire. Unpublished Ph.D. Thesis, University of Newcastle upon Tyne, 365pp.

55. Fowler, H J. & Kilsby, C G. 2002. A weather-type approach to analysing water resources drought in the Yorkshire region from 1881 to 1998. Journal of Hydrology. **262**. pp 177-192

56. Fowler, H. J. 2002. A regional frequency analysis of United Kingdom extreme rainfall from 1961-2000. International Journal of Climatology. Submitted September 2002.

57. Fowler, H. J. 2003. Private Communication.

58. Franks, T & Falconer, R. 1999. Developing procedures for the sustainable use of mangrove systems. Agricultural Water Management. **40**. pp.59-64.

59. Gessler, D. Hall, B. Spasojevic, M. Holly, F. Pourtaheri, H & Raphelt, N. 1999. Application of 3D Mobile Bed, Hydrodynamic Model. Journal of Hydraulic Engineering. Vol. **125**. No. 7 (July). pp.737-749

60. Gough, P. 1996. Potential impact of estuarine barrages on migratory fish in England and Wales. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

61. Halcrow. 1997. User Manual ISIS Flow, Halcrow/HR Wallingford, UK.

62. Havis, R. Alonso, C & King, J. 1996. Modelling Sediment in Gravel-Bedded Streams Using HEC-6. Journal of Hydraulic Engineering. Vol. **122**. No. 10 (October) pp. 559-564

63. Holly, F. & Spasojevic, M. 1999. Three-Dimensional Mobile-Bed Modelling of the Old River Complex, Mississippi River. Proceedings XXVIII IAHR Congress, Hydraulic Engineering for Sustainable Water Resources Management at the Turn of the Century. Graz, Austria, 22-27 August 1999.

64. Holz, K. & Feist, M. 1989. A Tracer Model for Morphological Simulations of an Estuary. In Sediment Transport Modelling Proc. Int. Symp, New Orleans, Louisiana, Aug 14-18 1989. Ed. S. Y Wang. ASCE. New York. ISBN 0-87262-718-7.

65. Hotchkiss, R & Bollman, F. 1997. Socio-economic Analysis of Reservoir Sedimentation. Energy and Water: Sustainable Development. Proc. 27th Congress of Internantional Assoc. for Hydr. Res. Water for a Changing Global Community. San Francisco, California. Aug 10-15, 1997

66. HR Wallingford. 1988. The Tees Weir – Upriver Morphological Model Studies, Report EX 1744 (July 1988)

67. H.R Wallingford. 1992 (a). Tees Barrage Study: Upriver Siltation, Report EX 2432. (February 1992)

68. HR Wallingford. 1992 (b). Tees Barrage Physical Model: Final Design Study, Report EX 2590. (October 1992).

69. HR Wallingford. 1996. Evaluation of 3D models for river flood applications. Report TR 6 (May 1996) I Lavedrine.

70. HR Wallingford. 1999. Guidelines for the Assessment and Planning of Estuarine Barrages: Report SR491. (June 1999)

71. HR Wallingford. 2002. Teesmouth Sediment Study, Report EX 4514. (March 2002)

72. Hudson-Edwards, K. Macklin, M. Taylor, M. 1997. Historic metal mining inputs to Tees River Sediment. The Science of the Total Environment. **194/195.** pp 437-445

73. Huggett, D. 1996. The Habitats Directive: a barrier to barrages? In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

74. Hunter, P. 1996. Cardiff Bay Barrage: design. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

75. Issacsen, D & Madsen, R. 1976. Markov Chains: Theory and Applications. John Wiley & Sons. USA. ISBN 471-42862-0

76. IPCC. 2003. The IPCC Data Distribution Centre. http://ipcc-ddc.cru.uea.ac.uk/asres/ghg_emissions.html (22.7.03)

77. James, G. 1992. Modern Engineering Mathematics. Addison-Wesley Publishers Limited. Wokingham. England. ISBN 0-201-18054-5

78. Janssen, M. Erlingsson, U. 2000. Measurement and Quantification of a Sedimentation Budget for a Reservoir with Regular Flushing. Regulated Rivers: Research and Management. **16**. pp 279-306

79. Jenkins, G. & Barron, E. 1997. Global climate model and coupled regional climate model simulations over the eastern United States: GENESIS and RegCM2 simulations. Global and Planetary Change. **15**. pp. 3-32

80. Jimoh, O. & Webster, P. 1996. The optimum order of a Markov chain model for daily rainfall in Nigeria. Journal of Hydrology. **185**. pp. 45-69.

81. Jimoh, O. & Webster, P. 1999. Stochastic modelling of daily rainfall in Nigeria: intra-annual variations of model parameters. Journal of Hydrology. **222**. pp. 1-17.

82. Jones, E. 2001. Private communication, email (27 July, 2001)

83. Kashefipour, S. Lin, B. Harris, E. & Falconer, R. 2002. Hydro-environmental modelling for bathing water compliance of and estuarine basin. Water Research. **36**. pp1854-1868

84. Kopmann, R. & Markofsky, M. 2000. Three-dimensional water quality modelling with TELEMAC-3D. Hydrological Processes. **14** pp. 2279-2292.

85. Kottegoda, N. T. 1980. Stochastic Water Resources Technology. The Macmillan Press Ltd. London. ISBN 0-333-22346-2

86. Lane, S. Biron, P. Bradbrook, K. Chandler, J. El-Hames, A. Richards, K & Roy, A. 1998. Numerical Modelling of Flow Processes at River Channel Confluences. Final Report to NERC Grant GR3/9715.

87. Lane, S. Bradbrook, K, Richards, K. Biron, P & Roy, A. 1999. The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches. Geomorphology. **29**. pp. 1-20

88. Lai, J & Shen, H. 1997. Desilting Reservoir Sediment Deposits by Drawdown Flushing. Energy and Water: Sustainable Development. Proc. 27th Congress of Internantional Assoc. for Hydr. Res. Water for a Changing Global Community. San Francisco, California. Aug 10-15, 1997

89. Lawrance, A. Kottegoda, N. 1977. Stochastic Modelling of Riverflow Time Series. J. R. Statistical Society, A. **140**. Part 1. pp1-47.

90. Lean, G, H. 1965. Accretion upstream of a weir. Civil Engineering and Public Works Review. Volume **60**. January. pp. 83-86.

91. Le Normant, C. 2000. Three-dimensional modelling of cohesive sediment transport in the Loire estuary. Hydrological Processes. **14** pp. 2231-2243.

92. Limbrick, K. Whitehead, P. Butterfield, D. & Reynard, N. 2000. Assessing the potential impacts of various climate change scenarios on the hydrological regime of the River Kennet at Theale, Berkshire, south-central England, UK: an application and evaluation of the new semi-distributed model, INCA. The Science of the Total Environment. **251/252**. pp. 539-555.

93. Lin, B. Kashefipour, S. Harris, E. & Falconer, R. 2001. Modelling Flow and Water Quality in Estuarine and Riverine Water: A Dynamically Linked 1-D and 2-D Models Approach. Proceedings of XXIX IAHR Congress, 21st Century: The New Era for Hydraulic Research and Its Applications. September 16-21, 2001 Beijing, China

94. Lin, B. & Falconer, R. 1997. Three-dimensional Layer-integrated Modelling of Estuarine Flows with Flooding and Drying. Estuarine, Coastal & Shelf Science. **44**. pp.737-751.

95. Lin, B. & Falconer, R. 2001. Numerical modelling of 3-d tidal currents and water quality indicators in the Bristol Channel. Proc. Instn. Civ. Engnrs. Water & Maritime Engineering. **148**. Issue 3. pp155-166.

96. Lourmas, G. 2002. Development of stochastic rainfall generators. Unpublished MSc thesis. Department of Civil Engineering, University of Glasgow.

97. Macklin, M. Hudson-Edwards, K. & Dawson, E. 1997. The significance of pollution from historic metal mining in the Penine orefields on river sediment contaminant fluxes to the North Sea. The Science of the Total Environment. **194/195**. pp 391-397.

98. Malcherek, A. 2000, Application of TELEMAC-2D in a narrow estuary tributary. Hydrological Processes. **14**. pp. 2293-2300.

99. Maskell, J & Barraclough, A. 1996. The Impacts of Barrages on Water Quality: Predictions and Reality. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

100. Matalas, M. C. 1967. Mathematical Assessment of Synthetic Hydrology. Water Resources Research. Vol **3**. No. 4. pp 937-945

101. McGarvey, C. 1996. Managing the impacts of a barrage on outdoor recreation. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

102. Meadowcroft, I. Bettess, R & Reeve, C. 1992. Numerical Modelling of Reservoir Sedimentation. In Water Resources and Reservoir Engineering. Ed. Parr, N. Charles, A. & Walker, S. Thomas Telford, London. ISBN 0-7277-1602-1

103. Metcalfe, A. 1997. Statistics in Civil Engineering. First Edition. Arnold. London. ISBN 0-340-676604

104. Metcalfe, A. 1994. Statistics in Engineering, A Practical Approach. First Edition. Chapman & Hall. London, Great Britain. ISBN 0-412-40220-2

105. Mitchell, D. 1990. The Use of Vegetation and Land-Use Parameters in Modelling Catchment Sediment Yields. In Vegetation and Erosion: Processes and Environment. J.B Thomas. pp 289-316.

106. Mitchell, T. & Hulme, M. 1999. Predicting regional climate change: living with uncertainty. Progress in Physical Geography. Vol. **23**. Issue 1. pp. 57-78

107. Montanari, A. Longoni, M. & Rosso, R. 1999. A Seasonal Long-Memory Stochastic Model for the Simulation of Daily River Flows. Phys. Chem. Earth (B) Vol. **24**. No.4. pp 319-324

108. Morvan H., Pender G., Wright N. and Ervine D. A. 2000. Three-dimensional modelling of flow mechanisms in flooded meandering channels. Proc. of Int. Symp. On Flood Defence. Kassel, Sept. 2000. Vol. 1. pp D153 - D162.

109. Morvan H., Pender G., Wright N.G. and Ervine D.A. 2001. Three-Dimensional

Hydrodynamics of Meandering Compound Channels. Journal of Hydraulic Engineering, ASCE, **128**(7), pp.674 – 682

110. Nelson, T. 1999. SIMBA: Sustainability in Managed Barrages. http://www.dur. ac.uk/t.j.nelson (12.02.03)

111. NRFA. 2002. National River Flow Archive. http://www.ncl.ac.uk/ih/nfra/index.htm (15/09/02)

112. Novis, C. 1999. Identification of Pollution Sources to the River Tees, vol. 1 – Report. Unpublished MSc thesis, Department of Engineering, University of Durham.

113. Odd, N. V. 1990. A Review of Methods of Extrapolating Tidal Model Predictions to Long Term Siltation Effects in Estuaries. Dept. of Energy Report – ETSU TID 4080

114. Onoz, B & Bayazit, M. 1995. Best-fit distributions of largest available flood samples. Journal of Hydrology. **167**. pp. 195-208

115. Onoz, B & Bayazit, M. 2001. Effect of the occurrence process of the peaks over threshold on the flood estimates. Journal of Hydrology. **224**. pp. 86-96

116. Otto, A J. 1999. Numerical modelling of long-term effects of rehabilitation measures on bedload transport. . Proceedings XXVIII IAHR Congress, Hydraulic Engineering for Sustainable Water Resources Management at the Turn of the Century. Graz, Austria, 22-27 August 1999.

117. Palmieri, A. Shah, F & Dinar, A. 2001. Economics of reservoir sedimentation and sustainable managements of dams. Journal of Environmental Management. **61**. pp. 149-163

118. Paquier, A. Massart, S. Krzyk, M & Cetina, M. 1999. 2-D Models for Suspended Sediment Transport – Comparitive Use for the Case of Ptuj Lake. Proceedings XXVIII IAHR Congress, Hydraulic Engineering for Sustainable

Water Resources Management at the Turn of the Century. Graz, Austria, 22-27 August 1999.

119. Paquier, A. 2001. Combined use of 1-D and 2-D Models for simulating dam-break waves. Proceedings of XXIX IAHR Congress, 21st Century: The New Era for Hydraulic Research and Its Applications. September 16-21, 2001 Beijing, China

120. Parkin, S. 2000. Sustainable development: the concept and the practical challenge. . Proc. of Instn. Civil Engrs. Civil Engineering. **138**. Special Issue 2. pp. 3-8

121. Pegram, G. 1980. A Continuous Streamflow Model. Journal of Hydrology. **47**. pp 64-89

122. Pegram, G. 1989. Why Stochastic Hydrology? Civil Engineer South Africa. Vol. **31**. 10. pp 345-356

123. Perrin, C. Michel, C. & Andreassian, V. 2002. Long-term low flow forecasting for French rivers by continuous rainfall-runoff modelling. BHS Occasional Paper No. 13. pp 21-29

124. Pilling, C. & Jones, J. 1999. High resolution climate change scenarios: implications for British runoff. Hydrological Processes. **13**. pp. 2877-2895.

125. Pilling, C. & Jones, J. 2002. The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye experimental catchment, mid-Wales. Hydrological Processes. **16**. pp. 1201-1213.

126. Price, M. 1998. Water storage and climate change in Great Britain – the role of groundwater. Proceedings Instn. Civil Engrs. Water Maritime & Energy. **130**. pp. 42-50.

127. Prudhomme, C. Reynard, N. & Crooks, S. 2002. Downscaling of global climate models for flood frequency analysis: where are we now? Hydrological Processes. **16**. pp. 1137-1150.

128. Randle, T. 1989. Sediment Transport Modelling Considerations. In Sediment Transport Modelling Proc. Int. Symp, New Orleans, Louisiana, Aug 14-18 1989. Ed. S. Y Wang. ASCE. New York. ISBN 0-87262-718-7.

129. Reeve, C E. 1992. Trapping efficiency of reservoirs. In Water Resources and Reservoir Engineering. Ed. Parr, N. Charles, A. & Walker, S. Thomas Telford, London. ISBN 0-7277-1602-1

130. Reynard, N. Prudhomme, C. & Crooks, S. 2001. The Flood Characteristics of Large U.K. Rivers: potential effects of changing climate and land use. Climatic Change. **48**. pp. 343-359

131. Reynolds, C. 1996. The threat of algal blooms in proposed estuarine barrages: models, predictions and risks. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

132. Roberts, G. 1998. The effects of possible future climate change on evaporation losses from four contrasting UK water catchment areas. Hydrological Processes. **12**. pp 727-739.

133. Robson, A & Reed, D. 1999. The Flood Estimation Handbook: Vol.3. Statistical procedures for flood frequency estimation. Wallingford. Institute of Hydrology. ISBN 0948540915. m

134. Rompaey, A. Govers,G. & Puttemans,C. 2002. Modelling Land Use Changes and their Impact on Soil Erosion and Sediment Supply to Rivers. Earth Surface Processes and Landforms. **27**. pp 481-494

135. Rosenbaum, M. Rosen, L. & Gustafson, G. 1997. Probabilistic models for estimating lithology. Engineering Geology. **47**. pp. 43-55

136. Rowentree, D. 1981. Statistics Without Tears. Penguin Books Ltd. Middlesex.

137. Sahin, A & Sen, Z. 2001. First-order Markov Chain approach to wind speed modelling. Journal of Wind Engineering and Industrial Aerodynamics. **89**. pp. 263-269

138. Salas, J. & Sin, H. 1999. Uncertainty Analysis of Reservoir Sedimentation. Journal of Hydraulic Engineering. Vol. **125**. No. 4. pp339-350

139. Samuels. 1989. Backwater lengths in rivers. Proc. Istn. Civil Engrs. Part 2. **87**. pp 571-582

140. Samuels, P. 1996. The Effects of the Cardiff Bay Barrage on Flooding in Cardiff City. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

141. Schreider, S. Jakeman, A Dyer, B. & Francis, R. 1997. A combined deterministic and self –adaptive stochastic algorithm for streamflow forecasting with application to catchments of the Upper Murray Basin, Australia. Environmental Modelling & Software. Vol. **12** No. 1. pp. 97-104

142. Shaw, E. M. 1994. Hydrology in Practise, 3rd Edition. Chapman & Hall. London. ISBN 0-412-48290-8

143. Shaw, T. 1995. Environmental effects of estuary barrages. Proc. Instn. Civil Engrs Water, Maritime & Energy. **112**. pp. 48-59

144. Sheail, J. 2000. A barrage of poisonous water – inter-war research on the river Tees. Water Policy. pp 299-312.

145. Simmons, I. & Tooley, M. 1981. The Environment in British Prehistory. Duckworth & Co. Limited. London. ISBN 07156-1441-X

146. Simpson, D. 2002. The River Tees. http://ourworld.compuserve.com /homepages/north_east_england_history_page/RIVER_TEES.htm (16/10/02)

147. Singh, R. 1998. Land use/cover changes, extreme events and ecohydrological responses in the Himalayan region. Hydrological Processes. **12**. pp 2043-2055

148. Sinha, S. Sotiropoulos, F & Odgaard, A. 1998. Three-Dimensional Numerical Model for Flow Through Natural Rivers. Journal of Hydraulic Engineering. Vol. **124**. No. 1. (January) pp. 13-24

149. Siyam, A M. Yeoh, J S. & Loveless, J H. 2001. Sustainable Reservoir Sedimentation Control. Proc. of XXIX IAHR Congress, Sept 16-21, Beijing, China.

150. Spearman, J R. Dearnley, M P. & Dennis, J M.1996. A Regime Approach to the Long-Term Prediction of the Impacts of Tidal Barrages on Estuary Morphology. In Barrages: Engineering Design and Environmental Impacts. Ed Burt, N & Watts, J. John Wiley & Sons Ltd. ISBN 0-471-96857-9

151. SRES. 2000. Special Report on Emission Scenarios: Summary for Policy Makers. A Special Reposrt of Working Group III of the Intergovernmental Panel on Climate Change.

152. Thorne, C. Hey, R.& Newson, M. 1997. Applied Fluvial Geomorphology for River Engineering & Management. First Edition. John Wiley. West Sussex, England. ISBN 0-471-96968-0

153. UKCIP (a) 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Briefing Report. Ed. Hulme, M. Turnpenny, J. & Jenkins, G. pub. Tyndall Centre for Change Research. Norwich. ISBN 0-902170-65-1

154. UKCIP (a) 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Ed. Hulme, M. Turnpenny, J. & Jenkins, G. pub. Tyndall Centre for Change Research. Norwich. ISBN 0-902170-60-0

155. Vardy, A. 1990. Fluid Principles. McGraw Hill Book Company. London. ISBN 0-07-707205-7

156. Walker, D. 2001. Modelling sedimentation processes in a constructed stormwater wetland. The Science of the Total Environment. **266**. pp. 61-68

157. Walker, J. 2001. The Use of Sediment Modelling Techniques to Address the Differing Needs of Management on the River Eden, Cumbria, UK. Journal of the Charted Instn. Of Water and Environmental Management. Vol. **15**. no. 4 (November) pp.252-257

158. Wass, P.J. & Leeks, G.J.L.1999. Suspended Sediment Fluxes in the Humber Catchment, UK. Hydrological Processes, **13**. pp 935-953.

159. Werrity, A. 2002. Living with uncertainty: climate change, river flows and water resource management in Scotland. The Science of the Total Environment. **294**. pp. 29-40.

160. Wheater, H. Onof, C. 1994, Improved fitting of the Bartlett-Lewis rectangular pulses model for hourly rainfall. Hydrol. Sci. J-des Sci. Hydrologiques **39**, pp. 663-680.

161. Wheater, H. Onof, C. 1995. Modelling of rainfall time series using the Bartlett-Lewis model. Proc. Instn Civ. Engrs Wat. Marit. & Energy **112**, pp. 362-374.

162. White, S (ed.). 2000 SIMBA Sustainability in Managed Barrages Year One Reports, April 2000.

163. White, S (ed.). 2001 SIMBA Sustainability in Managed Barrages Year Two Reports, April 2001

164. White, S (ed.). 2002 SIMBA Sustainability in Managed Barrages Year Three Reports, April 2002

165. White, P. Butcher, D & Labadz, J. 1997. Reservoir Sedimentation and Catchment Sediment Yield in the Strines Catchment, U.K. Phys. Chem. Earth. Vol. **22**. No. 3-4. pp. 321-328

166. White, W. 1990. Reservoir Sedimentation and Flushing. Proceedings of International Conference on Water Resources in Mountainous Regions, Lausanne, 27 August-1 September. Switzerland.

167. White, W. Milli, H. Crabbe, A. 1975. Sediment transport theories: a review. Proceedings of Instn. Civil Engrs. **59**. Part 2. pp. 265-292

168. Wilson, E, M. 1974. Engineering Hydrology. The Macmillan Press LTD. London. Second Edition. ISBN 0-333-17443-7

169. Wood, A. Lettenmaier, D & Palmer, R. 1997. Assessing Climate Change Implications for Water Resource Planning. Climatic Change. **37**. pp. 203-228.

170. Worrall, F. 2000. Private communication.

171. Worrall, F. & Burt, T. 1998. Decomposition of river water nitrate time-series – comparing agricultural and urban signals. The Science of the Total Environment. **210/211**. pp. 153-162

172. Worrall, F. Wooff, D. & McIntyre, P. 1998. A simple modelling approach for water quality: The example of an estuarine impoundment. The Science of the Total Environment. **219**. pp. 41-51

173. Wright, J. & Worrall, F. 2001. The Effects of River Flow on Water Quality in Estuarine Impoundments. Phys. Chem. Earth (B) Vol. **26**. No. 9. pp. 741-746

174. Wright, S. Holly, F M. Bradley, A A. & Krajewski, W. 1999. Long-term simulation of thermal regime of Missouri River. Journal of Hydraulic Engineering. Vol. **125,** no. 3, pp 242-252

175. Wu, Y. Falconer, R & Uncles, R. 1998. Modelling of Water Flows and Cohesive Sediment Fluxes in the Humber Estuary, UK. Marine Pollution Bulletin. Vol. **37**. Nos. 3-7. pp. 182-189.

176. Wu, Y. & Falconer, R. A mass conservative 3-D numerical model for predicting solute fluxes in estuarine waters. Advances in Water Resources. **23**. pp.531-543.

177. Xu, Z. Schumann, A. Brass, C. Li, J. & Ito, K. 2001. Chain-dependent Markov correlation pulse model for daily streamflow generation. Advances in Water Resources. **24**. pp. 551-564.

178. Zeigler, C. Nisbet, B. 1995. Long-term Simulation of Fine-Grained Sediment Transport in Large Reservoir. Journal of Hydraulic Engineering. Vol. **121**. No. 11. pp 773-781

179. Zhide, Z. & Xiaoqing, Y. 1997. Reservoir Sedimentation in China – Experiences and Lessons. Energy and Water: Sustainable Development. Proc. 27th Congress of Internantional Assoc. for Hydr. Res. Water for a Changing Global Community. San Francisco, California. Aug 10-15, 1997.

180. Zhou, F. Chen, B & Song, C. 1997. 2-D Flow and Sediment Simulation for the Flood Regulation of a Reservoir with Water Intake. Proc. 27th Congress of Internantional Assoc. for Hydr. Res. Water for a Changing Global Community. San Francisco, California. Aug 10-15, 1997.

APPENDIX A

Eigenvector Method for Climate Change Predictions

Having used the Markov Chain method to generate a long synthetic flow record which retains the statistical properties of the series, it would be convenient to perturb the transition matrix in some meaningful way so it can be used to create a new synthetic flow series which takes account of climate change.

Predictions for the change in precipitation and temperature in the region can be obtained for global climate models (GCM) for different possible climate change scenarios for 20, 50 or 80 years into the future. These temperature and precipitation predictions for the future can then be used to predict the future mean flow in the river under particular climate change scenarios. From the prediction of future mean flow for any season, an estimation of the new flow duration curve, which accounts for climate change, can be made. As an alternative to this method, future predictions of flow duration curves for a particular catchment may be found in literature as a result of the hydrological studies using rainfall generators and catchment models mentioned in chapter 2, section 2.3.3. This new flow duration curve now defines the river's predicted response to climate change, and it would be very useful to be able to use this information directly in the transition matrix.

One of the properties of irreducible, aperiodic, positive and persistent, first order Markov matrices and stochastic matrices is that, in general, there exists a 'long run distribution', otherwise known as an invariant probability distribution or stationary distribution π. This limiting distribution is found by multiplying the matrix **P** by itself many times ie. $\mathbf{P}^n$.

$$\lim_{n\to\infty} \pi_0 \mathbf{P}^{(n)} = \pi$$

Equation App A. 1

where π_0 is an arbitrary initial probability distribution

The proof of this theorem can be found in Isaacson & Madsen (1976). This long run distribution defines the overall invariant probability distribution. When applied to model flow, π is the probability density distribution for the various previously defined flow states. Hydrologists usually refer to the cumulative probability function or distribution as the flow duration curve (the probability density function is a derivative of the cumulative distribution function).

Finding this limiting distribution by consecutive multiplication of matrix **P** by itself can be time consuming. However, it can be shown (Isaacson & Madsen, 1976) that the stationary distribution also corresponds to the dominant eigenvector of the transition probability matrix. This gives the probability density function, which can be translated into a cumulative distribution function to give, in this case, the flow duration curve of the river.

This information can be used to formulate a strategy for perturbing the transition matrix. First consider decomposing the matrix:

$$\mathbf{P} = \mathbf{S}\mathbf{D}\mathbf{S}^{-1}$$

Equation App A. 2

where: **P**= original matrix

D= diagonal matrix with the eigenvalues down the major diagonal

$$\mathbf{D} = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_k \end{bmatrix}$$

where λ denotes the eigenvalues

S= matrix of eigenvectors $\mathbf{S} = \begin{bmatrix} \gamma_{\lambda 11} & \gamma_{\lambda 21} & \cdots & \gamma_{\lambda k1} \\ \gamma_{\lambda 12} & \gamma_{\lambda 22} & & \gamma_{\lambda k2} \\ \vdots & & \ddots & \vdots \\ \gamma_{\lambda 1k} & \gamma_{\lambda 2k} & \cdots & \gamma_{\lambda kk} \end{bmatrix}$

where $\{\gamma_{\lambda 1i}\}_{i=1}^{k}$ is the eigenvector relating to the eigenvalue λ_1

$\mathbf{S}^{-1}$= is the inverse of matrix **S**

A proof of this theorem can be found in Isaacson & Madsen (1976).

For many areas of the U.K predictions of flow exceedence curves under climate change scenarios exist (Fowler, 2002). However, they are usually the result of long and involved research projects. Practicing engineers will never have the resources available to reproduce rainfall in hydrological models that generate these. Therefore there is an urgent need for a method that can utilise the published estimates of flow duration curves.

The first column of matrix **S** is the dominant eigenvector and so is the stationary probability density distribution for flows. Now suppose that a new probability density distribution can be found from engineering literature as described. To construct synthetic time series that conform to this new probability density distribution one approach may be to just replace the old dominant eigenvector for the matrix derived from historic data, with the new probability density distribution. All the other columns in **S** remain the same.

Therefore, a new matrix is created using the equation:

$$\mathbf{P}_{\mathbf{new}} = \mathbf{SDS}^{-1}$$

Equation App A. 3

where: $\mathbf{P}_{\mathbf{new}}$= new transition probability matrix

D= diagonal matrix with the eigenvalues down the major diagonal – all eigenvalues stay constant (ie, the same as the original matrix)

$$\mathbf{D} = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{bmatrix}$$

S= matrix of eigenvectors using the new dominant eigenvector and leaving the non-dominant eigenvectors the same (in this case the remaining eigenvectors that were calculated from the original matrix)

$$\mathbf{S} = \begin{bmatrix} \gamma_{\lambda new1} & \gamma_{\lambda 21} & \cdots & \gamma_{\lambda k1} \\ \gamma_{\lambda new2} & \gamma_{\lambda 22} & & \gamma_{\lambda k2} \\ \vdots & & \ddots & \vdots \\ \gamma_{\lambda newk} & \gamma_{\lambda 2k} & \cdots & \gamma_{\lambda kk} \end{bmatrix}$$

where $\{\gamma_{\lambda newi}\}_{i=1}^{k}$ is the new eigenvector which defines the river's response to climate change

$\mathbf{S}^{-1}$= is the inverse of matrix **S**

Once the new matrix has been calculated, it can be used as the basis for constructing a new time series. The method would then take on the same form as that described in the flow chart of the technique (Chapter 4, Fig 4.5). Theoretically, if the matrix holds the new statistical properties of the series that account for climate change, then this should propagate through the matrix to the new predicted time series.

Unfortunately, this method has been considered to be non-viable. It became clear after extensive investigation and discussion that the proposed method may have been a mathematical over-simplification of the problem. The method proposes that the dominant eigenvector changes under climate change, however the re-composition of the matrix works on the assumption that the remaining eigenvectors and eigenvalues from the decomposition of the original matrix are unchanged. This assumption is considered to be too simple.

If the dominant eigenvector is changed, then it follows that each of the eigenvectors should be free to move during the re-composition of the matrix. However, if the eigenvectors, other than the dominant one, are free to move then their corresponding eigenvalues must also be free to move. Hence the proposed solution to the problem becomes non-unique due to the fact that it does not allow for enough constraints on the system during the re-composition of the new matrix. The remaining eigenvectors describe physical aspects of the time series, just as the dominant one describes the long-run distribution however, the properties of the other eigenvectors are not as easily defined. Therefore constraining them, or allowing them to move within certain, pre-defined limits, becomes an impossible task. The same problem arises for the eigenvalues, which should be allowed to move during the re-composition of the matrix. The dominant eigenvalue of the system will always be 1 and related to the dominant eigenvector, however the remaining eigenvalues can vary as long as the value is never equal to or greater than 1, and is never less than 0. The requisite constraints for the system become larger, as the original matrix increases; in fact, the number of constraints necessary double each time the matrix increases its size by one. Consequently this proposed method must be discarded as a possible method for perturbing a Markov matrix to account for climate change. This is because defining the numerous constraints required for the system is impossible at this stage unless a more detailed definition for the physical meaning for the eigenvectors of the system can be determined.

APPENDIX B

Gate Operation Rules for the Gated Weir

Rule1

IF (LEVEL(s1).GT.-2.15.AND.LEVEL(s1).LE.-2)

THEN MOVE=-0.25

END

Rule2

IF (LEVEL(s1).LE.-2.15.AND.LEVEL(s1).GE.-2.55)

THEN MOVE=0.0

END

Rule3

IF (LEVEL(s1).LT.-2.55.AND.LEVEL(s1).GE.-2.7)

THEN MOVE=0.25

END

Rule4

IF (LEVEL(s1).GT.-2.0.AND.LEVEL(s1).LE.-1.2)

THEN MOVE=-0.4

END

Rule5

IF (LEVEL(s1).LT.-2.7)

THEN MOVE=0.4

END

Where s1 is the node directly upstream of the barrage.