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WATER QUALITY PROFILE OF AN URBANISING CATCHMENT – NINGI CREEK CATCHMENT

Final Report

Steven Carroll
Les Dawes
Ashantha Goonetilleke
Megan Hargreaves

Centre for Built Environment and Engineering Research
Faculty of Built Environment and Engineering
Queensland University of Technology

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EXECUTIVE SUMMARY

Background

Contamination of waterways is becoming a critical issue, especially in areas undergoing rapid urban development. Faecal contamination of water resources is of critical importance specifically in relation to protection of public health. Additionally, increased pollutant loading into waterways can also cause significant environmental degradation. The Ningi Creek catchment in Caboolture Shire is a prime example of an area which is being subjected to increasing pressures due to changes in land use. Recent studies performed by the Department of Primary Industries (DPI) on the water in Ningi Creek, revealed high levels of faecal coliforms, indicating a serious faecal pollution problem. The catchment area of Ningi Creek contains a number of land uses, including forestry areas, farmland areas, aquaculture, rural-residential and residential developments serviced by on-site wastewater treatment systems. Any of these may cause contamination of the ground and surface water, particularly during rainfall events.

Project

The research project was confined to the Ningi Creek catchment in Caboolture Shire, focusing specifically on the surface and groundwater along the Creek. The main focus of the research project involved three main objectives:

1. To develop a water quality profile along the length of the Ningi Creek. This included the identification and assessment of faecal coliform levels and *Lyngbya* 'trigger parameters' which would enable the identification of land uses and regions within the catchment that contributes to pollutant loads.
2. To identify 'hot spots' for faecal coliforms and *Lyngbya* 'trigger contaminants' in Ningi Creek, and the corresponding contaminant sources.
3. To develop a critical point monitoring program for Ningi Creek catchment, to identify specific areas to be monitored in order to help safeguard the region's aquatic resources.

The project adopted a holistic approach, identifying significant factors contributing to the pollution of Ningi Creek, rather than just the sources of faecal contamination and other pollutants. Essentially, it is intended that the knowledge generated through this project will contribute to the development of a Waterway Management Plan for the Ningi Creek

Catchment. Whilst the source and impact of faecal coliforms on water quality in Ningi Creek with regard to the operation of oyster leases were the primary focus, useful knowledge was also created to address catchment management considerations in relation to the control of a selected number of 'trigger contaminants' for the cyanobacteria *Lyngbya majuscula*.

Outcomes

The summary of outcomes from the comprehensive study undertaken include:

1. The development of a water quality profile for Ningi Creek to enable an overall evaluation of the catchment and the different land uses that may contribute to the pollutant loading;
2. The identification of the various sources of faecal contamination in order to allow appropriate management strategies to be implemented to minimise faecal bacterial loading into Ningi Creek;
3. The identification of sources of the trigger parameters which cause and sustain *L. majuscula* blooms in Ningi Creek; and
4. The development of a critical point monitoring program to enable the Caboolture Shire Council to monitor, manage and mitigate the pollutant inputs into Ningi Creek.

The key findings and recommendations from the study are discussed below.

SUMMARY OF KEY FINDINGS

The key findings from the research project are as follows:

- The major sources of faecal contamination within Ningi Creek altered depending on the monitoring locations. Faecal sources in the upper catchment were found to be from nonhuman sources. This is a result of the mixed agricultural, natural bushland and pine plantations forming the major land uses in the upper segment of the catchment. However, in the downstream estuarine sections, human source faecal contamination increased with a majority of the faecal contamination around the urbanised development identified as human. This is most likely related to the increase in urbanisation and the increase in on-site wastewater treatment systems within this area. Although more detailed analysis is required to confirm the major non-human sources, present indications suggest that a majority of the non-human isolates found in the lower estuarine sections of Ningi Creek (SW1-SW7) are from wild sources, with sporadic increases at various locations of either domesticated animals or livestock following rainfall events. Conversely, in the upstream segments of the catchment the majority of non-human isolates were identified as domesticated animals, with occasional increases in wild isolates.

- The trigger parameters responsible for causing *Lyngbia majuscula* blooms are related to naturally occurring conditions, typically after prolonged periods of calm water, elevated temperature and light conditions. However, although certain contaminants may play a minor role in the initial onset of a bloom, several key contaminants assessed through this research play a significant role in sustaining blooms, which allows the bloom to spread and stay visible for extended periods. The key contaminants associated with sustaining these blooms are nitrate (NO_3^-), phosphate (PO_4^{3-}), dissolved organic carbon (DOC) and iron (Fe). Higher concentrations of PO_4^{3-} were evident following rainfall surrounding the more urbanised areas. In contrast, more steady supplies of DOC and Fe were found to be emitted from upstream segments, particularly from sampling points near the pine plantations. Therefore, as both PO_4^{3-} and Fe are utilised by *L. majuscula* during bloom outbreaks, it appears that abundant sources of the necessary contaminants are available continuously.

- The development of a water quality profile along Ningi Creek has enabled an overall evaluation of the catchment and the various land use sources that may contribute to the pollutant loading into the Creek. This will provide an essential basis for the development of catchment management protocols to minimise contaminant sources and loadings.

- Identification of the key critical parameters in relation to the water quality profile and the critical monitoring locations will allow more detailed assessment of Ningi Creek into the future. This will provide Caboolture Shire Council with the necessary key information required to ascertain trigger parameters to enable more effective management controls.

RECOMMENDATIONS

Based on the outcomes of the research undertaken and the developed water quality profile, the following recommendations are made:

1. The water quality profile developed for Ningi Creek should be used as a basis for assessing future land use changes in order to minimise pollutant loadings;
2. The development of management strategies based on identified faecal contamination sources to minimise faecal bacterial loadings to Ningi Creek;
3. The development of management strategies to control and reduce trigger parameters from identified sources to minimise major *L. majuscula* blooms;
4. To further refine the study on *L. majuscula* trigger parameters as more quantitative information relating to cell counts and bloom incidents become available; and
5. The implementation of the critical point monitoring program developed to provide continual monitoring of the critical pollutant parameters in Ningi Creek.

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ABBREVIATIONS

ARCC	Average Rate of Correct Classification
ARP	Antibiotic Resistance Pattern
BST	Bacterial Source Tracking
DA	Discriminant Analysis
DC	Total Dissolved Carbon
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPI	Department of Primary Industries
EC	Electrical Conductivity
E. coli	*Escherichia coli*
Fe	Total Iron
GPS	Global Positioning System
GW#	Groundwater monitoring location
IC	Total Inorganic Carbon
ICP–OES	Inductively Coupled Plasma–Optical Emission Spectroscopy
L. majuscula	*Lyngbia majuscula*
Mn	Total Manganese
NO_3^-	Nitrate
OWTS	On-site Wastewater Treatment System
PCA	Principal Component Analysis
PO_4^{3-}	Phosphate
SW#	Surface water monitoring location
TC	Total Carbon
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
WT	Water Table

CHAPTER 1.0

INTRODUCTION

1.1 Overview

Contamination of waterways is a critical issue, particularly in areas undergoing rapid development. Current land use practices and increasing anthropogenic activities can increase pollutant loadings into waterways causing detrimental impacts. Faecal contamination of water resources is of critical importance specifically in relation to the protection of public health. Coastal waterways in particular are widely used for aquaculture industry and recreational activities. Pollution of these water resources with pathogenic organisms is of prime concern. It is widely recognised in scientific literature that increases in faecal contamination typically occur after rainfall events (Ackerman and Weisberg 2003, Muirhead et al 2004, Noble et al 2003). This is caused by increased stormwater runoff from urban developments due to the presence of impervious area, and high faecal bacterial loading caused by the use of manure for fertilisation of agricultural land, as well as general agricultural practices such as livestock grazing near water courses. However, at present there is no easy and cost efficient means of distinguishing between human and non-human faecal sources, and general faecal and pathogenic organisms.

Unfortunately, faecal contamination is not the only threat faced by waterways in an urbanising catchment. Increased pollutant loading into waterways can also cause significant environmental degradation. Nutrient loadings caused by changes in land use or current management practices can cause nutrient enrichment of water resources, resulting in eutrophication, as well as triggering and sustaining algae blooms. The occurrence of large algae blooms is not only unsightly and aesthetically unpleasant, but certain strains, such as *Lyngbia majuscula*, can pose significant public health impacts.

This report investigates the impacts of urban development and changes in land use on the water quality of Ningi Creek, Caboolture Shire. An initial discussion of the effects of faecal contamination of water resources is provided, followed by a detailed discussion of the investigations undertaken to develop a surface water profile of faecal contamination and other environmental pollutants along Ningi Creek. The impacts of surrounding land

uses on the groundwater quality surrounding Ningi Creek, in particular in the vicinity of the urban development of Bribie Gardens was also investigated. The separation of faecal bacteria into human and non-human sources is investigated through the use of Antibiotic Resistance Pattern (ARP) analysis. This is an efficient and cost effective means of identification of faecal source contamination. Additionally, an assessment of chemical pollutants is also undertaken with emphasis on chemical trigger parameters for initialising and sustaining blooms of *Lyngbia majuscula*, a form of cyanobacteria common to the area with reports of blooms occurring on a regular basis.

1.2 Background

The Ningi Creek catchment in Caboolture Shire is a prime example of an area which is being subjected to increasing pressures due to changes in land use. Recent investigations by the Department of Primary Industries (DPI) (Beattie and Dexter 2002) on Ningi Creek revealed high levels of faecal coliforms, indicating a serious faecal pollution problem. This contamination was shown to follow rainfall events and has resulted in the closure of two existing oyster leases in the area. The catchment area of Ningi Creek includes a number of potential sources of faecal coliforms and other pollutants, including forestry areas, farmland areas and rural-residential and urban residential developments serviced by on-site wastewater treatment systems. Any of these may cause contamination of the waterway.

1.3 Research Aims and Objectives

The primary aims of the research conducted at Ningi Creek were:

1. To identify influential catchment factors that contribute to microbiological contamination and generation of *Lyngbya* 'trigger contaminants'.
2. To identify possible sources of faecal coliforms and *Lyngbya* 'trigger contaminants'.
3. To investigate linkages between surface and groundwater contamination along with any water table fluctuation which contribute to pollutant loads.

The primary objectives were:

1. To develop a profile of faecal coliform levels and *Lyngbya* 'trigger contaminants' along Ningi Creek which would enable the identification of land uses and regions within the catchment that contributes to pollutant loads.

2. To identify ‘hot spots’ for faecal coliforms and *Lyngbya* ‘trigger contaminants’ in Ningi Creek.
3. To identify specific areas to be monitored in order to develop a critical point monitoring program for Ningi Creek catchment to help safeguard the region’s aquatic resources.

1.4 Scope

The main focus of this research project was to conduct detailed groundwater and surface water investigations with the aim of identifying the major sources of faecal contamination within the Ningi Creek catchment. The identification of sources was limited to major land uses, and this report does not specifically pin point exact source locations. The outcomes of this research should be utilised to develop appropriate management strategies across the entire catchment, and not solely focus on individual pollutant sources.

Additionally, the research project also aimed to investigate the major trigger parameters that can cause and sustain blooms of *Lyngbia majuscula*, which is common to Ningi Creek and the surrounding Moreton Bay estuarine system. Unfortunately, no blooms were recorded during the sampling period, and assessment of collected data is only presumptive.

1.5 Project Area

The catchment under investigation is located in the Caboolture region, Queensland, Australia. Figure 1.1 shows the land uses in Ningi Creek catchment and the corresponding catchment boundary. Routine monitoring of the lower section of the catchment by the DPI (Beattie and Dexter, 2002) indicated that high levels of faecal coliforms were evident within the major waterways in the catchment. The Ningi Creek catchment covers 47.1km^2 and drains into the Pumicestone Passage and eventually into Moreton Bay. The catchment consists of relatively flat terrain with mixed land use. These include urban development, all of which rely on on-site wastewater treatment systems, agricultural areas mostly consisting of livestock production, small areas of pineapple farming, aquaculture and large areas of plantation and natural forest in the upper catchment. Essentially, the main area of concern in relation to human faecal contamination is the developed area of the catchment. The intertidal zone is surrounded by two urban residential developments, Bribie Gardens

located on the southern side, and Toorbul Point on the northern side of Ningi Creek. These urban residential developments are solely reliant on on-site wastewater treatment systems for the treatment and disposal of domestic sewage. It has been noted that these areas, particularly Bribie Gardens, may be a potential source of faecal contamination into Ningi Creek.

Ningi Creek has had several leases for the production oysters, which have recently been closed due to the identification of elevated faecal coliform counts, notably after rain events. A majority of the land use in the catchment, upstream of the developed areas of interest have mixed farmland and native bushland, with an increase in rural properties closer to the urban development. As such, a majority of the faecal pollution entering the developed areas would be expected to be caused by wild animals and livestock, with progressively increasing levels of domesticated animal and human contamination through and downstream of the urban developments. In addition, blooms of *Lyngbya majuscula* have been observed within the estuarine waters adjacent to Ningi Creek, in particular the surrounding Moreton Bay area (Arthur et al 2005, Roelfsema et al 2005, Watkinson et al 2005). The particular trigger parameters for causing these blooms are not clear. However, it is suspected that nutrients entering the Ningi Creek system may have an influence on sustaining the blooms.

1.6 Outline of Report

The report discusses the results of detailed field investigation and laboratory and data analysis undertaken for assessing the water quality profile of Ningi Creek catchment. Chapter 2 provides an overview of the issues involved in faecal contamination source identification, and outlines the basis of the adopted approach utilised for this research, Antibiotic Resistance Pattern (ARP) analysis. Additionally, a discussion on the major mechanisms associated with triggering and sustaining cyanobacteria blooms, in particular *Lyngbia majuscula*, is also provided. This gives an initial desktop investigation into the primary cause of these blooms, and the particular pollutants which need to be managed in order to help minimise future bloom events.

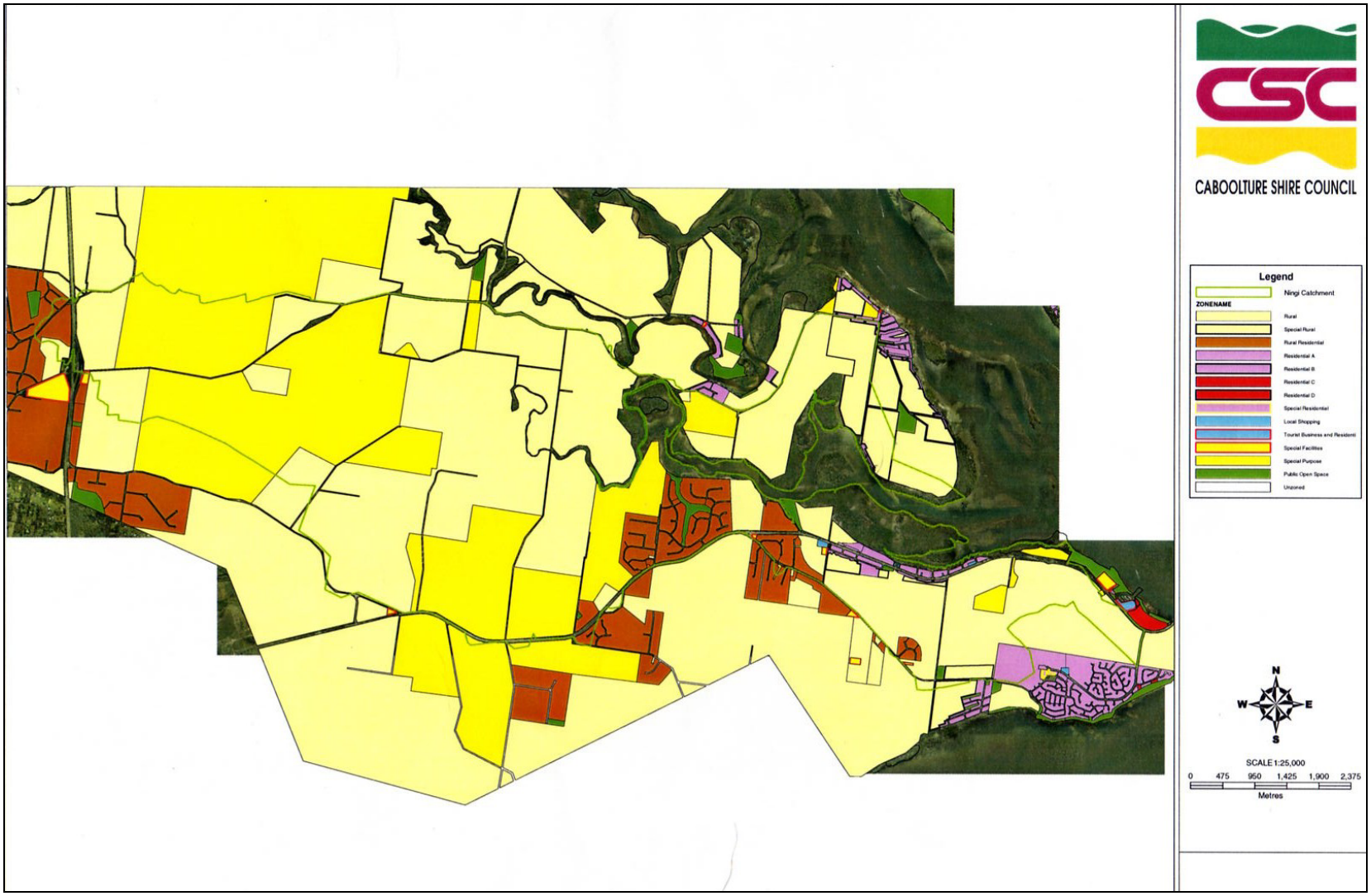

Figure 1.1: Ningi Creek catchment and surrounding land uses

Chapter 3 outlines the strategies adopted in formulating the research project. This includes details of the site selection based on land use types, field investigations conducted during the research project, laboratory analysis techniques and data analysis techniques used for appraisal of the collected data. Chapter 4 details the investigation and analysis of faecal contamination within the Ningi Creek catchment, and the identification of the major sources. A detailed description of the ARP analysis technique is provided, with the various sources of E. coli isolated during the sampling phase identified. Chapter 5 provides an assessment of the chemical pollutants in Ningi Creek, with the aim of constructing a profile of pollutants throughout the catchment. This information is also utilised to assess possible trigger parameters for *L. majuscula* blooms, and also any identified pollutants which may help maintain the blooms. The profile of chemical pollutants along Ningi Creek will allow a management regime to be implemented to minimise contamination, thereby reducing the impact of *L. majuscula* blooms. Following the establishment of the chemical and microbiological quality profile, Chapter 6 identifies the critical monitoring locations and the critical parameters that should be monitored to allow appropriate management strategies to be implemented for mitigating the potential environmental and public health issues identified through this research. Finally, Chapter 7 discusses the conclusions derived from the research project.

CHAPTER 2.0

WATER QUALITY IMPACTS FROM LANDUSE

2.1 Overview

Water quality impacts are a significant concern in relation to public health and environmental degradation. Increased faecal contamination of water resources needs to be adequately managed to ensure appropriate protection of public health. This is of particular importance for the Ningi Creek catchment, which has been used for aquaculture, with several oyster leases now closed due to increased faecal loadings from various land uses. Additionally, being in an estuarine environment, nutrients washed off into Ningi Creek contribute to frequent blooms of *Lyngbia majuscula*, a form of cyanobacteria which produces a contact toxin. In order to protect public health and environmental values, identification of the major sources of water pollutants need to be undertaken to allow the regulatory authority to implement appropriate management practices to minimise pollutant loadings into Ningi Creek. This chapter provides an overview of the impacts of pollutant loadings on water resources. In particular, this chapter reviews the available processes for the identification of the various sources of faecal contamination. Additionally, a review of the main trigger parameters for *L. majuscula* blooms is also discussed.

2.2 Water Quality Impacts

The influence of land use on groundwater and surface water quality has been widely investigated due to the detrimental impacts that can occur, mostly as a result of faecal contamination and nutrient enrichment (Ackerman and Weisberg 2003; Carroll and Goonetilleke 2004; Kelsey et al 2004; Fliesher et al 1998). From a public health perspective, faecal contamination of water sources is significant, as it points to the possible contamination of water sources with pathogenic organisms. In the case of Ningi Creek, this is important, particularly in the intertidal zones, as this is predominantly the main area of aquaculture use with several oyster leases located here. A study undertaken by Beattie and Dexter (2002) found that this area of the catchment is prone to elevated faecal coliform

counts, specifically after significant rainfall events. Subsequently, following this study, the oyster leases were restricted as a precaution against human health impacts.

Additionally, contamination of Ningi Creek with faecal bacteria can also increase the risk to public health through secondary effects. Ningi Creek is widely used for recreational activities such as boating, fishing and swimming. Although, the level of faecal bacteria required to substantiate a significant health risk is high (1000 cfu/100mL ANZECC (2004)), the recorded levels of faecal bacteria in Ningi Creek following storm events has been recorded in excess of this datum level (Beattie and Dexter 2002). Therefore, a public health risk has been identified, and appropriate management strategies are necessary.

Nutrient enrichment is also of prime concern, due to the detrimental impacts that can occur in surface water. Increases in nutrient loads can cause eutrophication of surface waters, leading to poor aesthetics and fish kills. Additionally, nutrient enrichment can also cause and sustain algae blooms, which can be both aesthetically unpleasant and also cause health impacts. In the case of Ningi Creek, numerous blooms of *Lyngbya majuscula* have been recorded. The research literature reviewed (for example Albert et al 2005, Arthur et al 2005; Dennison et al 1999; Osborne et al 2001) indicates various parameters that can cause and sustain *L. majuscula* blooms. Although one or two distinct parameters may onset a bloom, it is a mixture of parameters that provide the necessary energy source and conditions for the biomass to regenerate and sustain itself.

As nutrient enrichment and environmental degradation is a prime concern in surface water bodies, the actual sources of contaminants that lead to these conditions require appropriate management to minimise their impacts. Sources of contamination are typically associated with rainfall events, with nutrients, bacteria, and numerous other organic and inorganic contaminants washed into surface water following rainfall events (Kelsey et al 2004, Ackerman and Weisberg 2003). Agricultural practices such as the use of animal wastes as fertiliser, and general grazing practices can be sources of nutrients and faecal bacteria. Additionally, the waste products from tree plantations and general vegetation can also be pollutant sources in catchments. All of these pollutant sources can be found within the study catchment. Another indirect source is through groundwater discharge into surface water. The surrounding groundwater aquifers can be contaminated by various pollutants as they are recharged. On-site wastewater treatment systems, particularly septic tank-soil

absorption systems are a key source of pollutant input into groundwater systems and ultimately surface water (Carroll and Goonetilleke 2004, Lipp et al 2001, Perkins 1984). Two developments in close proximity to Ningi Creek are solely reliant on on-site systems for wastewater treatment and dispersal, which may be prominent sources of pollutants, particularly human faecal contamination.

2.3 Sourcing Faecal Pollution

Contamination of groundwater and surface water by faecal coliforms is of major concern in relation to environmental quality and public health. However, in order to develop appropriate management strategies to minimise the potential public health risks, the various sources of faecal contamination in a catchment need to be identified. Contamination of ground and surface water resources by stormwater runoff, overland flowpaths from agricultural sources and effluent discharged from on-site wastewater treatment systems is of critical concern due to health risks, and the degradation of recreational and drinking water resources due to nutrient inputs (Wiggins 1999, Hagedorn et al 1999). In order to effectively manage the pollution sources and to mitigate the inherent risks, identification of the sources of pollution is necessary. The most recent methods for identifying pollution sources are based on the use of bacterial source tracking (BST) techniques.

Faecal bacteria can be emitted from various sources, including agricultural sources, wild and domesticated animals, urban development and effluent treatment facilities such as on-site wastewater treatment systems (OWTS) (Kelsey et al 2004). Consequently, faecal coliforms are the most commonly used indicators of faecal pollution of water sources. However, the feasibility of adopting faecal coliforms as an indicator of faecal contamination is the subject of debate (Meays et al 2004, Hagedorn et al 1999). Although indicating that faecal contamination is apparent, indicators do not necessarily give an accurate portrayal of the transportation and survival of other pathogenic organisms they are intended to represent. This is compounded by the fact that the faecal indicators may not be from one particular source, but rather from a variety of sources in the region. The presence of faecal bacteria in water resources only indicates that faecal contamination has occurred (Meays et al 2004).

Faecal coliform bacteria inhabit the intestinal tract of all warm-blooded animals. Hence faecal coliform counts from a contaminated waterway will not provide information as to the actual source of the contamination. This information is important as faecal pollution resulting from human sources will establish a high public health risk due to the possible presence of pathogenic organisms. Additionally, if the faecal source is known, suitable management actions can be implemented to prevent contamination and to mitigate the health risks (Harwood et al 2000).

Due to the numerous possible sources of faecal bacteria, it has until recently been difficult to isolate on-site systems as an important source of faecal pollution. Several attempts at BST methods have been trialled in recent years with limited success (Hagedorn et al 1999, Meays et al 2004). These include: calculating the ratio of faecal coliform to faecal streptococci (Pourcher et al 1991, Howell et al 1996); determining proportions of thermotolerant coliforms to faecal sterols (coprostanol and 24-ethylcoprostanol) (Leeming et al 1998); and species differentiation of faecal streptococci amongst various animals (Deveries et al 1993). More current BST methods have employed molecular methods such as genetic makeup profiles of specific bacteria isolates, including random amplified polymorphic DNA or rep-PCR DNA extraction methods (Dombeck et al 2000, Parveen et al 1999). Additionally, the physiological characteristics used in biochemical BST techniques, such as Antibiotic Resistance Patterns (ARP) of different sources of faecal bacteria have also been used (Booth et al 2003, Wiggins 1996, Wiggins et al 1999, Wiggins et al 2003, Harwood et al 2000, Hagedorn et al 1999, Whitlock et al 2002). The main advantage of utilising ARP techniques over molecular methods is that ARP profiles can be used on more inclusive taxonomic groups of faecal coliforms and faecal streptococci, with hundreds of faecal isolates able to be analysed within a few days of sample collection at a fraction of the cost of molecular methods (Whitlock et al 2002). However ARP has been criticised with respect to its ability for accurately predicting faecal sources, as the grouping of isolates could be influenced by prior exposure to antibiotics (Dombeck et al 2000). This criticism assumes that antibiotic resistance is solely the result of acquired resistance, following exposure to a particular antibiotic and does not allow for inherent resistance patterns or mutations of analysed isolates. Nevertheless, due to the lower cost and faster turn-around time, ARP will continue to be a widely used method for source tracking faecal contamination.

ARP essentially utilises the resistance of selected faecal bacteria isolates, in this case *Escherichia coli (E. coli),* to several antibiotics at varying concentrations in order to obtain their resistance profiles. The underlying assumption of the ARP technique is that due to the increased use of antibiotics by humans and domesticated animals, isolated *E. coli* bacteria from these host sources will have higher resistance than that of wild animals (Wiggins 1996). The ARP technique requires a library of known *E. coli* isolates, from human and non-human sources, to be tested for their respective ARP. These are then analysed statistically using multivariate discriminant techniques to separate the respective patterns into source groups. Once the known source library has been developed, *E. coli* from the investigated water samples are tested for their ARP and compared to the known source library and categorised according to the respective grouping of known source isolates with similar ARPs.

2.4 Lyngbia Majuscula

Lyngbya majuscula (L. majuscula), or more commonly referred to as ‘fireweed’, ‘blanket weed’ or ‘mermaid hair’, is a filamentous marine cyanobacterium (of the family Oscillatoriacea) (Albert et al 2005, Arthur et al 2005). *L. majuscula* grows on solid or sandy substrates (such as rock or coral), anthropogenic structures and seagrasses forming blooms of matted masses of dark filamentous material of varying colours such as white, red and brown (Dennison et al 1999, Arthur et al 2005). As the blooms develop, the large masses can cause a blanketing effect, which can turn the sediment and bottom water anoxic. With suitable abiotic conditions, bubbles formed during the rapid photosynthesis by *L. majuscula* become trapped beneath the bloom, causing the filament matrix to float to the water surface (Albert et al 2005). This free floating biomass is one possible cause of sustaining and spreading of the blooms.

The appearance of large blooms of *L. majuscula* is common worldwide (Dolah 2000, Osborne et al 2001). In Australia, a large numbers of blooms have been reported in the Moreton Bay region off the Southeast Queensland coast (Watkinson et al 2005, Albert et al 2005, Arthur et al 2005, Dennison et al 1999). This is significant to the present study, as Ningi Creek forms one of the many contributory catchments that have an outfall into Moreton Bay.

L. majuscula has been found to have several toxic varieties, producing over 70 biologically active components, many of which have been identified as highly toxic (Osborne et al 2001). These toxic compounds can result in adverse effects on humans who come into contact with the algae, resulting in 'swimmers itch' or 'seaweed itch', a severe form of dermatitis, eye irritations and asthma like symptoms (Osborne et al 2001). In addition to direct contact with *L. majuscula*, oral ingestion through consumption of fish taken from affected waters, or through consumption of seaweed from infected areas can also cause human health problems. Accidental ingestion of *L. majuscula* while consuming seaweed can cause instant burning, with scalding of the mucous membrane reported several hours later (Osborne et al 2001). Therefore, increased blooms of *L. majuscula* are not only aesthetically unpleasant, but can also be detrimental to human health.

Numerous research studies have been conducted over the past several years in order to investigate the main factors contributing to *L. majuscula* blooms. A study undertaken by Watkinson et al (2005) investigated the role of several environmental factors in the stimulation of *L. majuscula* blooms in Deception Bay, Queensland. Two main stimulations were identified through this study. Firstly, abiotic factors, including light, water temperature, salinity and rainfall, were found to be important in the formation of yearly algae blooms. Prolonged high surface light conditions preceding a major rainfall event in conjunction with elevated water temperatures (temperatures >22°C typical of summer water conditions), still water conditions and upper range salinity conditions (typical of intertidal conditions) were found to be critical to the formation of a large *L. majuscula* bloom (Watkinson et al 2005).

In conjunction with these significant abiotic water factors, blooms were also found to be sustained longer by the presence of elevated nutrients and certain metals. In general, cyanobacteria are prolific nitrogen fixers, and in nitrogen limited areas such as Moreton Bay, it is not surprising to identify numerous blooms (Watkinson et al 2005, Roelfsema et al 2005). However, in areas without nitrogen limitations, phosphorus has been identified as a major limiting factor (Watkinson et al 2005), mainly in areas with relatively high phosphorus loadings attained from the surrounding environment, and particularly in high rainfall areas.

Similarly, in instances where phosphorus is available, other parameters, such as iron can become the limiting factor. The presence of high levels of iron in the water column can be important for sustaining *L. majuscula* blooms (Watkinson et al 2005). Cyanobacteria in general have a high demand for iron and phosphorus which are required for photosynthesis and nitrogen fixation (Albert et al 2005). Research on iron chemistry in salic water near algae blooms has identified that a large amount of the iron pool is organically bound (Rose and Waite 2003). Dissolved organic carbon (DOC) primarily in the form of humic and fulvic acids, has been shown to retain iron in solution, allowing the dissolved iron to become potentially biological available for uptake (Watkinson et al 2005). Following reductive processes which break up the unavailable iron compounds, cyanobacteria are able to uptake the soluble iron directly. As such, the level of bioavailable iron can fluctuate significantly in salic waters depending on the level of natural organic complexes such as organic carbon. Consequently, the levels of limiting factors, such as phosphorus, organic carbon and iron, can substantially increase after rainfall events due to these substances being washed off in excess and transported with runoff. This is further compounded in areas which use manure as fertiliser, such as in urban areas, as well as in areas such as pine plantations, which can substantially increase the level of organic carbon into adjacent waterways.

2.5 Conclusions

Research relating to the various pollutant sources that can influence the quality of water resources is widely discussed in research literature. However, the majority of the studies have assessed water quality based on commonly adopted parameters as specified in water quality guidelines, such as ANZECC (2004). However, there are only limited studies that investigate and identify the sources of contamination, particularly faecal contamination.

Faecal contamination is a widespread issue, and has been typically found to increase following rainfall events, particularly in urbanised regions. However, it has not been until recently that cost effective methods for identifying the actual sources of faecal contamination become available. Antibiotic Resistance Pattern (ARP) analysis is one such method that can provide accurate classification of the different sources of faecal bacterial isolates from water sources. Such techniques can help to improve the management of

faecal contamination, as the contamination sources can be identified and specifically targeted to reduce their impact.

Similarly, chemical contaminants such as nutrients can cause significant environmental degradation. However, due to the widespread availability of nutrients both from natural and anthropogenic sources, it is extremely difficult to isolate specific sources. Therefore, it is more appropriate to assess concentrations from various monitoring locations and extrapolate this information to specific sites. This information is important to reduce the input of chemical contaminants into waterways which can result in environmental degradation and algae blooms, such a *L. majuscula*. However, although not strictly responsible for triggering such blooms, excess concentrations of nutrients and other bioavailable elements such as organic carbon and iron, can sustain algae blooms for prolonged periods. As such, in order to minimise the spread of algae blooms, and to reduce their impact, management of chemical pollutant loadings to water resources is also important.

CHAPTER 3.0

RESEARCH FORMULATION AND DEVELOPMENT

3.1 Overview

To achieve the research aims and objectives, groundwater and surface water sampling locations needed to be identified to capture as many of the various land use types distributed throughout Ningi Creek catchment. Using available spatial data, a desktop study was undertaken to identify appropriate sampling locations for surface water sample collection and for the installation of shallow groundwater monitoring wells. This was followed by field inspections to 'ground truth' the identified locations to assess any access and/or sampling limitations.

Field investigations were undertaken once appropriate monitoring site locations were identified to obtain relevant information. The parameters identified for the analysis of groundwater and surface water samples were selected to allow assessment in relation to faecal source identification and chemical analysis of trigger parameters of *L. majuscula*. The testing regime followed the standard test procedures as outlined in APHA (1999) for standard chemical and microbiological testing. The identification of the sources of faecal contamination was achieved through the bacterial source tracking technique of Antibiotic Resistance Pattern analysis. The specific tests and analytical procedures undertaken for each investigation are discussed in the following sections.

Statistical analysis of physical and chemical parameters obtained from the analysis of water samples can be complex, and generally a large amount of data is generated. This makes it difficult to manipulate or evaluate the resulting data using standard univariate statistical methods. This problem can be overcome by the use of multivariate statistical approaches whereby large volumes of data can be processed for exploring and understanding relationships between different parameters. The use of procedures such as pattern recognition, classification and prediction can be beneficial as relationships between parameters can be clearly identified. The qualitative and quantitative data generated from the field investigations and laboratory testing was analysed using univariate and

multivariate statistical techniques including Principal component Analysis (PCA) and Discriminant Analysis (DA). The outcomes from the data analysis formed the basis for the development of catchment management recommendations.

3.2 Identification of Land Uses

A desktop study was undertaken utilising available GIS information, hardcopy topographical maps, and aerial photographs to identify the types of land uses in the Ningi Creek catchment. A land use map of the Ningi Creek catchment (Figure 1.1) identified different land use characteristics. These can have a significant impact on the catchment as a whole. Urban residential developments contribute a large amount of pollutants to local waterways due to the presence of impervious areas, which have reduced losses and lead to a resulting increase in runoff. Additionally, developments utilising on-site wastewater treatment systems can lead to the pollution of groundwater sources, which can ultimately leach into surface water bodies.

Four main land uses were identified within the Ningi Creek catchment. These include; (i) agriculture; (ii) urban development; (iii) plantation forestry (pine tree plantations); and (iv) natural bushland. Agricultural land uses identified include pineapple farms, strawberry farms, poultry and wide areas of land used for livestock grazing. It is presumed that fruit production uses manure as a source of fertiliser. One major residential development, Bribie Gardens, exists on the southern side of Ningi Creek and all the houses use on-site systems for the treatment of domestic sewage. This development has a grass swale running through the middle of the development to provide some treatment of storm water prior to discharging into Ningi Creek. Although the oyster leases within Ningi Creek have been closed, a prawn farm was still in operation on the southern side of the waterway over the duration of the research project (Figure 1.1). Large areas of the catchment consist of pine plantations which were harvested midway through the study.

3.3 Site Selection and Sampling

In order to accurately identify and assess the different sources of pollution within the Ningi Creek catchment, water quality monitoring locations were identified to encompass the different land use types throughout the catchment. This included both surface water and

groundwater monitoring locations throughout the catchment in order to obtain an indication of the background level of faecal coliforms and *E. coli* entering the developed region. Site details of the monitoring locations established are provided in Figure 3.1 and Table 3.1. Monitoring sites established also included sites located in the urbanised area, with several sites located downstream of areas where there is a significant increase in the number of OWTS. A total of twelve surface water sampling locations were established along the length of Ningi Creek for the establishment of a surface water quality profile. Eight monitoring locations (SW1 to SW8) were established within the estuarine environment of Ningi Creek. Establishing monitoring sites along the Creek was necessary as this section of the waterway is the major area of concern in relation to oyster farming and general recreational activities such as fishing. Where possible, groundwater sampling locations were installed as close as possible to the surface water monitoring locations, in order to allow correlation of the water quality results. The catchment is tidally influenced up to monitoring sites SW8 and GW8, which has an influence on the fate and transport of faecal coliforms and *E.coli* in the downstream end of the creek.

The groundwater wells were located so as to allow an adequate means of collecting data on the quality of the water, and also to provide the necessary information required to assess contaminant fate and transport. The locations and spacing of wells was based on the direction of groundwater flow, topographic conditions and proximity to surface water.

Groundwater monitoring wells were drilled by a motorised rotary auger to a depth of approximately 2-7m, depending on the underlying hydrogeological features. As depicted in Figure 3.2, 50mm diameter PVC pipes, with a 1.5m well screen was installed with 2-3mm pea gravel used as a filter pack around the screen to reduce sediment inflow. Concrete plugs were installed directly above the well screens to prevent surface water intrusion down the side walls of the wells. Well screens were installed at least 0.5m below the observed water table to ensure representative groundwater samples were collected. Security of the wells was achieved by installing concrete caps, complete with screwed PVC plastic lids, as shown in Figure 3.3.

Table 3.1: Monitoring site sample locations

Monitoring Site	East	North	Ground Level AHD (m)	Land Use/ Location
GW1	506842	7006704	3.86	Grass swale Bribie Gardens
GW2	506894	7007136	1.99	Grass swale Bribie Gardens
GW3	506757	7007476	1.52	End swale Bribie Gardens
GW4	507054	7007079	2.67	Top of concrete swale Bribie Gardens
GW5	506659	7007519	1.61	Fire break – control
GW6	507609	7007830	2.91	Otto Rd
GW7	507529	7007828	3.35	Otto Rd
GW8	504896	7007988	1.23	Cattle grazing –Voltz Rd
GW9	502372	7009684	3.83	Forestry – Humes Rd
GW10	500208	7009501	14.22	Forestry
SW1	500100	7008546	Lower Catchment	Northern side of island, opposite SW2
SW2	498864	7008597	Lower Catchment	Opposite boat ramp at Toorbul, southern side of island
SW3	508955	7007406	Lower Catchment	D/S prawn farm
SW4	509350	7007912	Lower Catchment	D/S Bribie Gardens
SW5	508118	7007355	Lower Catchment	D/S Bribie Gardens
SW6	507317	7007679	Lower Catchment	U/S Bribie Gardens
SW7	506971	7007797	Mid Catchment	Intersection with Pumicestone Rd
SW8	506623	7008038	Extent of tidal influence	Voltz Rd Grazing land
SW9	506443	7008968	Upper Catchment	Humes Rd
SW10	505403	7007990	Upper Catchment	Forestry
SW11	502361	7009681	Upper Catchment	Forestry
SW12	500168	7009477	Upper Catchment	D/S pineapples

D/S – Downstream GW – Groundwater monitoring location
U/S – Upstream SW – Surface water monitoring location

Figure 3.1: Locations of established sample monitoring locations along Ningi Creek. ◎ Surface water monitoring locations

◈ Groundwater monitoring locations

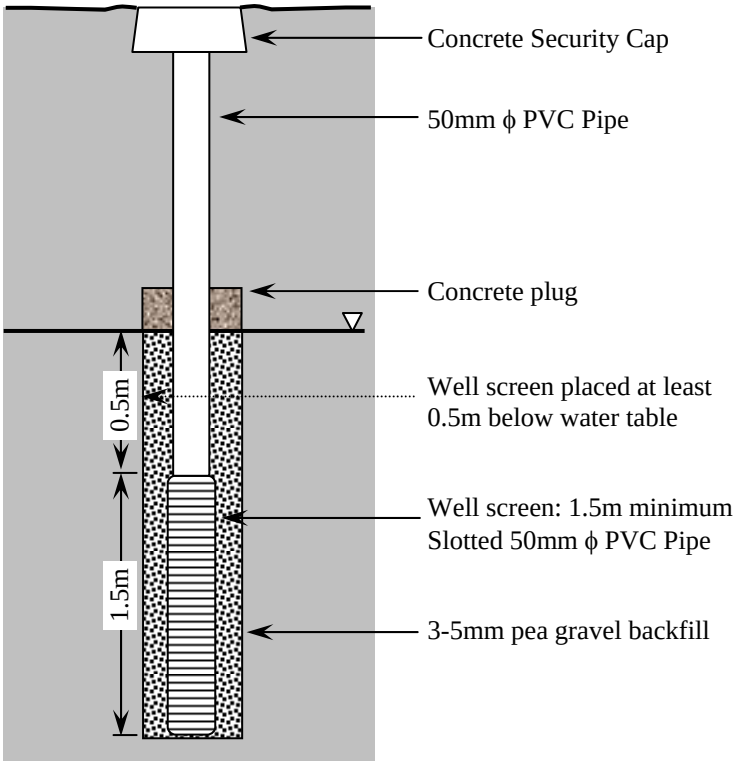

Figure 3.2: Groundwater monitoring well installation setup

Figure 3.3: Well security achieved by placing sealable concrete caps over monitoring wells flush with surface

A majority of the land use in the catchment upstream of the developed areas have mixed farmland and native bushland, with an increase in rural properties closer to the urbanised development. As such, most of the faecal pollution entering the developed areas would be expected to be caused by wild animals and livestock, with progressively increasing levels of domesticated animal and human contamination through the urban developments. A

further four surface water sampling locations (SW9 to SW12) were established upstream amongst other major land uses, including pineapple and strawberry farms, natural bushland and downstream of the pine forest plantations. A significant section of Ningi Creek, between sites SW8 and SW9, was unable to be monitored due to the inability to gain access to the creek for establishing monitoring locations.

3.4 Sampling Regime

Sampling at each location was conducted on a monthly basis from September 2004 to June 2005. This was conducted to allow assessment of seasonal changes in water quality. Water quality parameters such as pH, EC, DO, Temperature were measured in the field using portable meters at each groundwater and surface water sampling location. Water table depth at each groundwater monitoring location was measured prior to purging. All groundwater monitoring wells were purged prior to sampling using a peristaltic pump and acrylic hose. In line monitoring of pH and EC was conducted during purging of stagnant water in the monitoring wells, to ensure fresh groundwater was monitored and sampled. The acrylic hose was then washed with a soapy solution, rinsed with disinfectant and purged with distilled water prior to obtaining a water sample.

Surface water sampling locations within the estuarine region of Ningi Creek were reached using a dinghy, launched from the boat ramp at Toorbul Point. Sampling locations were identified using a GPS unit attached to a Doppler GPS antenna to obtain accurate coordinates. Surface water samples from locations SW9 to SW12 were collected via a sampling pole with the sampling bottle attached. All surface water samples were collected at a depth of 300mm below the surface water level to obtain representative samples of the water column.

Both groundwater and surface water samples were collected in sterilised PVC bottles and immediately placed in crushed ice in a portable refrigerator for transport back to the laboratory. All water samples were analysed for microbiological constituents within eight hours of collection, and chemical constituents within seven days. Following microbiological analysis, water samples were refrigerated until chemical analysis was conducted.

3.5 Laboratory Analysis

Table 3.2 and 3.3 provides the analytical methods used for the analysis of ground and surface water samples for chemical and microbiological parameters, respectively.

Table 3.2: Procedures for analysing water samples for chemical parameters

Parameter	Analytical Method
pH	Measured using TPS-81 pH-conductivity meter
Electrical Conductivity (EC)	Method 2520-Conductivity (APHA 1999) using TPS-81 pH-conductivity meter
Nitrates (NO_3^-)	Method 4500-NO_3^- F Automated Cadmium Reduction (APHA 1999) using HACH 4000DR spectrophotometer
Orthophosphate (PO_4^{3-})	Method 4500-P F Automated Ascorbic Acid Reduction (APHA 1999)
Total Organic Carbon (TOC) Total Inorganic Carbon (TIC) Dissolved Organic Carbon (DOC) Dissolved Inorganic Carbon (DIC)	Measured using Shimadzu TOC-5000A.
Total Iron and Total Manganese	Measured using ICP-OES

Table 3.3: Procedures used for analysing water samples for microbiological parameters

Parameter	Analytical Method
All microorganisms	*Method 9213-E* Membrane Filter Technique (APHA 1999) Appropriate dilutions filtered using 0.45mm, 47mm gridded filter membranes (Millipore Corporation, Bedford, Massachusetts) to allow countable numbers of colonies on filter membrane. Filter membranes transferred to petri-pads soaked in applicable medium outline below.
Faecal Coliforms (FC)	Water samples analysed via Membrane Filter Technique. Filter membranes transferred to petri-pads soaked in m-Endo broth (Millipore Corporation, Bedford, Massachusetts). Filtered samples incubated at 37°C for 24 hours. Colonies identified with a golden sheen were counted as Faecal Coliforms.
Escherichia coli (*E. coli)*	Water samples analysed via Membrane Filter Technique. Identified FC (colonies observed with golden sheen) were sub-cultured onto nutrient agar plates, and additionally tested for Indole reaction (growth in Tryptone water at 37°C for 24 hrs followed by addition of Kovac's Indole reagent) and growth in Brilliant Green Lactose Bile Broth (BGLBB – Eijkmann test). Positive reactions in both tests were recorded as confirmed *E. coli.*
Antibiotic Resistance Pattern Analysis (ARP)	Confirmed *E. coli* isolates were selected for ARP profiling. Confirmed *E. coli* isolates were inoculated into nutrient broth and incubated for 18 hrs at 37°C. Subsequent broths diluted to 0.5 MacFarland Standard in fresh nutrient broth. Diluted isolates were placed in multipoint inoculator cups (Denley Multipoint Inoculator A400) and inoculated on a series of 32 antibiotic treated agar plates (8 antibiotics x 4 concentrations). Plates were incubated at 37°C for 24 hours. Note: For detailed explanations of data analysis and antibiotic resistance profiling see Section 4.3.

3.6 Data Analysis

Sampling of both ground and surface water resulted in large amounts of collected data to be analysed. Table A.1 and A.2 (Appendix A) provides the results of analysed water samples for groundwater and surface water respectively. Analysis of this data was achieved using multivariate statistical techniques. The multivariate approaches utilised for assessing the data obtained through water quality investigations consisted of two common methods; (i) Principal Component Analysis (PCA); and (ii) Discriminant Analysis (DA).

3.6.1 Principal Component Analysis (PCA)

PCA is a multivariate statistical data analysis technique which reduces a set of raw data into a number of principal components which retain the most variance within the original data to identify possible patterns or clusters between objects and variables. Detailed descriptions of PCA can be found elsewhere (Massart et al 1988, Adams 1995; Kokot et al 1998). After decomposition of the raw data matrix, principal components (PC's) are chosen so that PC1 describes most of the data variance, followed by PC2 which retains the next largest amount of data variance and is orthogonal to PC1. This means that PC2 is independent of PC1. The advantage of PCA is that most of the data variance is contained within the first few PC's, reducing the dimensionality of the multivariate data matrix (Kokot et al 1998).

Objects (in this case water samples) that retain similar variances in the analysed variables will have similar PCA scores which will cluster together when plotted. Likewise, relationships between variables can be easily identified by the respective coefficients. Strongly correlated variables will generally have the same magnitude and orientation when plotted, whereas uncorrelated variables are typically orthogonal (perpendicular) to each other. Clusters of object data and their respective relationships with the analysed variable can clearly be seen when scores and coefficients are located on a biplot. This allows relationships between analysed variables and respective objects to be identified.

3.6.2 Discriminant Analysis (DA)

DA is a multivariate statistical analysis technique where a data set containing 'X' variables is separated into a number of pre-defined groups using linear combinations of analysed variables. This allows analysis of their spatial relationships and identification of the

respective discriminative variables for each group (Wilson 2002). Similar to PCA, objects that retain similar variances in the analysed variables will have similar discriminant scores and when plotted, will cluster together. Similarly, strongly correlated variables will also have the same magnitude and orientation when plotted, whereas uncorrelated variables will be orthogonal (perpendicular). These biplots are similar to the PCA biplots.

There are two main functions for which DA is commonly employed. Firstly, it is used to analyse the differences between two or more groups of multivariate data using one or more discriminant functions in order to maximally separate the identified groups. Secondly, DA can be employed to obtain linear mathematical functions which can be used to classify the original data, or new, unclassified data, into the respective groups (Brereton 1990). Both techniques were utilised in this research.

3.7 Conclusions

In assessing the water quality profile of Ningi Creek, an in-depth understanding of the physical, chemical and microbiological parameters and their interactions was crucial. The laboratory analysis of collected water samples was conducted following standard methods to ensure accuracy in the determination and assessment of the physical, chemical and biological factors inherent in the ground and surface water profiles.

The field investigations conducted through this research generated a significant amount of data with multiple variables. The analysis of this data using univariate statistical techniques was complex and it was difficult to evaluate the inherent relationships. This problem was overcome by the use of multivariate statistical techniques, where large data arrays with multiple variables was analysed, allowing the exploration of the relationships between different variables from multiple sites. The multivariate techniques employed included Principal Component Analysis for assessment of general water quality data, and Discriminant Analysis for determining the respective sources of faecal pollution.

CHAPTER 4.0

SOURCE IDENTIFICATION OF FAECAL CONTAMINATION

4.1 Overview

The main focus of the microbiological testing was to assess and quantify faecal indicators in surface and groundwater samples and to utilise the Antibiotic Resistance Pattern (ARP) technique in determining the potential sources of faecal contamination in the Ningi Creek catchment. This catchment has significant densities of on-site wastewater treatment systems along with mixed land uses such as farming, forestry, cattle grazing and aquaculture. Although faecal pollution is evident in Ningi Creek, no previous investigation has been conducted as to whether human, and consequently on-site wastewater treatment systems, are the major source of faecal contamination. The use of ARP provided a means of identifying the major sources of faecal contamination, and an assessment of the potential public health risk.

From an initial desk top study, several possible sources of faecal contamination were noted. Direct and indirect faecal pollution sources within the confines of Ningi Creek catchment include:

- Effluent from Prawn farm (SW3);
- On-site wastewater treatment systems in the Bribie Gardens Estate (187 Septics and 65 Aerobic Wastewater Treatment Systems) (SW4 and 5, GW1 to 4) and less dense upstream rural residential developments (GW8 and SW8);
- Faecal matter from agricultural farms, forestry and cattle grazing (GW8 to GW12 and SW8 to SW12); and
- Potential discharge from watercraft (SW1 and 2).

4.2 Faecal Coliform and E. coli Concentrations

A total of 117 surface water samples were collected from each of the twelve surface water monitoring locations and 73 groundwater samples were collected from the ten groundwater monitoring locations in the Ningi Creek catchment on a monthly basis over a ten month

period. This sampling period was selected to allow collection of samples during both the wet season and into the drier winter period.

The number of faecal coliforms and *E. coli* contained in the collected water samples indicated fluctuations between sampling events, as depicted in Table A.1 and A.2, Appendix A. This fluctuation is primarily related to the rainfall in the catchment, which typically causes an increase in the number of faecal coliforms and *E. coli*. Rainfall during the sampling period have been categorised into three classes, dry (less than 30mm/month), moderate (30 to 100 mm/month) and wet (greater than 100mm/month) as shown in Table 4.1. Rainfall records from South Caboolture Wastewater Treatment Plant (Appendix B) were used due to their proximity to the monitoring sites. Rainfall is generally regarded as having a significant influence on the level of faecal coliforms in surface water, and past research studies have shown high correlations between rainfall and faecal coliforms (Ackerman and Weisberg 2003, Muirhead et al. 2004, Noble et al. 2003). However, some counts during low rainfall periods remained quite high, and it is postulated that this is the result of a continuous source of contamination. Although rainfall will inevitably cause an increase in faecal coliforms counts, it would also have a dilution effect on continuous sources of contamination, thus reducing their number. However, other sources would increase their contribution due to stormwater runoff. This would be the case for OWTS adjacent to surface water sources or application of poultry manure to crops, which would provide a continuous stream of contamination into the surface water sources. Consequently, if this was the case, ARP of isolates would indicate a higher proportion of human source isolates during these high counts, with lower percentages of non-human sources.

Table 4.1: Rainfall classification of sampling periods

Sample Episode	Sample Date	Rainfall in month prior	Classification
1	15 September, 2004	22mm	Dry
2	16 November, 2004	120mm	Wet
3	14 December, 2004	180mm	Wet
4	14 February, 2005	-	Dry
5	30 March, 2005	42mm	Moderate
6	26 April, 2005	31mm	Moderate
7	25 May, 2005	68mm	Moderate
8	20 June, 2005	147mm	Wet

4.3 Antibiotic Resistance Analysis for Sourcing Faecal Contamination

4.3.1 Development of Source Library

ARP essentially utilises the resistance of selected faecal bacteria isolates, in this case to several antibiotics at varying concentrations, in order to obtain their resistance profiles. For this study, *E. coli,* the most prominent subset of faecal bacteria found in the intestinal tract of humans and warm-blooded animals, was utilised for ARP analysis. The ARP procedure requires a known source library of antibiotic resistance patterns to be developed from faecal samples collected from known sources in order to classify unknown samples enumerated from collected water samples. The *E. coli* ARP's were then analysed statistically using multivariate discriminant techniques to separate the respective patterns into source groups. Once the known source library was developed, *E. coli* from the investigated water samples were tested for their ARP and compared to the known source library and categorised according to the respective grouping of known source isolates with similar ARPs.

The development of the known isolate source library was initially undertaken to allow discrimination between human and non-human *E. coli* isolates. However, due to the diverse number of sources collected from different non-human sources, a preliminary discrimination between human, domestic animals, livestock and wild E. coli isolates was also undertaken.

To develop the source library of known *E. coli* isolates, samples were collected from human and the primary non-human sources of faecal matter within the catchment. Five faecal samples were collected directly from humans in order to ensure that actual human *E. coli* isolates were obtained. Two additional human faecal samples were also collected from a public septic tank system, as well as from a municipal wastewater treatment plant. Major non-human faecal sources included livestock, domestic and wild animals observed near monitoring locations. Nineteen samples representing the three major sources of domesticated animals in the catchment, including dogs, cats and poultry were collected. Additionally, fifteen livestock faecal samples representing beef and dairy cows, horses and goats were obtained from agricultural farms in the area. Eighteen faecal samples representing five wild animal sources were also collected. Sources included kangaroo,

wallaby, koala, possum, and waterfowl. All these sources were observed in the monitored areas during the sampling period.

4.3.2 Antibiotic Resistance Analysis

E. coli isolates from the collected known sources and water samples were analysed for their resistance to eight different antibiotics at four different concentrations as shown in Table 4.2. These antibiotics were chosen due to their common use in human and domesticated animals. Enumerated *E. coli* isolates (known and unknown) were inoculated to a series of 32 antibiotic plates (eight antibiotics, four different concentrations) and incubated.

Table 4.2: Antibiotics and concentrations used for determining ARP patterns

Antibiotic	**Concentrations (mg/mL)**			
Amoxicillin	5	10	15	20
Cephalothin	10	25	50	100
Erythromycin	20	50	100	200
Gentamicin	20	40	60	80
Ofloxacin	5	10	15	20
Chlortetracycline	20	40	60	80
Tetracycline	20	40	60	80
Moxalactam	5	10	15	20

After incubation, the relative growth for each antibiotic and concentration was recorded for each plate of isolates. Four different ratings (0 to 3) were initially used to distinguish respective ARPs. An isolate received a rating of 0 for no growth; 1 for filmous growth; 2 for restricted growth of colonies (growth of a few colonies); and 3 for full growth showing no resistance. Figure 4.1 depicts the process for assigning values to *E. coli* isolates. These ratings could be reduced to two ratings, 1 for no growth (Rating 0-1) and 2 for growth (Rating 2-3). The main reason for using the four ratings was to include more variability into the patterns than would be achieved through the use of just two values (0 and 1).

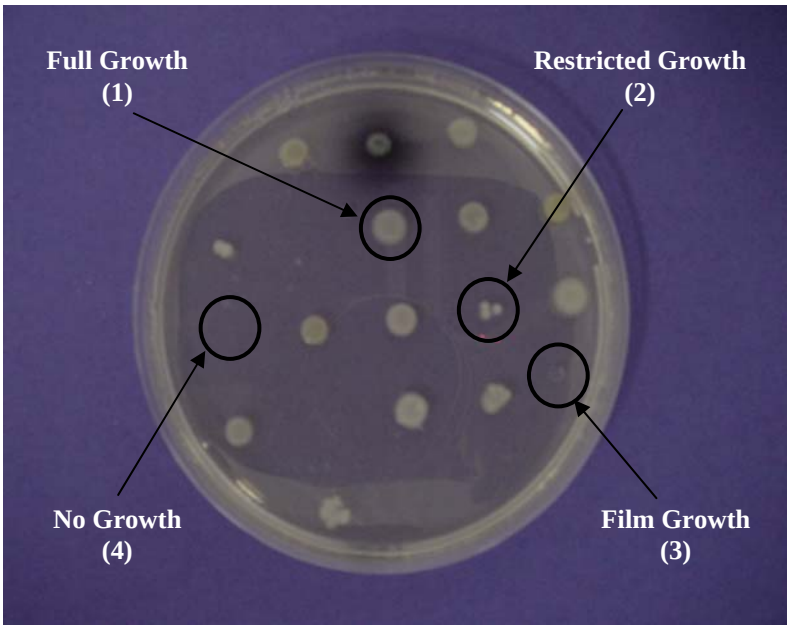

Figure 4.1: Assigning values representing E. coli antibiotic resistance

4.3.3 Antibiotic Resistance Patterns

From the 55 faecal samples collected from known sources, a total of 717 *E. coli* isolates were enumerated, and their patterns of antibiotic resistance determined. Analysed ARP for known source isolates indicated distinctive patterns depending on their respective sources. From all ARPs obtained for all known sources, no *E. coli* isolates were found to have any resistance to Gentamicin and Ofloxacin, except for domestic isolates which retained minor resistance to low concentrations of Gentamicin. This was due to one faecal sample which retained isolates with minor resistance to Gentamicin. Human isolates were found to have a lower resistance to higher concentrations of all antibiotics, although the best separation between humans and non-human isolates was found to be Amoxicillin (15 and 20 μg/mL) and Erythromycin (50, 100 and 200 μg/L), with minor separation for Cephalothin (50 and 100 μg/L), Chlortetracycline (40, 60 and 80 μg/L). Contrastingly, livestock sources (beef and dairy cows, horses and goats) had the best separation utilising Cephalothin (50 and 100 μg/L), Chlortetracycline (40, 60 and 80 μg/L). Wild isolates did not show any specific relationship between resistances to a certain antibiotic, although a slightly higher resistance was found for Erythromycin. Instead, the wild isolates retained similar patterns to those obtained for the other non-human sources, particularly livestock isolates. This is most likely due to the fact that most of the identified wild sources generally co-inhabited the same areas as livestock sources. Consequently, similar ARPs for non-human isolates in these catchments would retain similar relationships with respect to antibiotic resistance due

to being in the same geographic location, and having common food and water supply sources particularly if the water supply is a waterway.

4.3.4 Discriminant Analysis of *E.coli* Isolates

Antibiotic resistance patterns for each of the source and unknown *E. coli* isolates (based on the 1-4 scale for growth) were input into a spreadsheet and analysed using Discriminant Analysis (DA). DA was utilised to develop discriminant functions for the ARP of known *E. coli* isolates in order to distinguish specific separations on the basis of their respective source group. These group classifications were then utilised to classify the unknown *E. coli* isolates into the corresponding groups that closely matched their ARP profile. This classification procedure can be used to calculate the percentages of misclassified isolates and determine the average rate of correct classification (ARCC) of isolates in their respective categories (Wiggins 1996).

To provide a more rigorous predictive ability for the source library, a cross-validation procedure (also referred to as *hold-out analysis* or *jack-knifing*) was undertaken. This procedure randomly removes isolates from the known source library and treats them as an unknown source to test the classification ability of the library (Harwood et al 2000). The process utilised in this study followed similar procedures to the pulled-sample cross-validation process described by Wiggins et al (2003). As multiple isolates from the same sample may have similar resistance profiles, the library may appear to be more representative due to this profile similarity. To overcome this issue, all isolates from the same sample were removed during the pulled-sample cross-validation procedure, and reclassified according to the resistance profiles of the remaining isolates. For the human versus non-human pooled analysis, five random samples from the human category and ten from the non-human category were individually pulled out and reclassified.

As the main aim of the study was to determine the percentage of human versus non-human sources, all non-human sources were initially pooled together into one category. This consisted of pooling the ARP of all wild, livestock and domesticated animal isolates and all human isolates into single individual pooled categories. The pooled category method was expected to provide higher average rates of correct classification for the source library, as has been found in past studies (Wiggins et al 1999, Harwood et al 2000, Booth et al

2003). However, in order to assess the ability of the library to classify between different non-human sources, an additional analysis was performed with pooled categories consisting of human, livestock, domestic and wild animal isolates.

Discriminant analysis of the pooled human versus non-human isolates performed exceptionally well, obtaining an average rate of correct classification (ARCC) of 86.5%. Table 4.3 provides the classification rates and ARCC for human vs non-human source isolates obtained through the discriminant analysis. Both the human and non-human categories indicated clear discrimination between analysed isolates. Figure 4.2 provides a plot of the obtained discriminant functions for the human and non-human sources. From this plot, the separation between human and non-human source isolates can be clearly identified. These rates of correct classification are similar to those derived through other studies which achieved ARCC of >80% for human versus non-human pooled categories (for example Booth et al 2000, Carroll et al 2005, Wiggins et al 1999, Harwood et al 2000, Whitlock et al 2002). To assess whether the source library retained enough isolates to correctly classify the unknown sources, a pulled-sample cross-validation was conducted. The overall ARCC for the libraries used to reclassify randomly pulled human samples was 86.2%. For reclassifying randomly pulled non-human source samples, the ARCC for the source libraries was 81.3%. These ARCC values were very similar to the values obtained for the original source library. Therefore, the ARCC's indicated that the library was sufficiently large enough to provide adequate discrimination between human and non-human sources. Pulled non-human source samples had slightly lower correct classification rates mostly due to the relationship between the wild and livestock categories.

Table 4.3: Classification rates and ARCC for human vs non-human source isolates

Source	Number & %CC isolates classified as		
	Non-Human	Human	Correctly Classified
Non-Human (*n = 767*)	676	91	88.1%
Human (*n = 139*)	31	108	77.7%
Average Rate Correct Class. (ARCC)			86.5%

For the pooled categories of human, livestock, domestic and wild isolates, the respective classification rates for categorical discrimination are provided in Table 4.4. The ARCC for discriminating human, domestic, livestock and wild sources was much lower at 68.5%. Compared to the previous human versus non-human analysis, an overall lower ARCC was obtained. The reason for this was the lower separation mostly due to the similar ARP profiles between wild and livestock categories, as indicated in Figure 4.2, with wild and livestock ARP profiles retaining similar DA scores. However, the classification rate for human sources was 70.6%, indicating that discrimination between human and livestock, domestic and wild sources was still relatively high. The main source of misclassification was for wild isolates, with 46.9% of isolates misclassified.

Table 4.4: Classification rates and ARCC for human, domestic, livestock and wild source isolates

Source	Number & %CC isolates classified as				
	Domestic	Livestock	Wild	Human	Correctly Classified
Domestic (*n = 206*)	139	34	15	17	67.8%
Livestock (*n = 320*)	21	254	37	8	79.4%
Wild (*n = 241*)	26	59	128	28	53.1%
Human (*n = 139*)	6	9	32	113	70.6%
Average Rate Correct Class. (ARCC)					68.5%

Overall, in assessing the representativeness and ability of the developed source library for correctly classifying human from non-human sources, it was apparent that the library retains sufficient source isolates to accurately predict the source of unknown isolates from the catchment studies as either human or non-human. However, in order to discriminate non-human isolates into appropriate representative sources, the library may require more non-human source isolates in order to develop a more representative collection. Nevertheless, as the main focus for this study was to determine the percentage of human isolates at monitored locations, the library was able to provide an acceptable classification.

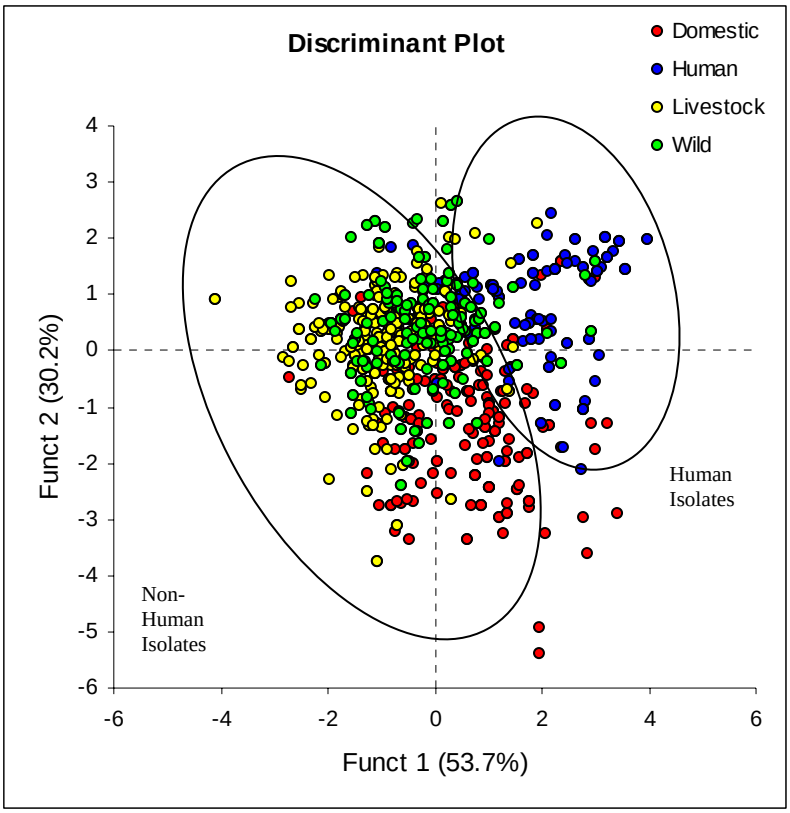

Figure 4.2: Discriminant plot showing source classification separation between human and non-human source isolates, and the less accurate separation between wild and livestock isolates.

4.4 Classification of Faecal Contamination Sources in Ningi Creek

From the samples collected over the ten months of sampling from the ten monitored groundwater locations and twelve surface water locations, 252 unknown isolates were enumerated for assessment of the ARP. Applying DA to the unknown source isolates and utilising the human versus non-human source library, the percentage of human isolates contained in the collected water samples were obtained. Tables 4.5 and 4.6 provide the percentages of human and non-human isolates from the catchment. Although high percentages of human *E. coli* isolates were found in several of the monitoring locations, this does not necessarily indicate that the majority of faecal contamination is from human sources. As observed in groundwater samples collected from the Bribie Gardens estate, high levels of human source *E. coli* isolates were observed. However, the total number of *E. coli* colonies identified in collected samples was not large. Therefore, in assessing the potential sources of faecal contamination, due consideration must be given to both, the identified source and the overall number.

From the DA analysis of samples obtained from the groundwater, 60%, 100%, 100% and 67% of the isolates from GW1 to GW4 (located within Bribie Gardens Estate) respectively, were classified as human with an average of 82% classified as human source isolates. However, only a small number of *E. coli* where obtained from monitoring locations GW1 to GW4, averaging 72 cfu/100mL (maximum of 625 cfu/100mL). In addition, most groundwater monitoring wells retained minimal *E. coli* counts over the sampling period, with occasional peaks in E. coli numbers observed. However, these peaks were not related to rainfall events. Therefore, although human source faecal contamination is evident in the groundwater below the estate, the overall number of *E. coli* identified from the monitoring wells is relatively low, with an even smaller number of *E. coli* identified from human sources. Consequently, although some contamination of groundwater below the development is evident, this does not indicate that contamination of Ningi Creek is occurring due to the transport of human faecal contamination through the groundwater system, and ultimately into Ningi Creek. GW5 was utilised as a control site upstream of Bribie Gardens Estate and away from any influence of on-site wastewater treatment. The monitoring site was located in a firebreak west of the estate. Analysis of *E. coli* isolates obtained from GW5 indicated no human source isolates. From the other classified sources (Table 4.5), it was obvious that in the upper regions of the catchment (GW6 to GW10), the major source of faecal pollution is mostly non-human or animal sources. The average classified as non-human isolates being 71%. In comparison to the samples obtained from the estate, significantly lower faecal coliform counts were evident in the upper catchment (Average 108 cfu/100mL).

From the DA analysis of samples obtained from Ningi Creek surface water, 46% of the isolates were classified as human and 54% as non-human. In the lower catchment (SW1 to SW5) source identification identified the split between human and non-human isolates to be 51% human and 49% non-human. *E. coli* counts obtained from surface water samples in the lower catchment (SW1-SW5) averaged 71 cfu/100mL (maximum 398 cfu/100mL). Almost all samples showed continuous levels of *E. coli* throughout the monitoring period, with significant elevated E. coli counts observed following major rainfall events. The percentage of human source *E. coli* in this downstream section of the creek (49% human source isolates) does suggest that runoff from human sources is contributing to the *E. coli* levels identified in Ningi Creek, as indicated by the monitoring locations near the development (SW4-SW5). However, due to the tidal effects of Ningi Creek, the overall

contribution of contamination directly from the urban development is difficult to ascertain with the current information. It is possible that the human *E. coli* identified in the downstream sections of Ningi Creek is a mix from the urban development and upstream sources However, it must be noted that human faecal source contamination from the urban development will occur, particularly following rainfall.

From the other classified sources (Table 4.6), it was obvious that in the middle regions of the catchment (SW6 to SW8), the major source of faecal pollution is contributed mostly from non-human or animal sources (59%). Interestingly, the upper catchment (SW11 and SW12) where sample locations were located downstream of pineapple farming and forestry showed greater than 50% isolates of human origin. Samples collected from these sites during the dry periods may have exacerbated these numbers. Forestry logging and pineapple harvesting may have also contributed to this high number. As the creeks meander through rural property and urbanised areas, increases in the percentage of human *E. coli* isolates occurred. *E. coli* counts upstream were significantly higher than that found in the downstream segments (average counts for SW6-SW8: 280 cfu/100mL, maximum: 1450 cfu/100mL. Average counts for SW9-SW12: 2640 cfu/100mL, maximum: 22770 cfu/100mL). Similarly to that found for sites SW1-SW5, increases in the number of *E. coli* occurred following major rainfall events. Although a higher proportion of the faecal contamination was classified as non-human (59%), a high number of human source contamination is still evident with increased levels of *E. coli* observed. Therefore, although the use of animal manure as fertiliser and grazing land are potentially the major source of non-human source faecal contamination, a significant source of human faecal contamination is still evident, and is washed downstream following significant rainfall events.

Subsequent analysis of the groundwater samples using the human, domestic, livestock and wild isolate source library indicated that the majority of the sources identified in the upper regions of the Ningi Creek catchment originated from domestic, human and wild sources. The percentage of wild isolates in the groundwater samples were significantly less at monitoring wells located in the rural areas, with subsequent increases in domestic and livestock isolates. Within the urbanised areas where on-site wastewater treatment systems are used, human source *E. coli* remained the most dominant source of faecal contamination in the groundwater. This would be mostly in relation to the high density of on-site systems

(particularly septic tanks with subsurface disposal) within this developed environment. Analysis of *E. coli* isolates in the surface water using the human, domestic, livestock and wild isolate source library indicated similar percentages of human source isolates. The non-human source isolates however were dominated mostly by domestic and wild animals, with domestic animals being more dominant downstream and wild animals more dominant in the upstream segment of Ningi Creek. However, due to the close interaction between wild and livestock source isolates, a more defined library is needed to separate these source groups in order to accurately classify the *E. coli* isolates in more detail. However, this was not within the scope of the project.

Table 4.5: Source identification of unknown isolates from groundwater monitored sites

Monitoring Site	No. Isolates[a]	Source Identification (%) of unknown source isolates					
		Human[b]	Non-human[b]	Human[c]	Domestic[c]	Livestock[c]	Wild[c]
Ningi Creek Groundwater	*(n = 53)*						
GW1	10	60	40	20	30	10	40
GW2	2	100	0	50	0	0	50
GW3	4	100	0	50	25	0	25
GW4	6	67	33	67	17	0	16
GW5	2	0	100	0	100	0	0
GW6	7	14	86	0	71	0	29
GW7	7	14	86	0	71	0	29
GW8	9	55	45	0	56	11	33
GW9	6	33	67	33	50	0	17
GW10	0	-	-	-	-	-	-

[a] Unknown isolates from collected from monitored sites over sampling period
[b] Pooled source categories for human vs non-human isolate DA
[c] Pooled source categories for human, domestic, livestock and wild isolate DA

Table 4.6: Source identification of unknown isolates from surface water monitored sites

Monitoring Site	No. Isolates[a]	Source Identification (%) of unknown source isolates					
		Human[b]	Non-human[b]	Human[c]	Domestic[c]	Livestock[c]	Wild[c]
Ningi Creek Surface Water	*(n = 199)*						
SW1	15	67	33	53	20	0	27
SW2	14	57	43	43	14	14	29
SW3	19	37	63	32	26	0	42
SW4	21	52	48	33	29	9	29
SW5	10	40	60	40	10	0	50
SW6	19	26	74	16	58	5	21
SW7	17	47	53	47	18	18	17
SW8	16	50	50	37	44	6	13
SW9	29	41	59	38	31	0	31
SW10	14	36	64	29	50	0	21
SW11	4	50	50	50	50	0	0
SW12	16	56	44	56	25	0	19

[a] Unknown isolates from collected from monitored sites over eleven months sampling period
[b] Pooled source categories for human vs non-human isolate DA
[c] Pooled source categories for human, domestic, livestock and wild isolate DA

4.5 Conclusions

Antibiotic resistance pattern analysis was utilised to track enumerated *E. coli* isolates obtained from sampling locations, to their source. This proved particularly useful in determining human from non-human faecal contamination and consequently allowed the identification of areas which were highly susceptible to human faecal contamination, thus indicating a significant public health risk.

The results of the ARP analysis conducted on isolates collected indicated faecal contamination was occurring in the groundwater directly below Bribie Gardens development. However, although the antibiotic resistance analysis indicated that the

majority of the *E. coli* were of human origin (>80% human), the overall number of *E. coli* identified in collected water samples was relatively low, indicating that contamination of Ningi Creek via transportation of faecal contamination through groundwater systems was not overly strong. A similar scenario is evident in the surface water samples surrounding the urban development, with greater than 40% of *E. coli* isolates extracted around the urban residential areas (SW4-SW5) identified as being of human origin. The overall number of *E. coli* isolates observed in Ningi Creek at these surface water monitoring locations was also low (<100cfu/100mL). However, peak *E. coli* counts are evident following major rainfall events. As such, the overall level of human source faecal contamination consequently increases following rainfall. *E. coli* isolates collected from upstream monitoring locations (GW5-GW10 and SW5 to SW12) were found to be mostly of non-human origin, with a majority being domestic or wild animal sources. However, more source *E. coli* isolates would be needed to strengthen the source library to enable a more detailed source classification between non-human source isolates. Increases in human source isolates occurred as the Creek meandered through the more developed regions of the catchment. This is of importance in relation to management of the Ningi Creek catchment, particularly for application of oyster leases, as the potential public health risk is significantly greater with increasing percentage of human source faecal contamination.

CHAPTER 5.0

ASSESSMENT OF WATER QUALITY PROFILE AND LYNGBIA TRIGGER PARAMETERS

5.1 Overview

The investigation of *Lyngbya majuscula* 'trigger contaminants' was of a limited nature and was built around the test results of the surface water samples collected from Ningi Creek and the shallow groundwater monitoring wells installed at identified 'key' points within the catchment. The parameters tested for assessing the possible 'trigger parameters' included total iron, dissolved and total organic carbon, and nutrients (nitrate and orthophosphate). Assessment of general water quality parameters, including pH, EC, temperature and E. coli were also assessed as part of the analysis to investigate any additional correlations between identified trigger parameters and standard water quality parameters. Analysis of these parameters was undertaken using PCA in order to assess both the individual relationship between different parameters and the possibility of the effect of multiple variables each providing a significant role in triggering and sustaining *L. majuscula* blooms.

5.2 PCA of Water Quality Parameters

PCA was conducted on the chemical data obtained from the sampling. Variables included in the analysis were; pH, electrical conductivity (EC), Temperature (Temp), Dissolved Oxygen (DO), Phosphate (PO_4^{3-}), Nitrate (NO_3^-), Total Iron (Fe), Total Manganese (Mn), E. coli, Total Carbon (TC), Total Dissolved Carbon (DC), Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Total Inorganic Carbon (TIC), Dissolved Inorganic Carbon (DIC), 7-day rainfall prior to sampling date (Rain), and water table depth (WT) for groundwater samples only. Analysis was conducted through a logical sequence of steps, in order to derive the most relevant information relating to the contamination and transportation of pollutants through the catchment. This involved separation of the data obtained into several sub matrices as follows;

1. Separated into different matrices for groundwater and surface water. This was undertaken to remove any bias that may occur due to the different environments for each water resource. An initial analysis of all groundwater and surface water was initially undertaken;
2. For surface water samples, sub matrices were developed for estuarine and fresh water conditions (SW1-SW8 being estuarine and SW9 to SW12 being fresh). Sampling location SW8 was included in both data sets as this location is at the interchange between the fresh and estuarine water sections of Ningi Creek and is highly influenced by both tidal events and rainfall events. As such, analysis for estuarine conditions was conducted including and excluding SW8. This was also undertaken for fresh water, with analysis undertaken, both with and without SW8 to assess the overall significance of this location in relation to the other site locations;
3. For groundwater samples, sub matrices were developed for groundwater wells installed in the swales within the urban development, and groundwater wells installed outside the urban development. This was to investigate the influence of land use and in particular urban and rural land use.

5.2.1 Analysis of Surface Water Quality

PCA was initially undertaken for all surface water monitoring locations, SW1 to SW12. From the analysis of surface water samples, two main objects groups were formed separated on the basis of estuarine (SW1-8) or fresh water (SW9-12) conditions as indicated in Figure 5.1. Objects (in this case water samples) that retain similar variances in the analysed variables will retain similar PCA scores forming a separate cluster when plotted. Additionally, strongly correlated variables will generally have the same magnitude and orientation when plotted, whereas uncorrelated variables are generally orthogonal (perpendicular) to each other. Although retaining a close relationship with the other estuarine monitoring locations, SW8 was more sparsely separated on PC2 with increasing positive scores, which had a high correlation with rainfall. SW8 is located at the upper most section of Ningi Creek which is the furthest most sampling location which is tidally influenced. Additionally, it is also the first surface water monitoring location within the estuarine section of Ningi creek that receives runoff from the upstream segments of the catchment. Therefore, site SW8 can be influenced by the intake of freshwater following significant rainfall events.

The estuarine group of monitoring locations was found to be associated with the inorganic carbon fractions, which makes up the majority of the total carbon concentration. Some minor correlation with rainfall is observed. However, this is specifically related to the influence of freshwater on SW8. The separation of the freshwater group was signified by higher concentrations of nutrients, *E. coli* and organic carbon, which all retained positive scores on PC1. Additionally, the freshwater group was further subdivided by rainfall, temperature, *E. coli* and organic carbon (positive on PC2) with a second group separated on the basis of orthophosphate (PO_4^{3-}) and nitrate (NO_3^-). This is strongly influenced by SW11 and SW12 which showed increased levels of nutrients, particularly after rainfall. SW12 is located just below a pineapple plantation, which would be expected to contribute some nutrients into the surface water due to the application of fertiliser. The additional correlation with *E. coli* at SW12 indicates that these agricultural land uses could be using animal manure as fertiliser, rather than chemical fertilisers. This would undoubtedly increase faecal contamination of surface water with runoff during rainfall events. SW11 is located just downstream of a pine plantation, which was harvested over several weeks towards the middle of sample collection period. Samples with high levels of E. coli, Fe, Mn and organic carbon also retain significant relationships with rainfall, indicating that a majority of faecal pollution to the freshwater environment occurs after rainfall events. Due to the distinct separation between estuarine and freshwater conditions, separate sub matrices were formed between these sampling extremes. Analysis was conducted for both estuarine and fresh water samples individually, with each set including and excluding SW8, which was influenced by both surface water conditions.

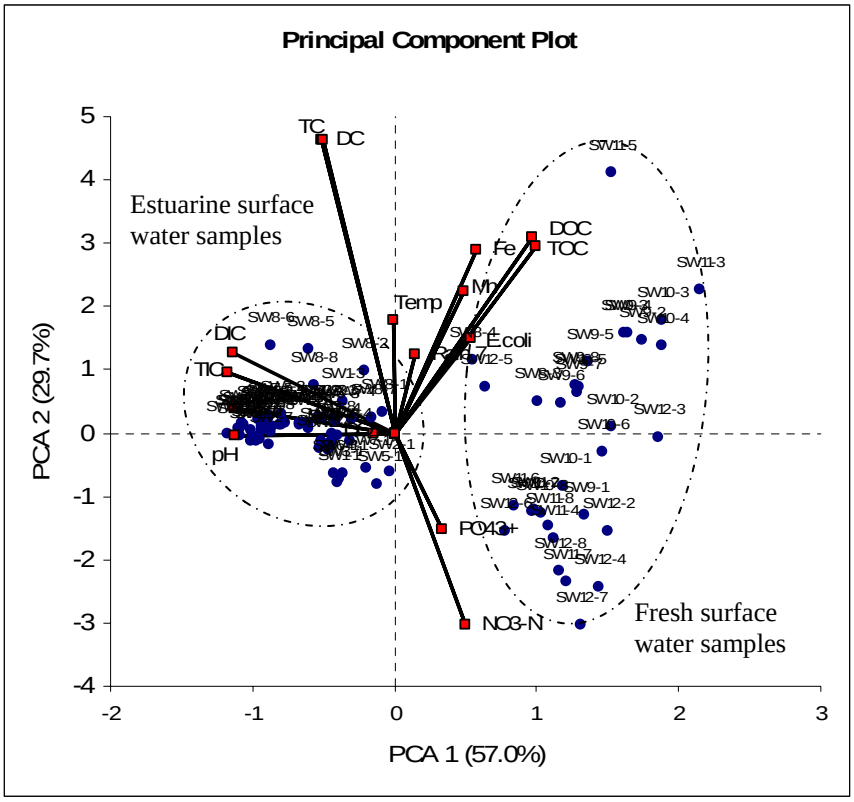

Figure 5.1: Analysis of all surface water monitoring locations

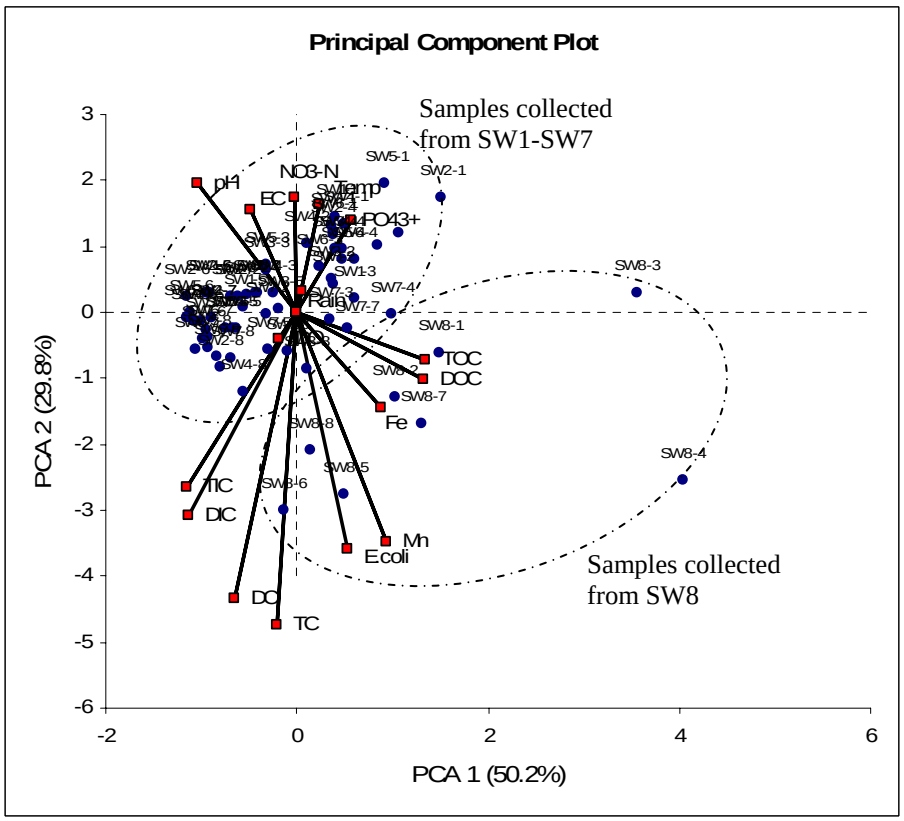

Figure 5.2: Analysis of estuarine surface water monitoring locations (including SW8)

PCA was conducted on surface water samples taken in the downstream estuarine segments of Ningi Creek. This included sampling locations SW1 to SW8. Figure 5.2 provides the PCA biplot of the analysis of the estuarine surface water samples. The resulting biplot showed two distinct clusters, one distinguished by sampling locations SW1-SW7, and a slightly less distinct cluster formed by only SW8 samples. SW8 is closely associated with the organic carbon fractions, Fe, Mn and *E. coli* levels. Some minor relationship exists with TC and DC. The distinct separation between SW8 and the remaining estuarine samples compare with earlier predictions that SW8 is influenced by the upstream freshwater conditions of Ningi Creek. Due to the similar scores achieved for SW1 to SW7, a secondary PCA analysis was undertaken to assess the relationship between analysed variables and sampling locations strictly within the estuarine environment.

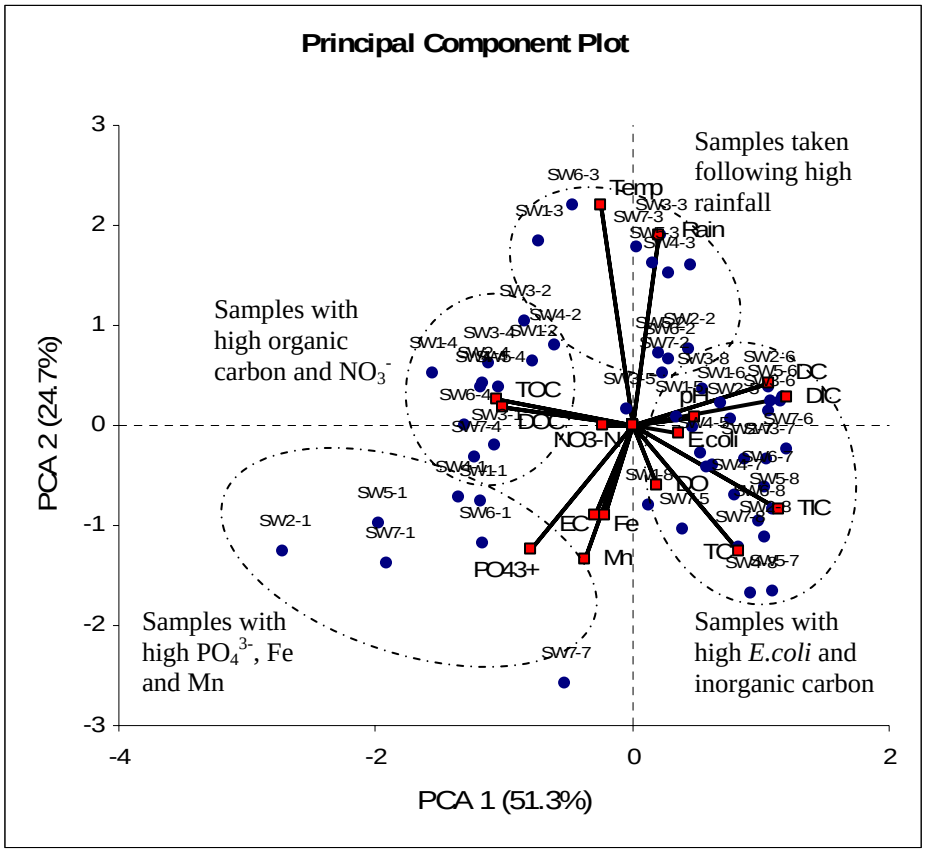

Figure 5.3: Analysis of estuarine surface water monitoring locations (excluding SW8)

Analysis of estuarine samples without the inclusion of SW8 provided a view of the influential factors related strictly to SW1 to SW7. As shown in Figure 5.3, four distinct clusters are formed on the basis of the corresponding relationships between the analysed

variables. The most noticeable difference between analysed estuarine samples (SW1-SW7) to that of analysed fresh water samples (SW9-SW12) is that no correlation exists between rainfall and levels of *E. coli*. This is a determining factor, as the level of *E. coli* within the estuarine systems is not dependant on rainfall events. The tidal influence of the Ningi Creek system is too dominant for any rainfall runoff to significantly increase the level of *E. coli* to above that of ambient conditions. However, with this in mind, the dominant sources of *E. coli* within the estuarine environment may change significantly following rainfall events. During little or no rainfall, the dominant source may be associated with wild animals, such as water birds that harbour on the banks of the creek system. Following rainfall, the dominant source may alter, for example to livestock, as higher levels of *E. coli* are washed downstream. The tidal influence however results in a dilution factor that appears to keep *E. coli* numbers to similar magnitudes. In comparison to the *E. coli* levels, a similar situation occurs with nutrients which show little association with rainfall. The other major separation of groups is between organic carbon and inorganic carbon fractions.

Considering specifically the separation of the individual groups based on monitoring locations, organic carbon is shown to exist in higher concentrations at the downstream sampling locations (SW1-SW5), most significantly during the first four sampling episodes. These were taken during a period of high rainfall (as indicated by increasing positive scores on PC2). High levels of *E. coli* and nutrients were found in the upstream segments of the estuarine environment. As samples were taken during high tide conditions, it is noteworthy that most pollutants will have migrated upstream with the incoming tide. Therefore, higher levels of pollutants at these locations may indicate that the expected sources of pollution would have originated from downstream sources in the tidally influenced zone.

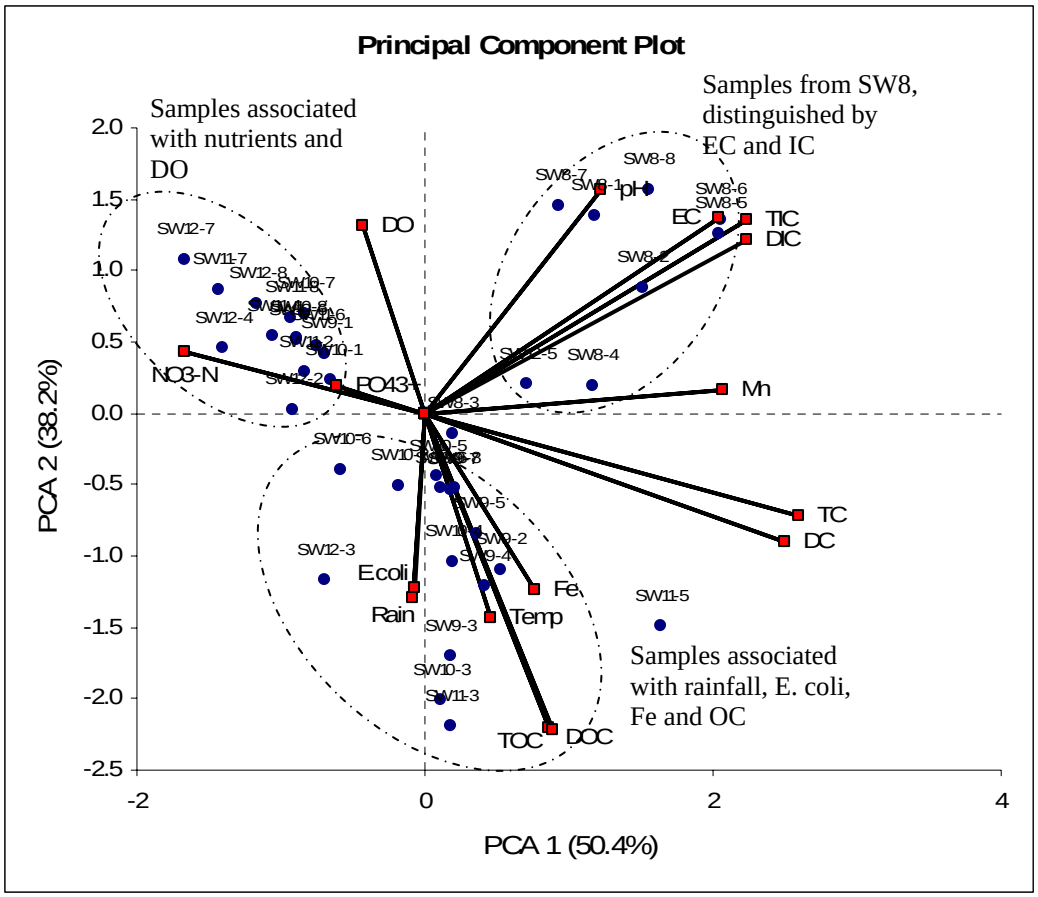

Figure 5.4: Analysis of freshwater monitoring locations (including site SW8)

PCA analysis of freshwater samples (including SW8) indicated a similar scenario to that for the estuarine environment including SW8 as depicted in Figure 5.4. Distinct groupings were formed in the analysis with SW8 forming an individual group based on higher EC levels. SW8 also had higher levels of inorganic carbon, which is typical of estuarine environments. Two other groups were also separated in this analysis, based on the relationships with nutrients (PO_4^{3-} and NO_3^-) and DO separating into one group, with a relationship between rainfall, *E.coli*, Fe and organic carbon forming another distinct cluster. These clusters however were not based strictly on monitoring location, with an even distribution between locations observed. Rather, their separation is based more on the sampling episode, related to rainfall. Additionally, the cluster associated with nutrients is also correlated with DO. The nutrients assessed are those in their most mobile form, namely nitrate and phosphate, which are highly influenced by aerobic processes within the water column. As such, high levels of these nutrients are expected in areas which are also highly aerobic. However, in order to obtain a better understanding of the variables strictly within the freshwater environment, an analysis excluding SW8 was conducted.

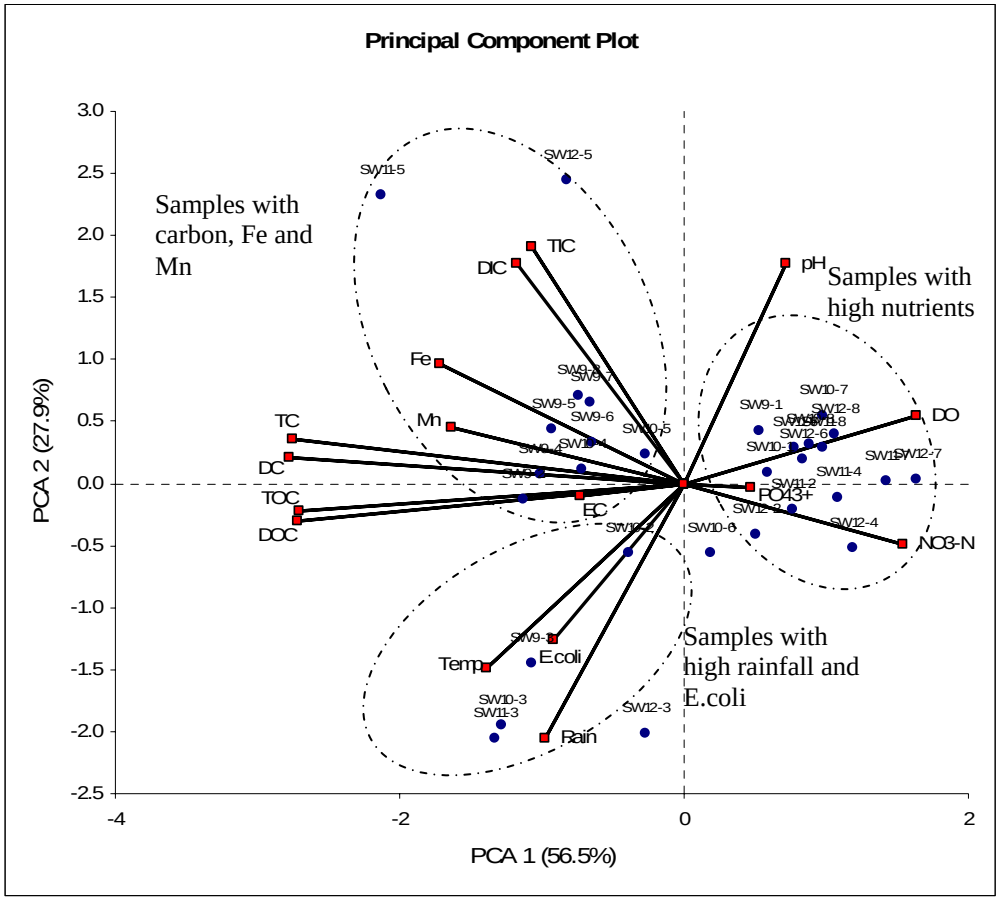

Figure 5.5: Analysis of freshwater monitoring locations (excluding site SW8)

Analysis of only the freshwater samples (SW9 to SW12) indicated some significant relationships between variables and sampling episodes, as shown in Figure 5.5. Firstly, three distinct clusters were formed, again with separations based on rainfall, and its close relationship with *E. coli* and temperature. This group was clustered strongly around the third sampling episode, which recorded the highest rainfall during the sampling program. Similar to the above analysis, two other groups were also noted. One retained higher correlations with nutrients and involved samples associated with relatively lower rainfall periods (positive scores on PC1). These were also closely related to sampling locations adjacent to agricultural land uses such as the pineapple farm. SW9 retained a strong relationship with organic carbon, with only a minor relationship with the inorganic fraction. SW9 is located downstream of a major pine plantation, which was harvested during the sampling period. Higher organic loadings have been found to occur in areas with large pine plantations (Albert et al 2005). Additionally, significant correlations between organic carbon and Fe were also identified. In the presence of organic ligands that

readily complex with soluble Fe, oxidation and precipitation of Fe is decreased. This allows Fe to be more persistent in the water environment. This agrees with the outcomes of the PCA analysis which indicated higher levels of dissolved Fe in the presence of organic carbon.

5.2.2 Analysis of Groundwater Samples

PCA analysis of all groundwater samples indicated several key relationships between the variables, which also caused separation of the water samples into distinct groups signified by the respective monitoring locations. Figure 5.6 provides a biplot of the resulting PCA analysis. Three clusters were developed as indicated in Figure 5.6, separated on the respective correlation with the groups of variables; (i) TC and DTC, TIC and DIC; (ii) DO, WT and to a lesser extent, pH; (iii) Rain, Temperature, EC, TOC, DOC, Fe, Mn, E.coli, NO_3^- and PO_4^{3-}. GW4 was separated out of the remaining monitoring locations strictly on the basis of total and inorganic carbon. GW4, as indicated in Figure 3.1 is positioned at the outfall of the swale in the urban residential area. This behaviour is most likely the result of the runoff concentration effect as water flows through the swale and into Ningi Creek. The remaining two groups are separated mostly in relation to EC levels, with both GW3 and GW8 retaining the highest recorded EC levels. GW8 is located near to where the estuarine tidal system reaches, and consequently is influenced by more saline conditions in the groundwater. Additionally, both GW3 and GW8 indicate that they retain the highest level of pollutants. Both of these sites also retain a significant relationship with rainfall, indicating that rainfall plays a significant role in terms of pollutant transport into groundwater during recharge. Interestingly, from the analysis DO was found to be more correlated with groundwater monitoring locations that had deeper water tables. However, most of the wells that were associated with DO (Figure 5.6) are located in freshwater areas, indicating that DO may be influenced by rainfall more so in fresh groundwater conditions.

The groundwater monitoring wells were located to allow an assessment of groundwater conditions throughout Ningi Creek catchment in order to develop an overall water quality profile. GW1 to GW4 were installed throughout the urban residential development, Bribie Gardens. As this is a prominent land use within the catchment, a PCA assessment of groundwater monitoring wells installed in the swale of the urban residential development was conducted separate to that of the remaining groundwater sampling locations.

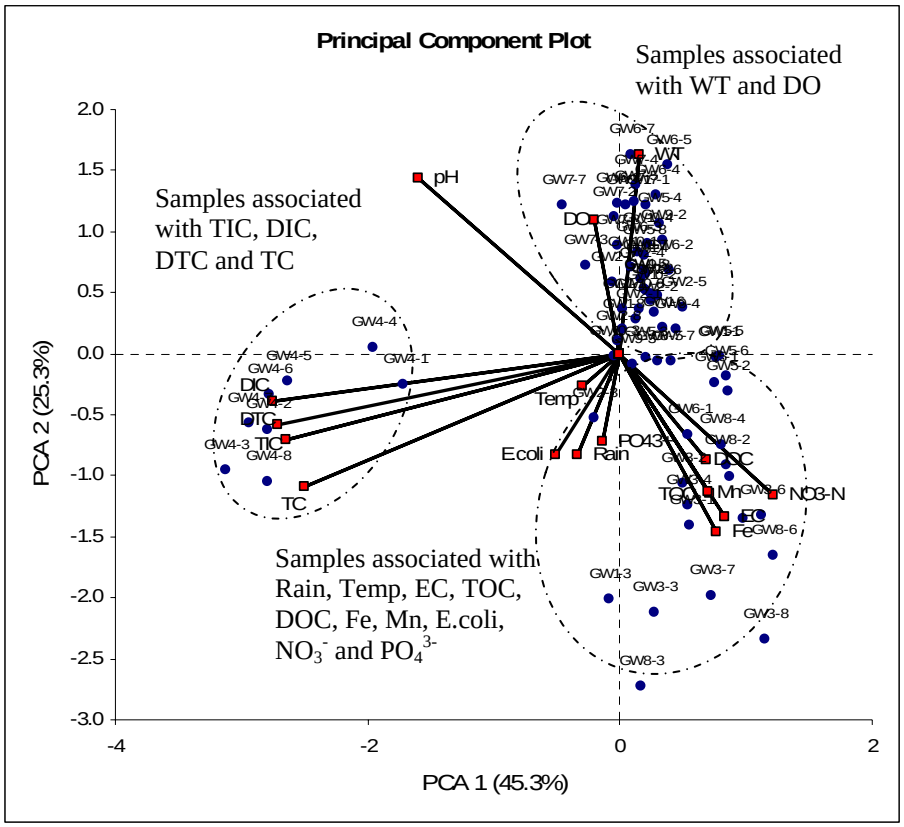

Figure 5.6: Analysis of all groundwater monitoring locations

Analysis of groundwater samples taken from monitoring wells located within the swale collecting runoff from urban development provided a more thorough assessment of the different parameters taken from geographically similar locations. Figure 5.7 provides a biplot of groundwater data for monitoring wells located in Bribie Gardens urban development. Rainfall and *E. coli* concentrations are shown to retain a very minor correlation. The inorganic carbon (both dissolved and particulate) were highly correlated, and made up the majority of the carbon, retaining a significant correlation with TC. These variables showed a distinct relationship with GW4, as was observed in the analysis of all GW monitoring wells (Figure 5.6). Additionally, *E. coli* and PO_4^{3-} were also correlated with GW4 samples, but did not retain as high a correlation. High levels of Fe, Mn and NO_3^- in groundwater samples were found to be closely correlated with samples extracted from GW3. This monitoring well penetrated a deeper groundwater aquifer, which also had high levels of salinity as indicated by its relationship with EC. GW3 had the highest levels of *E. coli* and PO_4^{3-}. Finally, GW1 and GW2 formed a distinct group separation of their

own, having a significant relationships with organic carbon, and also having a minor relationship with NO_3^- (retaining negative scores on PC1).

Rainfall did not seem to have a significant impact on any of the GW monitoring wells, although it did retain minor correlations with GW3 and GW4. The low correlations are most likely due to the fact that the swale is allowing effective drainage of stormwater away from the urban development and therefore not allowing adequate time for recharge of the shallow aquifers. Several conclusions can be drawn from relationships between the analysed variables and the separation between sampling locations. Firstly, organic carbon, mostly in the form of vegetative matter and attached to suspended solids, will be trapped effectively in the grass swale. Consequently, higher concentrations of organic carbon were found in shallower groundwater aquifers. The inorganic forms appear to concentrate at the lower end of the swale at GW4. The highest levels of PO_4^{3-} were also identified at GW4. PO_4^{3-} is highly reactive and will typically precipitate out of solution depending on the pH. pH has a significant influence on the reactivity of phosphate, with lower pH increasing the level of reactivity of the phosphate ion. GW4 was also found to have the lowest pH level as indicated in Figure 5.7. Therefore PO_4^{3-} will be more highly reactive at GW4, providing higher concentrations.

Finally, concentrations of NO_3^-, Fe and Mn were found to be higher in the groundwater monitoring wells that had deeper water table levels. All these parameters were assessed in their dissolved state, indicating that they are highly mobile and can move relatively easily into deeper groundwater.

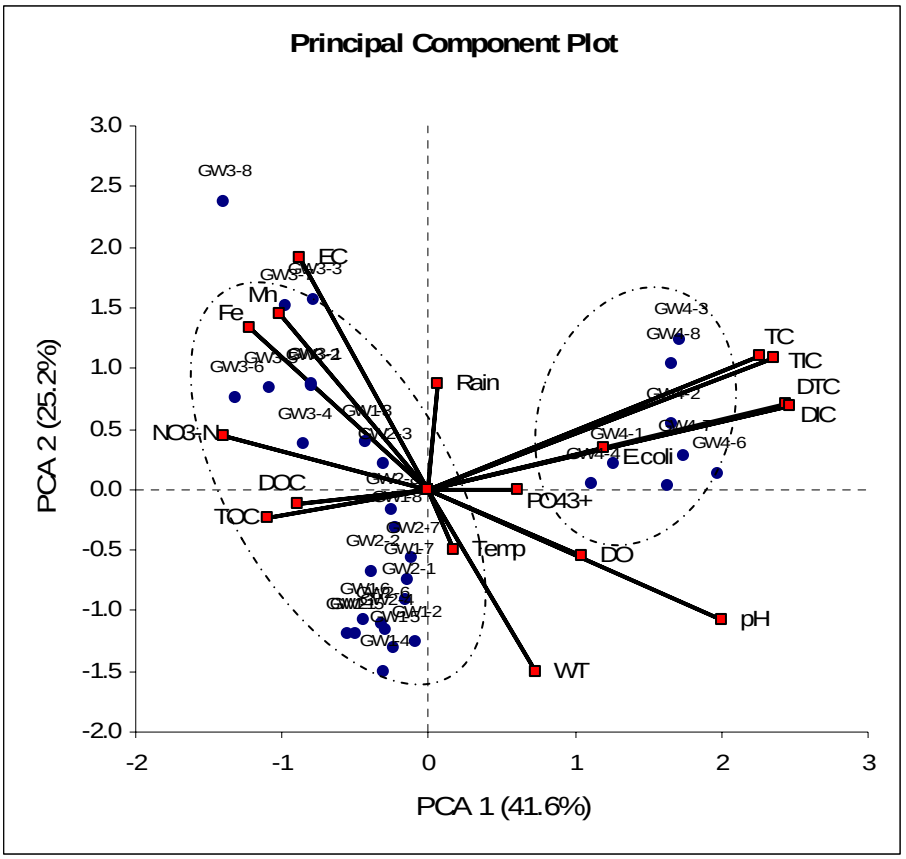

Figure 5.7: Analysis of groundwater monitoring locations located in the swale within Bribie Gardens

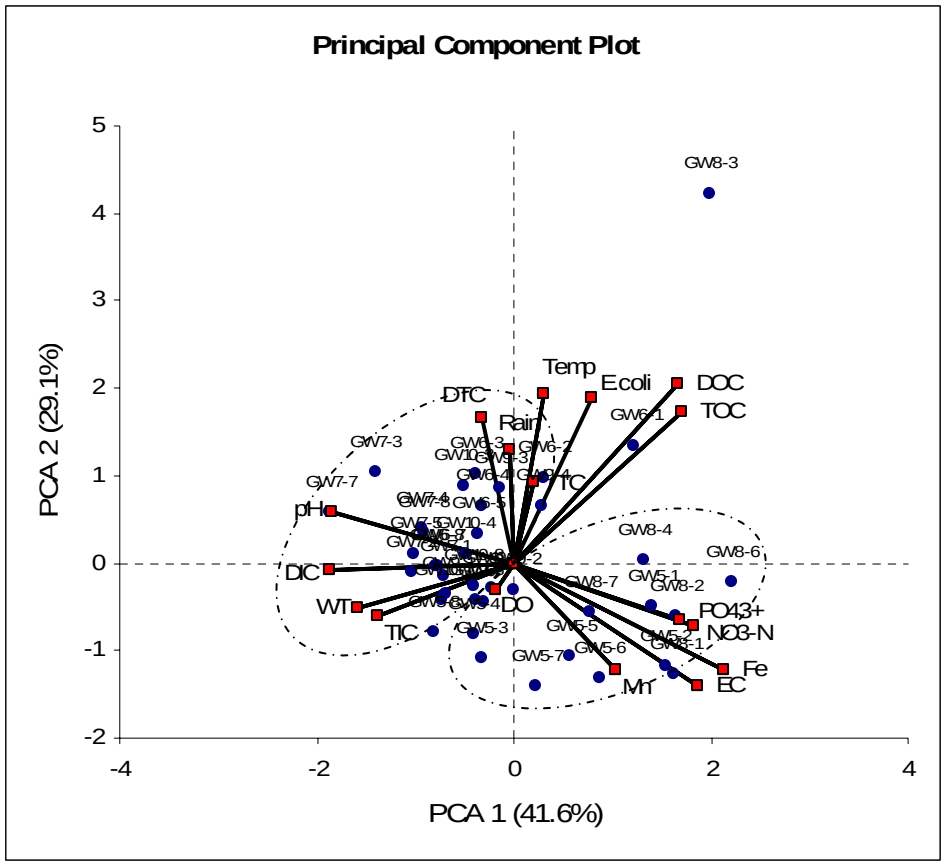

Figure 5.8: Analysis of groundwater monitoring locations located in upper segments of Ningi Creek.

Analysis of groundwater conditions in the more rural extremities of the catchment showed a more diverse range of relationships, as indicated in Figure 5.8. No distinct separations were identified. However, some separation is evident in the case of GW5 and GW8 when compared to the other monitoring well locations. Both GW5 and GW8 retained higher EC levels than other monitoring locations, indicating more saline groundwater conditions. Consequently, a higher relationship was also found with PO_4^{3-}, NO_3^-, Fe and Mn. This is particularly significant as higher concentrations of these parameters were found within the more saline groundwater conditions, which can ultimately aid in the development and sustaining of *L. majuscula* blooms within the estuarine environment. Both GW5 and GW8 are located in more natural environments with little anthropogenic activity affecting the immediate vicinity of these wells. This suggests that a majority of nutrients would originate from natural sources (such as decaying vegetation). GW8 however is located in an area which is used for livestock grazing. Therefore, in the case of GW8, livestock would also contribute to the pollutant loadings. Additionally, GW5 and GW8 have a strong

negative correlation with water table depth, indicating very shallow water table levels. This indicates that a relatively immediate impact between rainfall infiltration and groundwater recharge would occur. Therefore, and nutrients and minerals discharged from surface sources will have an immediate impact on the shallow groundwater.

Higher levels of *E.coli* were found in the upstream parts of the catchment, in particular GW9 and GW10, with varying levels identified in GW6 and GW7. These levels are also highly correlated with rainfall, as well as temperature and organic carbon fractions. This leads to two significant conclusions. Firstly, the level of *E.coli* in the groundwater is associated with groundwater recharge following rainfall events, with bacteria being transported into the aquifer. This would occur readily in sandy soils which allow almost direct recharge, as is the case with GW 6-10. Secondly, with TC being highly correlated with TOC, which in turn is highly correlated with the DOC fraction, indicates the easy mobility of the organic carbon.

5.3 Assessment of Lyngbya Majuscula

5.3.1 Identification of Trigger Parameters

From the analysis of chemical elements assessed for groundwater and surface water samples along Ningi Creek, several parameters that may have a major influence on the onset and the sustaining of *L. majuscula* blooms in the estuarine environment have been identified and their respective sources located. Unfortunately, no blooms of *L. majuscula* were reported in Ningi Creek during the course of the research project. As such, quantitative assessment related to bloom trigger parameters was not possible. However, from the research literature reviewed and assessment of the collected data from monitoring locations, the following conclusions can be derived:

1. *Lyngbia majuscula*, a marine cyanobacterium, are prone to high salinity or estuarine environments. Hence, any bloom onset could be identified in the downstream tidally influenced segments of Ningi Creek.
2. The onset of *L. majuscula* blooms is related to a number of key physical and chemical parameters, all of which have been identified in Ningi Creek. These include elevated surface water temperatures; prolonged calm water and light conditions which substantially increase photosynthesis and metabolic rate; and increased concentrations

of limiting chemical elements, particularly iron and phosphorus, which are necessary for photosynthesis and nitrogen fixation, essential for sustaining algae blooms.

However, although these factors aid in the initial onset or trigger *L. majuscula* blooms, being able to find the available elements necessary for sustaining an increasing biomass is also critical. Most blooms become noticeable following substantial rainfall, even though the initial trigger parameters may have already initiated a bloom. Cyanobacteria in general have a high demand for iron and phosphorus which is required for both photosynthesis and nitrogen fixation. Increases in the concentration or availability of necessary elements required for this process, including elevated nutrients and iron, also occur following rainfall events.

5.3.2 Correlation of Trigger Parameters

Analysis of the collected data and detailed assessment of the water quality profile along Ningi Creek allowed the investigation of correlations among the various identified parameters and the relationships in triggering *L. majuscula* blooms. First and foremost, through the assessment of analysed data, no individual parameter appears to be ultimately responsible for triggering *L. majuscula* blooms. Without more detailed information relating to *L. majuscula* cell counts, and records of actual bloom events, detailed relationships between individual parameters and bloom occurrences cannot be determined conclusively. However, based on research literature, and the outcomes of the multivariate analysis, *L. majuscula* blooms are most likely triggered and sustained through the combination of several key trigger parameters, both naturally occurring, and those caused by changes in land use and anthropogenic activities.

The trigger parameters for blooms to occur appear to be related to specific physical conditions necessary for *L. majuscula* to expand. These parameters are discussed in Section 5.3.1. Some minor effects caused by elevated concentrations of nutrients and other chemical pollutants may aid in the initial formation. However, these pollutants do play a significant role in sustaining the bloom, once it has been created.

The analysis of collected data has indicated the following correlations among parameters that will have a direct result in sustaining *L. majuscula* blooms:

1. Increases in nutrient concentrations occur in the estuarine section of Ningi Creek following rainfall events. The land uses in upper segments of the catchment are agricultural based. Excess nutrients resulting from fertiliser application, either chemical or organic in nature would flow down the catchment particularly following rainfall.
2. Elevated nutrient concentrations were not found in surface water near the more urbanised sections of the catchment. However, elevated nutrient concentrations were identified in groundwater monitoring wells installed in these areas.
3. Where phosphorus is limited in the water column, *L. majuscula* utilise dissolved iron for photosynthesis and nitrogen fixation. Iron is sustained in dissolved form where increased concentrations of organic carbon are found, which allows the Fe to become more bioavailable. In the case of Ningi Creek, increase concentrations of DOC, and consequently Fe, were identified in the upstream segments of the catchment, especially directly below the pine plantations.
4. Negative correlations between PO_4^{3-}, Fe and DOC were found, with higher concentrations of PO_4^{3-} identified in the estuarine environment near the prawn farm and the urban developments, with slight increases occurring from upstream after rainfall. However, in contrast to this, the higher concentrations of DOC and Fe from the upstream segments (resulting from the pine plantations) of Ningi Creek seem to occur continuously, with further increases occurring after rainfall. This indicates that a majority of the *L. majuscula* blooms over the recent dry periods would have resulted and sustained from the pollutant contributions upstream, rather than the periodic input of excess nutrients occurring after rainfall.

From the outcomes of the conducted data analysis, and without the benefit of more quantitative information relating to *L. majuscula* cell counts, or recorded bloom incidences, it can be concluded that the onset of *L. majuscula* blooms are most likely caused by a series of factors, both natural and caused by anthropogenic factors, occurring concurrently. However, based on previous scientific studies, and the outcomes from this study, source contamination as a result of surrounding land use and anthropogenic activities are mostly likely responsible for sustaining blooms once they have been triggered.

5.4 Conclusions

Analysis of the collected data from groundwater and surface water monitoring locations has provided insight into the relationship between elevated pollutant concentrations and the corresponding land uses in the catchment. Critical monitoring locations and the corresponding critical parameters are discussed in detail in *Chapter 6.0*. Agricultural land use practices in the upstream segments of the catchment are prime sources of nutrient loadings to Ningi Creek. This most likely results from the application of fertilisers to land for the production of crops. Additionally, several parts of Ningi Creek meander through grazing pasture, with direct access to the creek by livestock. This would result in a significant input of nutrients through the direct addition of animal waste into the stream, as indicated by samples collected from sampling locations GW8-GW9 and SW8 to SW12. This was further confirmed through the faecal source identification conducted, indicating increased levels of non-human faecal sources in this area of the catchment.

When nutrient concentrations are low, levels of iron have been identified as a possible limiting element for *L. majuscula*. The availability of iron is generally increased in the presence of organic matter which reduces the precipitation and oxidation of iron and keeps in its dissolved state. Analysis of collected water samples indicated that increased organic carbon occurs in the upstream segments of the catchment, most notably downstream of pine plantations.

Increased levels of nutrients were also identified in groundwater monitoring wells and surface water samples surrounding the urban residential developments (GW3, GW4 and SW4, SW5). These increased levels of contaminants generally occur following rainfall. The sources of these pollutants can be related to two major sources, the use of fertilisers applied to gardens and the discharge of excess nutrients, notably nitrate and phosphate, from OWTS. Finally, increased nutrient concentrations were also identified on several occasions in Ningi Creek surrounding the prawn farm (SW3-SW4). Interestingly, increased concentrations of PO_4^{3-} were more prominent, but several incidences of increased NO_3^- did occur, but not simultaneously. The increased levels of PO_4^{3-} are more of a concern, as it is a primary limiting nutrient for *L. majuscula*.

Therefore, from the results of the analysis of water quality, the actual trigger parameters for *L. majuscula* blooms appear to be caused by naturally occurring physical conditions such as temperature, light and prolonged calm conditions, in conjunction with increased nutrient loads caused by pollutant inputs such as nitrogen, phosphorus and iron from the different land uses located throughout the catchment. However, most blooms have been observed to appear following rainfall events (Beattie and Dexter 2002). This is most likely due to the increase in nutrients and chemical pollutants following rainfall which sustain the blooms, allowing them to spread and become more noticeable. Therefore, management of the pollutant sources such as nutrients will reduce the size and period of the bloom, but not necessarily prevent it from occurring.

CHAPTER 6.0

CRITICAL POINT MONITORING

6.1 Overview

The assessment of groundwater and surface water quality at several locations along Ningi Creek has allowed the development of its water quality profile. This profile identifies the various parameters that are a cause for concern, and the sources that contribute to the consequent contamination. The establishment of the chemical and microbiological quality profile has also allowed the identification of the critical monitoring locations and the critical parameters that should be monitored to allow appropriate management strategies to be implemented for mitigating the potential environmental and public health issues identified through this research.

6.2 Development of a Critical Point Monitoring Program

Critical Point Monitoring (CPM) is a process used in a risk management context for the management and mitigation of environmental and public health impacts. Essentially, critical parameters identified through a series of investigations at specific monitoring points are used as triggers to develop specific management processes to reduce the targeted critical parameter back to safe levels. The development and implementation of a CPM program for Ningi Creek will allow the Caboolture Shire Council to monitor the critical parameters at specified monitoring locations to reduce the faecal contamination load from identified sources, as well as implement appropriate management strategies to reduce the specific parameters which can trigger and sustain *L. majuscula* blooms in the lower catchment. Figure 6.1 provides the generic steps employed in a CPM program. The first three steps of the CPM program are determined through the monitoring process undertaken and establishment of a water quality profile for Ningi Creek. The final steps provide the management context of the CPM, to be conducted when the critical parameters identified exceed the trigger values. Step four is the linkage between the assessment and management stages, and requires continual monitoring of all the identified critical parameters on a regular basis.

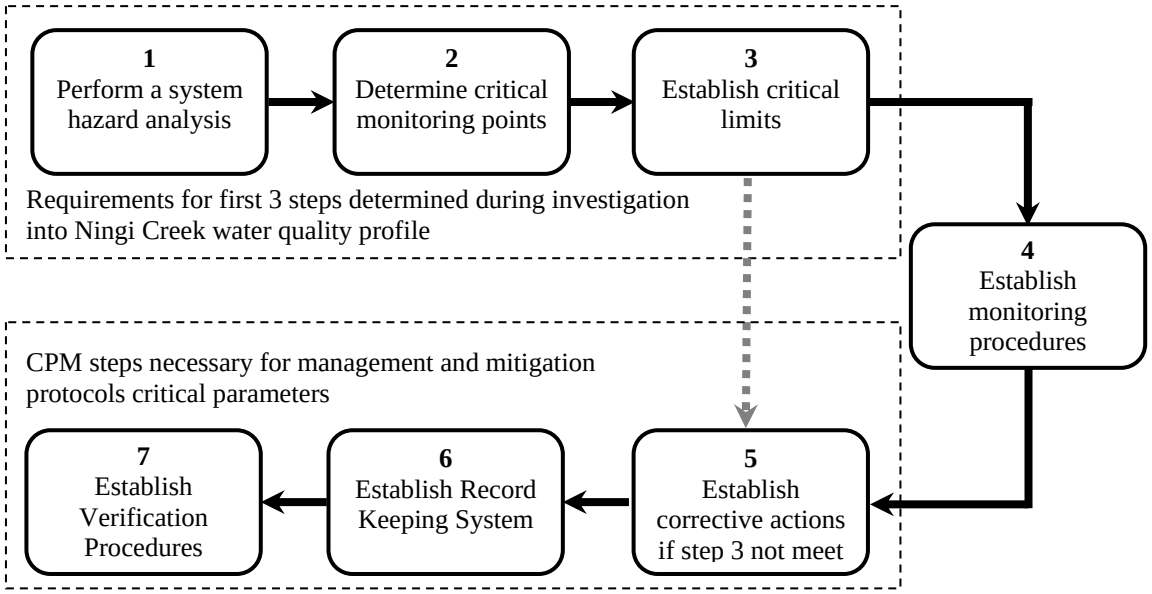

Figure 6.1: Critical Point Monitoring Process (adapted from Eliasson et al 2001)

6.3 Water Quality Profile of Ningi Creek and Critical Parameters

Detailed evaluation of the collected data obtained from the Ningi Creek catchment study has enabled the development of a water quality profile. This profile essentially identifies the major sources of contamination along Ningi Creek in respect of the specific pollutants assessed. Table 6.1 and 6.2 provides the major contaminant parameters at each monitored site for groundwater and surface water pollutants. Identified potential sources of contamination based on land use type are also provided.

Table 6.1: Major parameters at monitored groundwater locations along Ningi Creek

Monitoring Site	Major Contaminants	Potential Contaminant Source
GW1	Organic Carbon	• On-site systems in urban development • Decomposing organic matter (eg vegetation) • Runoff from surrounding development
GW2	Organic Carbon	• On-site systems in urban development • Decomposing organic matter (eg vegetation) • Runoff from surrounding development
GW3	NO_3^- *E. coli* Fe and Mn	• On-site systems, organic and inorganic fertilisers in urban developments (Bribie Gardens) • Natural occurring dissolved metals leaching from sediments • Runoff from surrounding development concentrated through swale
GW4	Inorganic Carbon (IC) PO_4^{3-} *E. coli*	• Runoff from surrounding development concentrated through swale • Naturally occurring carbon sources • On-site systems in urban development • Decomposing organic matter and fertilisers
GW5	NO_3^-, PO_4^{3-} Fe, Mn IC	• Naturally occurring sources, decomposing vegetation • Dissolved metals leaching from soils
GW6	*E. coli* OC	• Seepage of runoff from surrounding rural areas • Naturally occurring carbon sources • On-site systems • Agricultural organic fertilisers (ie manure)
GW7	*E. coli*	• On-site systems • Agricultural organic fertilisers
GW8	NO_3^-, PO_4^{3-} Fe	• Seepage of runoff from surrounding rural areas upstream of monitoring location • Agricultural organic fertilisers • Livestock
GW9	TC (both IC and OC)	• Total carbon from upstream plantations, particularly pine forestry plantations
GW10	TC (both IC and OC)	• Total carbon from upstream plantations, particularly pine forestry plantations

Table 6.2: Critical parameters at monitored surface water locations

Monitoring Site	Major Contaminants	Potential Contaminant Source
SW1	Organic Carbon (OC)	• Decomposing organic matter from numerous sources in surrounding area
SW2	DIC and OC	• Decomposing organic matter from numerous sources in surrounding area • Runoff from urban developments, upstream sources • Greatly influenced by tidal fluctuations
SW3	Organic Carbon (OC) NO_3^-	• Leaching wastewater from commercial prawn farm • Decomposing organic matter from numerous sources in surrounding area • Mangrove covered islands and wild animals • Minor influence from on-site systems
SW4	Organic Carbon (OC) NO_3^-	• Decomposing organic matter from numerous sources in surrounding area • On-site systems from urban developments • Runoff from urban developments (swale)
SW5	Inorganic Carbon (IC) NO_3^-	• Decomposing organic matter from numerous sources in surrounding area • On-site systems from urban developments • Runoff from urban developments (swale) influenced through tidal fluctuations (contaminants carried upstream with high tide) • Minor influence from runoff from upstream sources including agricultural practices, pine plantations
SW6	Inorganic Carbon (IC) NO_3^- and PO_4^{3-} *E. coli*	• Decomposing organic matter from numerous sources in surrounding area • On-site systems from upstream residential areas • Runoff from upstream sources including agricultural practices, livestock, pine plantations • Surrounding mangroves and wild animals
SW7	NO_3^- and PO_4^{3-} Fe and Mn *E. coli*	• Runoff from upstream sources including agricultural practices, livestock, pine plantations • Surrounding mangroves and wild animals • Leaching of groundwater into surface water carrying dissolved metals
SW8	Inorganic Carbon (IC) NO_3^- and PO_4^{3-} Fe *E. coli*	• Runoff from upstream sources including agricultural practices, livestock, pine plantations • Surrounding mangroves and wild animals • Leaching of groundwater into surface water carrying dissolved metals
SW9	OC and IC Fe and Mn *E. coli*	• Runoff from upstream sources with a major influence from pine plantations • Runoff from surrounding forestry plantation • Surrounding forestry and wild animals
SW10	NO_3^- and PO_4^{3-} *E. coli*	• Runoff from surrounding forestry plantation • Surrounding forestry and wild animals
SW11	IC NO_3^- and PO_4^{3-} *E. coli*	• Runoff from surrounding agricultural land use • Livestock • Upstream on-site systems from residential areas
SW12	IC NO_3^- and PO_4^{3-} *E. coli*	• Runoff from surrounding agricultural land use ie pineapple plantations • Livestock • Upstream on-site systems from residential areas

6.4 Critical Monitoring points and critical parameters

From the developed water quality profile for Ningi Creek, the critical monitoring points and related critical parameters for monitoring faecal contamination and trigger parameters for *L. majuscula* blooms are outlined in Tables 6.3 and 6.4 respectively

Table 6.3: Critical monitoring locations and parameters to be checked for faecal contamination

Monitoring Site	Major Landuse	Critical Contaminants
GW 4	Urban residential development utilising on-site wastewater treatment systems. Pollutants concentrated at these locations due to direction of runoff through swales	• E. coli • NO_3^- • PO_4^{3-}
GW5	Natural Bushland Site provides good monitoring of natural pollution sources	• NO_3^- • PO_4^{3-}
GW6 & 7	Rural residential development and minor agriculture land use	• *E. coli*
GW8	Agriculture, mostly related to livestock Ideal monitoring location between fresh and estuarine conditions	• NO_3^- • PO_4^{3-} • *E. coli*
SW3, 4 & 5	Urban residential development and on-site systems	• NO_3^- • *E. coli*
SW8	Agricultural, livestock and pine plantations Critical location for monitoring change between fresh and estuarine water, and also effect of upstream landuses following major rainfall events	• NO_3^- • PO_4^{3-} • *E. coli*
SW9	Agriculture and pine plantation Critical location for monitoring effect of manure spreading for fertiliser on farm land,	• E. coli
SW11	Agriculture and rural residential development Critical location for monitoring effect of manure for fertilisation of farm land	• NO_3^- • PO_4^{3-} • *E. coli*

Table 6.4: Critical monitoring locations and trigger parameters to be checked for *L. majuscula*

Monitoring Site	Reasons	Critical Contaminants
GW 4	Urban residential development utilising on-site wastewater treatment systems. Pollutants concentrated at these locations due to direction of runoff through swales	• Organic and inorganic carbon • NO_3^- • PO_4^{3-}
GW5	Natural Bushland Site provides good monitoring of natural pollution sources	• Fe • Mn • NO_3^- • PO_4^{3-}
GW8	Agriculture, mostly related to livestock Ideal monitoring location between fresh and estuarine conditions	• NO_3^- • PO_4^{3-}
SW3 & 4	Urban residential development and on-site systems	• Organic Carbon • NO_3^-
SW8	Agricultural, livestock and pine plantations Critical location for monitoring change between fresh and estuarine water, and also effect of upstream landuses following major rainfall events	• Fe • NO_3^- • PO_4^{3}--
SW9	Agriculture and pine plantation Critical location for monitoring effect of manure spreading for fertiliser on farm land, and effect of organic carbon and Fe obtained through pine plantation land use	• OC and IC • Fe and Mn • NO_3^- • PO_4^{3}--

6.3 Conclusions

The developed water quality profile and CPM program developed for Ningi Creek will allow Caboolture Shire Council to establish appropriate management processes to reduce the overall impact from the various land uses, and pollutant issues identified. The incorporation of these processes into a catchment management process, will allow Ningi Creek catchment to accommodate the various land uses in a sustainable manner.

CHAPTER 7.0

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Faecal contamination has become a critical issue in Ningi Creek, with several oyster leases closed due to elevated faecal coliform counts. These increases have typically been found to increase following rainfall events. However, although elevated faecal coliform levels have been observed, the sources of the faecal contamination have not been identified previously. Antibiotic Resistance Pattern analysis was undertaken to identify the sources of faecal contamination. The results of the ARP analysis conducted on isolates collected indicated faecal contamination was occurring in the groundwater directly below Bribie Gardens development. However, although the antibiotic resistance analysis indicated that the majority of the *E. coli* were of human origin (>80% human), the overall number of *E. coli* identified in collected water samples was relatively low. Collected surface water samples surrounding the urban development, indicated that greater than 40% of *E. coli* isolates extracted around the urban residential areas were of human origin. *E. coli* isolates collected from upstream freshwater monitoring locations were found to be mostly of non-human origin, with a majority being domestic or wild animal sources. Increases in human source isolates occurred as the Creek meandered through the more developed regions of the catchment. The outcomes of this source identification have allowed the faecal coliforms to be accurately classified as human or non-human sources. This will allow a more appropriate risk assessment to be conducted based on more detailed information relating to human source faecal contamination.

The second objective of this study was to develop a water quality profile along Ningi Creek with the aim of identifying the trigger parameters causing *Lyngbia majuscula* blooms. Numerous bloom occurrences have been observed in Ningi Creek and the greater Moreton Bay area. Although several studies have investigated the impacts of these blooms and identified several parameters which are associated with these blooms, no accurate studies have been undertaken to identify respective 'trigger parameters' related to the surrounding land use. This is necessary in order to allow appropriate management strategies to be implemented to control bloom outbreaks.

Analysis of the collected data from groundwater and surface water monitoring locations allowed identification of the major critical contaminants related to *L. majuscula* blooms, and the land uses that contribute to the increase in the possible trigger parameters. Unfortunately, without more detailed quantitative assessment related to *L. majuscula* cell counts and identified outbreak locations and timeframes, identification of individual trigger parameters was not possible. Therefore, from the results of the analysis of water quality, preliminary conclusions can be drawn that the actual trigger parameters for *L. majuscula* blooms appear to be caused by naturally occurring physical conditions such as temperature, light and prolonged calm conditions, in conjunction with increased nutrient loads associated with the different land uses, in particular agriculture (crop and livestock), pine plantation and urban residential development. Agricultural land use practices in the upstream segments of the catchment are prime sources of nutrient loadings to Ningi Creek. This most likely results from the application of fertilisers to land for the production of crops. Additionally, significant input of nutrients through the direct addition of animal waste into Ningi Creek, due to areas with livestock access, is also occurring. Increased levels of nutrients were also identified in groundwater monitoring wells and surface water sampling locations surrounding the urban residential development. The sources of these pollutants can be related to two major sources, the use of fertilisers applied to gardens and the discharge of excess nutrients, notably nitrate and phosphate, from OWTS. Finally, increased nutrient concentrations were also identified on several occasions in Ningi Creek surrounding the prawn farm. The outcomes from this analysis has allowed the critical parameters associated with *L. majuscula* blooms, in association with the sources of faecal contamination, and the critical monitoring locations to be identified.

Critical point monitoring locations and the corresponding critical parameters were identified through the assessment of the water quality profile along Ningi Creek. Agricultural land use practices in the upstream segments of the catchment have been identified as prime sources of nutrient loadings into Ningi Creek. This is related to the application of manure and inorganic fertilisers to agricultural land for the production of crops. Additionally, several segments of Ningi Creek meander through grazing pasture, with direct access to the creek by livestock. This can result in significant input of nutrients through animal waste into the stream. This conclusion was further strengthened with the identification non-human faecal source contamination in these areas, with a preliminary detailed analysis of non-human faecal source identification indicating livestock sources.

The summary of outcomes from the comprehensive study undertaken include:

1. The development of a water quality profile for Ningi Creek to enable an overall evaluation of the catchment and the different land uses that may contribute to the pollutant loading;
2. The identification of the various sources of faecal contamination in order to allow appropriate management strategies to be implemented to minimise faecal bacterial loading into Ningi Creek;
3. The identification of sources of the trigger parameters which cause and sustain *L. majuscula* blooms in Ningi Creek; and
4. The development of a critical point monitoring program to enable the Caboolture Shire Council to monitor, manage and mitigate the pollutant inputs into Ningi Creek.

7.2 Recommendations

Based on the outcomes of the study, the following recommendations are made:

1. The water quality profile developed for Ningi Creek should be used as a basis for assessing future land use changes in order minimise pollutant loadings;
2. The development of management strategies based on identified faecal contamination sources to minimise faecal bacterial loadings to Ningi Creek;
3. The development of management strategies to control and reduce trigger parameters from identified sources to minimise major *L. majuscula* blooms;
4. To further refine the study on *L. majuscula* trigger parameters as more quantitative information relating to cell counts and bloom incidents become available; and
5. The implementation of the critical point monitoring program developed to provide continual monitoring of the critical pollutant parameters in Ningi Creek.

CHAPTER 8.0

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APPENDIX A

CHEMICAL AND MICROBIOLOGICAL DATA FROM SAMPLED SITES

Table A.1a: Chemical Data for Groundwater Sites

Sampling Location	Date	Water Table m	pH	EC uS/cm	DO mg/L	Temp °C	TC mg/L	TIC mg/L	TOC mg/L	DTC mg/L	DIC mg/L	DOC mg/L	NO_3-N mg/L	PO_4^{3+} mg/L	Total Fe mg/L	Total Mn mg/L
GW1	15/09/2004	1.66	5.42	726.00	0.71	20.50	18.66	4.49	14.17	6.68	0.50	6.19	7.95	0.68	0.52	0.10
	16/11/2004	1.41	6.18	829.00	2.73	23.20	25.07	11.14	13.93	7.80	4.83	2.97	3.86	0.50	0.04	0.08
	14/12/2004	0.36	5.58	893.00	0.58	24.10	73.31	31.54	41.77	23.65	9.04	14.61	7.54	0.14	0.02	0.09
	15/02/2005	1.20	6.86	840.00	0.76	28.60	21.38	8.05	13.33	12.99	0.56	12.43	0.00	0.08	0.10	0.17
	30/03/2005	1.50	5.83	861.00	0.56	25.60	25.91	11.95	13.96	12.36	5.67	6.69	0.92	0.19	0.67	0.12
	26/04/2005	1.30	5.11	825.00	1.11	24.20	27.36	8.34	19.02	13.44	3.30	10.14	0.21	0.16	0.67	0.06
	25/05/2005	0.75	5.43	834.00	2.89	21.70	36.61	22.96	13.65	15.55	5.73	9.82	0.17	0.14	0.03	0.19
	20/06/2005	0.51	4.92	1082.00	2.08	19.20	40.76	30.93	9.83	11.33	2.22	9.11	0.00	0.19	0.02	0.16
GW2	15/09/2004	1.34	5.19	1114.00	0.77	20.80	32.85	22.46	10.39	10.75	3.57	7.18	0.00	0.53	0.04	0.61
	16/11/2004	0.92	5.72	1095.00	0.65	23.20	25.80	19.40	6.40	7.98	2.22	5.76	3.94	0.15	0.18	0.33
	14/12/2004	0.10	5.27	897.00	0.60	24.80	42.97	30.80	12.17	18.56	6.86	11.70	0.00	0.13	1.30	0.28
	15/02/2005	0.83	6.83	863.00	0.58	26.10	20.90	10.79	10.11	11.87	1.19	10.69	0.00	0.17	2.90	0.27
	30/03/2005	1.16	5.47	874.00	1.86	25.80	24.12	4.38	19.74	6.96	3.97	2.99	4.30	0.15	0.58	0.07
	26/04/2005	0.90	5.60	915.00	2.94	24.90	28.02	4.61	23.41	7.47	3.35	4.13	0.00	0.16	0.32	0.02
	25/05/2005	0.48	5.17	775.00	3.58	21.40	41.03	28.87	12.16	10.32	4.99	5.33	0.00	0.00	0.00	0.03
	20/06/2005	0.23	5.17	556.00	1.60	19.40	40.62	30.26	10.36	12.44	4.20	8.24	0.39	0.21	0.00	0.15
GW3	15/09/2004	0.79	3.42	13220.00	0.74	21.10	43.01	26.98	16.03	13.45	3.67	9.78	1.08	0.47	224.00	2.80
	16/11/2004	0.49	4.65	11280.00	0.81	23.40	31.25	21.86	9.39	15.14	10.04	5.10	5.71	0.19	220.00	2.40
	14/12/2004	0.22	4.24	9500.00	0.58	25.90	45.68	32.21	13.47	19.02	6.43	12.59	0.33	0.27	360.00	5.80
	15/02/2005	0.60	6.61	13190.00	0.63	27.40	33.40	16.65	16.75	19.84	0.00	19.84	1.96	0.15	270.00	4.30
	30/03/2005	0.74	3.58	12300.00	0.63	27.00	25.78	20.92	4.86	4.07	1.23	2.84	9.11	0.32	250.00	3.70
	26/04/2005	0.63	4.51	14340.00	0.95	24.70	26.49	2.51	23.98	5.75	1.63	4.12	7.78	0.02	230.00	2.60
	25/05/2005	0.46	4.23	12980.00	1.87	21.40	46.63	31.09	15.54	8.65	1.46	7.18	2.93	0.28	570.00	3.80
	20/06/2005	0.31	1.98	12990.00	0.62	18.90	41.22	27.44	13.78	7.23	2.19	5.04	4.46	0.18	2.50	29.00
GW4	15/09/2004	1.27	6.54	4930.00	0.85	22.00	84.61	78.20	6.41	35.48	35.33	0.15	0.41	0.35	1.90	0.34
	16/11/2004	1.12	6.78	4780.00	0.47	23.80	89.91	86.13	3.78	81.78	80.56	1.22	0.08	0.62	0.04	0.35
	14/12/2004	0.84	6.61	4810.00	0.50	24.20	104.30	100.10	4.20	84.54	84.36	0.18	0.59	0.25	0.03	0.26
	15/02/2005	0.56	6.97	4900.00	2.80	27.30	67.46	65.99	1.47	62.34	55.65	6.69	0.00	0.20	0.68	0.23
	30/03/2005	0.79	7.48	5026.00	4.34	27.10	88.05	75.94	12.11	80.83	75.59	5.24	0.00	0.32	0.00	0.15
	26/04/2005	1.25	7.50	5090.00	4.14	25.70	90.58	81.00	9.58	80.67	74.94	5.73	0.00	0.23	0.01	0.10
	25/05/2005	0.94	6.92	219.20	2.68	22.20	111.44	98.10	13.34	82.73	75.70	7.03	0.00	0.27	0.31	0.11
	20/06/2005	0.82	6.25	4580.00	0.88	20.00	104.60	95.66	8.94	82.46	74.45	8.01	0.00	0.25	0.36	0.12

Table A.1a: Chemical Data for Groundwater Sites (cont)

Sampling Location	Date	Water Table m	pH	EC uS/cm	DO mg/L	Temp °C	TC mg/L	TIC mg/L	TOC mg/L	DTC mg/L	DIC mg/L	DOC mg/L	NO_3-N mg/L	PO_4^{3+} mg/L	Total Fe mg/L	Total Mn mg/L
GW5	15/09/2004	2.39	4.6	20200.0	4.1	20.8	32.4	10.8	21.7	14.7	0.4	14.2	0.6	0.2	56.0	4.4
	16/11/2004	2.09	4.9	17690.0	4.5	21.3	16.3	5.3	11.0	15.6	4.8	10.7	5.4	0.5	59.0	4.7
	14/12/2004	1.85	4.4	18800.0	0.8	22.3	23.7	23.3	0.4	10.8	10.4	0.4	0.0	0.1	35.0	3.1
	15/02/2005	1.87	6.6	20380.0	4.4	23.9	15.0	12.3	2.7	9.9	5.5	4.4	0.8	0.1	14.0	1.5
	30/03/2005	2.33	4.9	18600.0	0.7	23.5	16.5	10.2	6.3	10.3	5.3	4.9	6.5	0.2	26.0	1.7
	26/04/2005	2.37	5.6	24190.0	0.8	23.8	18.4	10.8	7.7	6.4	3.3	3.1	7.8	0.2	59.0	1.4
	25/05/2005	1.75	3.3	19290.0	2.8	22.2	32.5	27.7	4.8	10.1	8.9	1.2	1.9	0.2	61.0	1.4
	20/06/2005	2.38	3.3	6010.0	3.4	20.2	30.5	26.3	4.2	11.9	9.2	2.8	0.0	0.1	0.3	0.9
GW6	15/09/2004	2.03	5.6	364.0	0.9	22.0	49.0	7.9	41.1	15.8	1.1	14.8	4.7	0.5	0.5	0.1
	16/11/2004	1.63	6.9	382.0	5.1	25.9	18.1	2.8	15.3	16.7	2.1	14.6	4.6	0.3	0.0	0.0
	14/12/2004	1.35	6.2	199.0	5.4	26.1	23.2	7.1	16.1	10.0	2.4	7.6	0.0	0.0	0.0	0.0
	15/02/2005	1.74	6.8	91.9	3.5	27.8	16.9	2.8	14.1	7.9	0.0	7.9	0.0	0.1	0.1	0.0
	30/03/2005	1.99	6.3	4.9	4.9	26.6	12.7	0.2	12.4	6.7	0.0	6.7	0.0	0.1	0.1	0.0
	26/04/2003	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	25/05/2005	1.50	6.9	33.4	6.0	22.4	18.5	11.5	7.0	9.7	2.8	7.0	0.0	0.1	0.1	0.0
	20/06/2005	1.64	6.2	365.0	4.7	21.0	18.9	14.0	4.9	7.6	4.6	3.0	0.0	0.1	0.0	0.0
GW7	15/09/2004	3.10	5.8	456.0	-	21.9	25.2	16.5	8.8	9.8	2.9	6.9	0.1	0.2	0.5	0.0
	16/11/2004	2.80	6.4	438.0	0.7	21.7	21.6	15.6	6.0	16.9	12.2	4.7	0.7	0.4	1.0	0.0
	14/12/2004	2.85	6.2	332.0	1.0	22.9	28.3	19.2	9.1	26.8	18.1	8.7	0.5	0.1	2.1	0.0
	15/02/2005	3.13	6.9	462.0	0.5	22.9	19.5	9.6	9.8	16.5	6.9	9.7	0.0	0.1	1.9	0.0
	30/03/2005	3.04	6.3	86.1	1.0	23.1	22.8	11.7	11.1	15.7	11.1	4.6	2.0	0.1	1.6	0.0
	26/04/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	25/05/2005	3.04	6.3	531.0	1.4	22.9	32.6	25.6	7.0	28.0	22.5	5.6	0.0	0.1	0.0	0.0
	20/06/2005	3.00	5.7	582.0	1.2	21.6	32.6	22.0	10.6	19.3	10.2	9.1	1.0	0.2	1.7	0.0
GW8	15/09/2004	0.85	3.2	26270.0	1.0	20.1	27.8	15.0	12.8	9.4	1.5	7.9	1.4	0.4	82.0	1.4
	16/11/2004	0.32	3.8	8560.0	0.9	21.4	14.7	3.9	10.9	10.6	1.2	9.5	4.2	0.8	35.0	0.3
	14/12/2004	0.00	3.4	6080.0	1.0	29.9	44.1	11.6	32.6	25.8	1.1	24.6	0.1	0.1	25.0	0.2
	15/02/2005	0.40	3.8	15450.0	0.6	24.6	20.9	7.3	13.6	12.4	0.0	12.4	1.5	0.2	51.0	0.3
	30/03/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	26/04/2005	0.37	3.9	23930.0	0.5	23.2	21.8	0.9	20.9	10.6	0.0	10.6	8.7	0.4	36.0	0.2
	25/05/2005	0.35	3.6	635.0	6.0	20.1	37.4	23.6	13.8	9.5	3.2	6.3	1.9	0.3	66.0	0.4
	20/06/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

Table A.1a: Chemical Data for Groundwater Sites (cont)

Sampling Location	Date	Water Table m	pH	EC uS/cm	DO mg/L	Temp °C	TC mg/L	TIC mg/L	TOC mg/L	DTC mg/L	DIC mg/L	DOC mg/L	NO_3-N mg/L	PO_4^{3+} mg/L	Total Fe mg/L	Total Mn mg/L
GW9	15/09/2004	1.67	6.1	63.2	4.2	20.6	27.2	18.9	8.3	10.8	4.9	5.9	0.0	0.2	0.4	1.3
	16/11/2004	1.15	6.0	825.0	4.6	21.8	12.2	4.3	7.9	10.4	2.9	7.4	0.2	0.4	6.2	1.5
	14/12/2004	0.48	5.6	755.0	0.8	27.2	23.5	13.6	9.9	13.7	5.4	8.3	0.0	0.1	0.7	2.5
	15/02/2005	0.62	5.4	853.0	0.7	24.1	15.4	5.6	9.7	14.1	0.2	13.9	0.0	0.1	0.2	1.5
	30/03/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	26/04/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	25/05/2005	0.98	5.3	1153.0	2.7	21.6	28.0	21.2	6.9	6.7	0.9	5.8	0.1	0.2	0.2	1.7
	20/06/2005	0.96	4.5	1034.0	2.3	20.0	29.0	21.3	7.7	9.7	4.3	5.5	0.0	0.2	0.0	1.3
GW10	15/09/2004	1.54	5.0	230.0	0.8	20.9	34.7	26.4	8.3	7.7	4.4	3.4	0.4	0.1	0.1	0.3
	16/11/2004	0.73	5.6	228.1	0.8	21.4	17.1	10.9	6.1	10.8	5.8	5.0	1.3	0.4	0.0	0.2
	14/12/2004	0.36	5.2	196.5	0.8	26.9	27.6	20.1	7.5	12.9	6.5	6.4	0.0	0.1	0.6	0.3
	15/02/2005	0.85	6.7	489.0	0.8	23.2	20.6	10.6	10.0	7.0	0.8	6.2	0.0	0.0	0.2	0.3
	30/03/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	26/04/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	25/05/2005	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	20/06/2005	1.15	4.3	199.9	1.9	19.2	41.2	26.8	14.5	7.2	3.1	4.2	0.0	0.2	0.0	0.2

Table A.1 b: Microbiological data for groundwater samples

Sampling Location	FC cfu/100mL	E.coli cfu/100mL	Sampling Location	FC cfu/100mL	E.coli cfu/100mL
GW1	0	0	GW7	300	0
	270	0		250	0
	>2500	0		230	0
	90	10		0	0
	340	57		0	0
	40	10		---	---
	80	50		220	110
	70	16		30	20
GW2	20	0	GW8	700	0
	10	1		490	0
	>2500	0		>2500	>2000
	0	0		0	0
	0	0		---	---
	80	10		120	30
	0	0		270	180
	10	10		---	---
GW3	270	0	GW9	30	8
	0	0		0	0
	20	0		200	0
	0	0		640	213
	0	0		---	---
	0	0		---	---
	0	0		80	20
	100	40		80	20
GW4	>2500	>625	GW10	360	0
	200	0		0	0
	>2500	0		460	0
	0	0		0	0
	90	10		---	---
	2100	525		---	---
	900	20		---	---
	1900	475		20	0
GW5	840	0			
	190	0			
	1210	0			
	0	0			
	0	0			
	0	0			
	0	0			
	300	25			
GW6	0	0			
	10	0			
	2050	0			
	10	0			
	0	0			
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	10	0			
	1320	770			

Table A.2a Chemical data for surface water samples

Sampling Location	Date	pH	EC mS/cm	DO mg/L	Temp °C	TC ppm	TIC ppm	TOC ppm	DC ppm	DIC ppm	DOC ppm	NO_3^-N mg/L	PO_4^{3+} mg/L	Total Fe mg/L	Total Mn mg/L
SW1	15/09/2004	8.1	56100.0	9.1	20.0	24.8	21.1	3.7	11.5	8.4	3.1	0.1	0.3	0.0	0.0
	16/11/2004	8.3	49900.0	7.8	27.9	26.7	19.6	7.1	24.9	18.2	6.7	0.0	0.2	0.0	0.0
	14/12/2004	8.1	41700.0	8.0	28.0	27.4	19.0	8.5	24.7	16.7	8.0	0.1	0.0	0.0	0.0
	15/02/2005	8.4	52700.0	8.4	26.2	23.0	14.6	8.4	19.2	13.3	6.0	0.0	0.1	0.1	0.0
	30/03/2005	8.5	54600.0	8.4	24.2	27.7	23.1	4.6	25.9	23.1	2.8	0.3	0.0	0.0	0.0
	26/04/2005	9.2	51800.0	9.3	23.5	26.9	24.2	2.7	25.3	23.6	1.7	0.1	0.1	0.0	0.0
	25/05/2005	8.5	48000.0	10.6	20.5	25.1	23.3	1.8	24.8	23.0	1.8	0.0	0.1	0.0	0.0
	20/06/2005	7.8	48600.0	8.4	17.2	29.8	24.4	5.4	25.1	20.0	5.2	0.0	0.0	0.0	0.0
SW2	15/09/2004	8.1	57000.0	8.5	20.6	23.8	14.6	9.2	12.0	5.6	6.4	0.1	0.5	0.0	0.0
	16/11/2004	8.2	50500.0	7.6	27.9	26.1	23.8	2.3	24.5	22.6	1.9	0.0	0.0	0.0	0.0
	14/12/2004	7.5	42000.0	8.0	27.6	25.2	23.9	1.3	23.5	23.1	0.5	0.1	0.1	0.0	0.0
	15/02/2005	8.4	52800.0	8.6	25.9	22.5	16.4	6.1	19.3	15.6	3.7	0.0	0.1	0.0	0.0
	30/03/2005	8.5	54800.0	8.3	24.9	25.8	25.3	0.5	24.9	24.2	0.6	0.4	0.1	0.0	0.0
	26/04/2005	9.2	52000.0	9.8	24.0	25.8	25.3	0.5	24.9	24.2	0.6	0.2	0.0	0.0	0.0
	25/05/2005	8.5	46300.0	10.7	20.1	26.7	25.5	1.1	25.5	24.9	0.6	0.0	0.1	0.0	0.0
	20/06/2005	7.8	49000.0	8.7	17.3	30.1	27.9	2.2	26.5	25.3	1.2	0.0	0.1	0.0	0.0
SW3	15/09/2004	8.1	49500.0	9.1	20.5	23.9	20.0	3.9	12.9	9.8	3.1	0.0	0.2	0.0	0.0
	16/11/2004	8.2	50700.0	7.5	28.8	25.0	15.7	9.3	24.7	20.9	3.8	0.0	0.1	0.0	0.0
	14/12/2004	8.0	40300.0	7.2	31.3	24.8	23.2	1.5	22.6	21.1	1.5	0.1	0.1	0.0	0.0
	15/02/2005	8.3	53300.0	8.5	26.1	23.0	16.4	6.6	20.3	15.6	4.7	0.0	0.0	0.0	0.0
	30/03/2005	8.4	54900.0	8.1	24.4	27.2	21.8	5.4	26.7	21.5	5.2	0.2	0.1	0.0	0.0
	26/04/2005	9.1	52000.0	10.0	23.7	28.5	25.4	3.1	25.7	24.7	1.1	0.0	0.0	0.0	0.0
	25/05/2005	8.4	48200.0	10.3	20.0	27.4	25.8	1.6	25.4	25.2	0.2	0.0	0.1	0.0	0.0
	20/06/2005	8.1	48.3	8.0	17.2	28.3	23.6	4.7	26.2	21.6	4.6	0.0	0.1	0.0	0.0
SW4	15/09/2004	8.0	59300.0	8.2	20.5	24.5	20.1	4.4	12.1	8.1	4.0	0.1	0.2	0.0	0.0
	16/11/2004	8.2	50800.0	7.5	28.4	25.3	20.6	4.7	16.3	13.8	2.5	0.0	0.1	0.0	0.0
	14/12/2004	7.6	40400.0	8.0	28.8	24.5	22.9	1.6	22.2	21.8	0.4	0.1	0.0	0.0	0.0
	15/02/2005	8.2	53100.0	8.0	26.3	23.5	16.7	6.7	20.1	15.8	4.3	0.0	0.1	0.0	0.0
	30/03/2005	8.3	54900.0	7.7	24.2	28.0	24.7	3.3	27.3	24.4	2.8	0.2	0.0	0.0	0.0
	26/04/2005	9.0	52200.0	8.8	23.6	27.1	25.8	1.2	26.1	25.0	1.1	0.0	0.0	0.0	0.0
	25/05/2005	8.3	48300.0	10.8	19.8	27.4	25.8	1.6	25.4	25.2	0.2	0.4	0.1	0.0	0.0
	20/06/2005	8.1	48700.0	8.4	17.2	29.9	27.3	2.5	27.5	25.4	2.1	0.0	0.1	0.0	0.0

Table A.2a: Chemical data for surface water samples (cont)

Sampling Location	Date	pH	EC mS/cm	DO mg/L	Temp °C	TC ppm	TIC ppm	TOC ppm	DC ppm	DIC ppm	DOC ppm	NO_3^-N mg/L	PO_4^{3+} mg/L	Total Fe mg/L	Total Mn mg/L
SW5	15/09/2004	8.0	51500.0	9.0	20.0	25.5	19.4	6.1	12.1	6.7	5.4	2.2	0.3	0.0	0.0
	16/11/2004	8.2	51700.0	7.4	28.5	27.1	23.1	3.9	24.2	21.7	2.4	0.3	0.0	0.0	0.0
	14/12/2004	8.0	40300.0	7.4	29.0	24.7	22.6	2.1	22.4	21.5	0.9	0.9	0.0	0.0	0.0
	15/02/2005	8.2	53500.0	8.3	26.2	23.7	16.8	6.9	19.9	15.9	4.0	0.0	0.1	0.0	0.0
	30/03/2005	8.2	54900.0	7.4	24.2	28.3	25.4	2.9	27.5	25.3	2.2	0.2	0.1	0.0	0.0
	26/04/2005	9.0	52000.0	8.5	23.5	27.1	25.8	1.2	26.1	25.0	1.1	0.0	0.0	0.0	0.0
	25/05/2005	8.3	48800.0	9096.0	19.6	28.5	26.8	1.7	25.8	25.0	0.8	0.0	0.1	0.0	0.0
	20/06/2005	8.1	48900.0	7.4	17.2	27.8	27.2	0.6	26.1	25.5	0.6	0.2	0.0	0.0	0.0
SW6	15/09/2004	7.9	59500.0	7.9	20.1	25.7	21.5	4.3	13.0	10.4	2.6	0.2	0.3	0.0	0.0
	16/11/2004	8.1	52000.0	7.4	28.6	25.6	23.2	2.4	24.6	22.9	1.8	0.1	0.0	0.0	0.0
	14/12/2004	7.9	39400.0	7.3	29.0	24.2	19.1	5.1	22.9	18.4	4.5	0.3	0.0	0.0	0.0
	15/02/2005	8.1	53500.0	8.0	26.4	24.4	16.9	7.5	20.5	15.9	4.6	0.0	0.2	0.0	0.0
	30/03/2005	8.2	54800.0	7.2	24.2	28.1	25.3	2.8	27.5	25.3	2.2	0.3	0.1	0.0	0.0
	26/04/2005	8.9	52200.0	8.3	23.3	26.7	25.6	1.1	27.0	26.2	0.8	0.1	0.0	0.0	0.0
	25/05/2005	8.2	48500.0	11.4	19.5	28.7	26.9	1.8	25.5	25.0	0.5	0.0	0.1	0.0	0.0
	20/06/2005	8.0	48800.0	7.9	17.1	29.0	27.0	2.0	26.2	25.2	1.0	0.0	0.1	0.0	0.0
SW7	15/09/2004	7.6	58600.0	7.6	20.5	26.5	20.2	6.3	12.2	6.3	5.9	0.0	0.4	0.0	0.0
	16/11/2004	8.0	51600.0	6.8	28.5	28.7	23.5	5.2	25.1	22.3	2.8	0.0	0.1	0.0	0.0
	14/12/2004	7.8	36300.0	6.5	28.7	24.3	20.3	4.0	23.3	19.9	3.4	0.1	0.1	0.0	0.0
	15/02/2005	8.0	51600.0	7.5	26.4	25.8	16.7	9.0	21.8	15.6	6.2	0.0	0.1	0.1	0.0
	30/03/2005	8.1	54600.0	6.6	23.9	29.2	25.4	3.8	28.4	25.2	3.2	0.0	0.3	0.0	0.0
	26/04/2005	8.7	52300.0	8.0	23.3	27.7	26.3	1.4	25.8	25.7	0.1	0.0	0.1	0.0	0.0
	25/05/2005	8.1	46900.0	12.8	19.0	28.2	24.6	3.7	18.1	15.4	2.7	0.0	0.1	0.3	0.0
	20/06/2005	7.8	48100.0	9.5	17.2	28.4	27.1	1.3	25.6	24.4	1.2	0.0	0.1	0.0	0.0
SW8	15/09/2004	7.3	59900.0	6.6	17.9	33.7	23.8	9.9	16.1	8.2	8.0	0.0	0.3	0.0	0.1
	16/11/2004	7.1	42600.0	4.1	27.6	31.0	20.9	10.1	26.3	20.9	5.4	0.0	0.1	0.0	0.1
	14/12/2004	6.3	9550.0	8.8	28.8	19.8	6.2	13.6	17.8	5.0	12.8	0.0	0.0	0.2	0.1
	15/02/2005	6.9	35600.0	3.0	25.9	30.3	12.2	18.1	24.5	10.8	13.7	0.0	0.1	0.5	0.1
	30/03/2005	7.3	53600.0	3.5	23.1	34.7	27.0	7.7	34.1	26.8	7.3	0.0	0.1	0.0	0.1
	26/04/2005	7.7	48900.0	4.6	22.1	38.0	30.8	7.2	35.5	29.2	6.3	0.0	0.1	0.0	0.1
	25/05/2005	7.1	31600.0	10.2	17.2	29.6	22.9	6.8	23.6	17.1	6.6	0.0	0.3	0.0	0.1
	20/06/2005	7.1	40900.0	7.0	16.9	32.5	27.2	5.3	30.1	25.2	4.9	0.0	0.1	0.0	0.1

Table A.2a: Chemical data for surface water samples (cont)

Sampling Location	Date	pH	EC mS/cm	DO mg/L	Temp °C	TC ppm	TIC ppm	TOC ppm	DC ppm	DIC ppm	DOC ppm	NO_3^-N mg/L	PO_4^{3+} mg/L	Total Fe mg/L	Total Mn mg/L
SW9	15/09/2004	6.3	434.0	4.5	18.5	16.4	2.8	13.6	7.6	0.6	7.0	0.5	1.6	0.5	0.0
	16/11/2004	5.4	255.3	1.2	23.9	27.5	2.3	25.2	26.8	1.7	25.1	1.3	0.1	1.1	0.1
	14/12/2004	5.3	202.0	2.6	28.4	30.0	1.0	29.0	27.9	0.6	27.4	0.0	0.2	0.6	0.0
	15/02/2005	5.7	229.2	0.6	24.2	28.0	2.1	25.9	26.4	0.9	25.5	0.0	0.0	2.6	0.1
	30/03/2005	5.3	270.0	0.8	20.7	31.5	5.0	26.5	24.8	3.8	21.0	0.0	0.1	0.8	0.1
	26/04/2005	5.9	472.0	0.7	20.6	24.5	5.2	19.3	23.0	4.0	19.0	0.5	0.1	0.4	0.0
	25/05/2005	5.5	290.0	1.7	18.0	29.9	7.0	22.9	22.9	3.0	19.9	0.0	0.5	0.6	0.0
	20/06/2005	5.2	373.0	1.5	16.6	28.8	7.6	21.3	21.9	3.8	18.1	0.0	0.1	1.0	0.1
SW10	15/09/2004	6.5	306.0	6.3	21.1	16.7	0.0	16.7	8.9	0.0	8.9	0.6	0.3	0.4	0.0
	16/11/2004	5.6	655.0	2.8	26.4	18.0	0.7	17.3	15.4	0.3	15.0	1.3	0.1	0.6	0.1
	14/12/2004	5.2	404.0	0.6	29.5	28.0	1.9	26.1	25.8	1.6	24.2	0.0	0.1	0.6	0.0
	15/02/2005	5.9	282.0	3.1	25.2	20.9	0.0	20.9	20.8	0.0	20.8	0.0	0.1	4.9	0.1
	30/03/2005	7.2	337.0	6.2	23.9	24.6	0.3	24.3	21.8	0.0	21.8	0.2	0.1	1.0	0.0
	26/04/2005	6.2	286.0	3.1	20.3	16.3	0.4	15.9	13.8	0.2	13.6	1.0	0.1	0.6	0.0
	25/05/2005	6.2	182.2	9.4	15.9	11.9	2.9	9.0	9.6	0.7	8.9	0.0	0.1	0.1	0.0
	20/06/2005	5.7	174.2	6.9	14.6	11.6	3.0	8.6	9.2	0.8	8.5	0.0	0.1	0.1	0.0
SW11	15/09/2004	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	16/11/2004	6.4	191.7	5.2	25.3	17.1	1.8	15.3	1.2	0.3	0.9	0.6	0.1	0.0	0.0
	14/12/2004	5.1	208.0	4.5	28.9	30.7	1.7	29.0	30.3	1.7	28.6	0.9	0.1	0.5	0.0
	15/02/2005	6.6	200.6	7.3	24.5	7.6	0.0	7.6	7.6	0.0	7.5	4.0	0.0	0.2	0.0
	30/03/2005	7.8	260.0	8.2	24.6	47.9	9.3	38.6	42.8	9.2	33.6	0.2	0.1	6.0	0.0
	26/04/2005	6.8	215.7	6.2	21.8	10.6	2.5	8.1	10.0	2.3	7.7	0.1	0.0	0.2	0.0
	25/05/2005	6.3	237.3	8.1	18.9	5.6	1.8	3.8	4.4	1.3	3.2	6.6	0.1	0.1	0.0
	20/06/2005	6.6	287.3	6.7	16.3	8.9	2.0	6.9	6.3	1.1	5.2	1.1	0.1	0.1	0.0
SW12	15/09/2004	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	16/11/2004	6.2	370.0	3.5	24.9	13.7	1.1	12.6	12.9	0.7	12.2	2.1	2.4	0.0	0.0
	14/12/2004	4.2	215.0	4.3	29.8	20.9	1.0	19.9	17.5	1.0	16.5	6.6	0.1	0.2	0.0
	15/02/2005	6.2	210.5	3.5	24.4	6.8	0.4	6.4	5.5	0.0	5.5	8.9	0.5	0.1	0.0
	30/03/2005	7.0	241.0	2.7	22.5	27.3	13.8	13.6	25.0	12.7	12.4	0.7	0.2	0.7	0.1
	26/04/2005	6.6	238.2	3.1	22.6	7.0	3.3	3.7	6.9	3.2	3.7	0.3	0.1	0.1	0.0
	25/05/2005	6.1	214.8	7.7	19.2	3.9	2.5	1.5	2.9	1.7	1.2	11.2	0.2	0.0	0.0
	20/06/2005	5.8	207.7	5.0	16.6	9.2	4.3	4.9	7.7	3.4	4.3	7.1	0.2	0.1	0.0

Table A.2b: Microbiological data for surface water samples

Sampling Location	FC cfu/100mL	E. coli cfu/100mL	Sampling Location	FC cfu/100mL	E. coli cfu/100mL
SW1	115	38	SW7	360	0
	23	0		>250	0
	3	1		1020	765
	>250	>83		860	469
	82	20		750	313
	0	0		1210	403
	83	48		40	40
	33	28		380	127
SW2	23	0	SW8	1000	0
	31	0		10	10
	>250	0		>250	>100
	660	0		>2500	>1458
	390	163		2500	625
	640	160		2400	600
	230	96		3600	1200
	230	96		600	200
SW3	55	0	SW9	>250	0
	40	0		400	0
	>250	0		6300	1260
	880	0		290	211
	280	100		780	390
	980	160		550	46
	310	181		340	198
	340	198		410	103
SW4	51	0	SW10	0	0
	47	0		170	136
	>250	>125		20400	---
	860	0		380	311
	290	70		5500	917
	1120	280		28900	9632
	420	10		20	0
	530	398		10	10
SW5	300	0	SW11	---	---
	>250	0		2200	0
	420	0		69000	0
	1150	192		0	0
	890	0		18000	5999
	230	78		2000	0
	310	77		8000	5000
	480	200		15000	5000
SW6	54	0	SW12	---	---
	29	0		1500	0
	>250	0		21200	3029
	720	0		2500	1875
	170	43		5700	1900
	1060	177		4900	1633
	290	97		4500	2250
	280	70		100	100

APPENDIX B

RAINFALL DATA SOUTH CABOOLTURE WASTEWATER TREATMENT PLANT

Table B.1 Rainfall data from South Caboolture Wastewater Treatment Plant

Month	July	August	September	October	November	December	January	February	March	April	May	June
Date	Rain	Rain	Rain	Rain	Rain	Rain	Rain	Rain	Rain	Rain	Rain	Rain
1			10	1.5							13	
2		2										
3					2	12					3.5	
4			7							2.5	3.5	
5			5		10	7	1.5			0.5		
6						15	29			2	3	
7					54	28				7	6.5	
8					29	3				14	5.5	2
9					22.5	20	2			3.5	1	1
10	2					17			4	5.5	0.5	0.5
11					1	9				1	14	
12									2.5	19	17	
13						3			9	10		
14						30			3			10
15				0.5		2			3.5			4
16				0.5								
17	1.5			8.5			2				1.5	
18		0.5		35.5			9		5			
19				12.5							6.5	
20				5	7	14						3
21			3				20			6		
22					9		0.5		14	10		
23										0.5		
24			1.5	1		0.5						
25						15.5	29			12		
26						1.5	12.5					6
27						3	14	2.5		1.5		13
28												29.5
29												85
30				7.5			0.5		1			10
31		9.5										
Totals mm	**4**	**12**	**27**	**73**	**134.5**	**180.5**	**120**	**2.5**	**42**	**95**	**76**	**164**