The Regional Distribution and Significance of Stream Turbidity in Victoria

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Declaration

I declare that this contains no material which has been accepted for the award of any other degree or diploma in any university or institution and to the best of the author’s knowledge and belief, contains no material previously written or published by another person, except where due reference is made in the text. The content of the thesis is the result of work which has been carried out since the official commencement date of the program in February 2002, and any editorial work, paid or unpaid, carried out by a third party is acknowledged. The length of this thesis is less than 90,000 words; exclusive of maps tables, references and appendices.

Dale Watson

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Abstract
This thesis investigates the distribution and significance of stream turbidity in Victoria; specifically exploring the factors that may have influenced the pattern of regional variation in turbidity, and factors that give it significance in the regional, social, cultural and environmental context.

The limits to water availability are set, not only by the quantity of water in storages or streams but, more fundamentally, by acceptable levels of water quality and catchment health. To make effective judgements of water availability managers of water resources need to know the significance of measured natural resource condition in the regional context.

Stream turbidity can be considered by the agricultural community as a sign of soil erosion and a loss of agricultural potential, while from the ecological perspective it can be considered a sign of deteriorating river health. Fundamentally, levels of turbidity are closely bound with land use practice and, in the Australian context, turbidity can be considered a measure of the consequences of land management practices on soil erosion and run-off.

Measured levels of turbidity in Victoria should be interpreted within the context of a unique history and geography. The spread of European colonisation and the introduction of massive land use change to the Victorian landscape have meant that over most of Victoria current levels of turbidity reflect the effects of over a hundred and fifty years of large scale intervention with its controlling factors.

In Victoria current levels of turbidity are interpreted in a cultural context far different from that of early colonists or even of a few decades ago. The concept of Ecologically Sustainable Development which has dominated natural resource management in recent times brings new responsibilities to resource managers. Ecologically sustainable management means that resources must be considered in a more inclusive spatial and temporal context.

In the early stage of Victoria’s history sustainable management of water meant having enough water left from winter rains to supplement summer
supply. However, in recent years, it has begun to have more complex associations; sustainable water use is now, almost universally considered to include maintenance of the environmental health of waterways, and by implication, the environmental health of the whole catchment. In this context, stream turbidity can be considered a useful indicator of catchment health, in particular, because levels of turbidity bear a direct physical relationship to catchment processes.

New tools are needed to explore the relationship between land use and water quality at the regional scale. The results of this current research include a regional statistical model of stream turbidity, which is conceptually designed to offer useful predictions of stream turbidity and underpin sustainable resource management. The statistical model was used as input to the development of a unique map display using Geographic Information Systems (GIS). The GIS is used to display the distribution of model predictions over a large region of south-eastern Australia.

The practical advantage of this modelling approach is that it provides managers with the ability to identify locations in Victoria where measured water quality differs significantly from modelled water quality and flag them for further investigation.

The major project outputs are a map of Victorian Water Quality Monitoring Network (VWQMN) catchments showing catchments in Victoria where measured turbidity differs from model predictions and a raster representation of the state of Victoria in which cell values indicate predicted stream turbidity. Important to this project was the novel use of GIS technology to process large national and regional scale digital data sets using tools developed for catchment scale hydrological models.
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CHAPTER 1. INTRODUCTION

There has been widespread and mounting community concern for the quality of water in Victorian rivers and streams. In 2004, a state-wide snapshot of overall stream condition found that only about 21% of major rivers and tributaries in Victoria were in good or excellent condition, while 47% were in moderate condition and 32% were considered in poor or very poor condition (Department of Sustainability and Environment, 2005).

Understanding whether measured values of water quality indicators represent good or poor condition is essential to managing the health of Victorian streams. Some important qualities of water, such as suspended sediment and turbidity, can vary widely over the region and measured values that appear to be excessive, can often be explained by a close examination of the biophysical conditions of the catchment above where the sample was taken.

Whether a particular measured water quality value is considered to be excessive has, traditionally, involved assessing the fitness of that water for a number beneficial uses (Goudey, 2001) (see Table 6-2 for a complete list of beneficial uses for Victorian streams). In the past, these uses were primarily focused on human activities, such as human consumption, industrial and commercial use, aquaculture and recreation but in recent times it has become common to also consider the environmental characteristics of water in the estimation of quality (ANZECC & ARMCANZ, 2000, chapter 2.1 ). In fact the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (hereafter called the National Water Quality Guidelines) state explicitly that
beneficial uses in the context of ecological condition should now be called ‘environmental value’ (ANZECC & ARMCANZ, 2000. chapter 2.1.3).

For stream turbidity, quality objectives are currently assessed with reference to statistically-derived percentile values within three broad water quality regions (Goudey, 2001). The specific stream turbidity targets represent the 75th percentile of expected values with 95% confidence limits for historical data collected within those regions (Goudey, 2001) (see Figure 6-7). The water quality regions were developed by interrogating data from a number of reference sites across Victoria for biological similarity (see chapter 6.5).

![Figure 1-1 Turbidity objectives for Victoria (Environment Protection Authority Victoria, 2001)](image)

However, within these three broad geographic regions there is still significant heterogeneity (see chapter 8.7). The objective of this thesis is to investigate this heterogeneity and examine the factors that determine the regional distribution and significance of stream turbidity in Victoria.

Whether measurements of stream turbidity which fall outside targets for water quality actually represent poor quality requires a detailed analysis. While seemingly anomalous values may represent the effects of local land
management practices they may also represent the effect of long term environmental change, such as the slow migration of a sediment slug along a stream. However, what may appear to be an anomalous value may in fact also be explained by expected variation within the broad water quality regions.

From a management point of view an assessment of poor water quality would also need to consider the level of environmental value attributed to the water body. If the water body is not perceived as having high environmental value, it may not be a priority for remediation or other management strategies.

This process is explicitly recognised within the National Water Quality Guidelines. The guidelines recommend that the process of setting water quality objectives should begin by identifying the environmental values to be protected for a particular water body and, based on those values, set the management goals (ANZECC & ARMCANZ, 2000).

In the local context, information needed to establish the significance of local measured water quality values may be developed through consultation with local stakeholders. However, to understand patterns of environmental value at the regional scale requires a specific set of information and data. At the local scale, relevant information may include the pattern of subdivision, specific local agricultural management practices such as pesticide and fertiliser use, tillage practices or the history of urban development. At the regional scale, however, relevant information may include the historical, social and environmental context for those local effects. This information might consist of broad-scale settlement patterns, broad-scale soil fertility and regional land sub-division policies.

At this scale the patterns of broad social-cultural and historical attitudes and experience are etched into the landscape. The progress of agricultural development of Victoria was as much a product of historical politics, as a rational development of natural resources.

The investigation of the regional significance of stream turbidity also requires the consideration of these broad scale social-cultural and historical patterns. Taking this into consideration, the problem has been disaggregated into several broad questions.
• What is the physical context of our understanding of stream turbidity; what are the underlying regional environmental patterns, including the major drivers of climate, land cover and water availability?

• What is the historical and social-cultural context in which we interpret stream turbidity; what are current and historical land use patterns and what factors have determined land management practices?

• How have water management practices in the region contributed to the regional characteristics of water and, in particular, practices that have implications for stream turbidity?

1.1 The regional environmental pattern

The regional state of the environment in Australia and, specifically, in Victoria has been, in recent times, the subject a number of investigations. The Australian Federal Government, for instance, has initiated significant investigations into the current state of water resources and the environment in general. Funding, available from the National Heritage Trust, has been made available under the umbrella of the National Land and Water Resources Audit to collect and collate environmental information over the whole continent (Department Of Agriculture Fisheries And Forestry - Australia, 2003). Since 1996 the Federal Government has also begun to conduct regular assessments of the status of the Australian natural environment, including water resources, in its State of the Environment reporting (Department of the Environment and Heritage, 2004b). In 2002 it also conducted a parliamentary investigation into the state of urban water resources (Commonwealth of Australia, 2002) and rural water resources.

In Victoria, there have, in recent times, been a State Government initiated investigation into the allocation of water resources (Environment and Natural Resources Committee, 2001b), an investigation into the distribution of farm dams (Government of Victoria, 2001), and the release of a significant white paper outlining reforms to the supply and management of water resources (Department of Sustainability and Environment, 2004c). The Index of Stream Condition (ISC) is now being used across Victoria to provide regular snapshots of the health and status of rivers and streams (Department of
The common approach employed by the ISC, means that stream condition in various parts of the state can now be compared with each other.

Impetus for this kind of broad regional analysis has come from the, increasingly, clear evidence that regional and global use of natural resources is exceeding the capacity of natural systems. At the global scale declining biodiversity (United Nations Environment Programme (UNEP), 2002), global warming (Commonwealth Bureau of Meteorology, 2003) and depletion of the ozone layer (Global Atmosphere Watch, 2002) have focussed world attention on the need for global scale environmental management. At the regional scale, dryland salinity (Department of Sustainability and Environment, 2004a), deforestation (Department of Environment and Heritage, 2001), soil erosion (Lu et al., 2001c) and declining water quality (Department of Agriculture Fisheries and Forestry and Department of Environment and Heritage, 2004) have been identified as needing regional scale approaches to environmental management.

1.2 Factors that determine the regional distribution of environmental condition.

Research targeted at these national and regional issues has provided significant qualitative and quantitative information that might form the basis for the exploration of national and regional patterns of resource use and condition. In the context of this thesis, outputs from the National Land and Water Resources Audit were found to be particularly useful.

There have been a number of studies, relevant to this thesis, that have sought to identify the local-scale factors that might explain sediment delivery to streams (and by inference, stream turbidity); for instance see a study by Sadek (1998) which predicted stream turbidity in the Traralgon Creek catchment in Gippsland. However, these local explanatory models are difficult to fit to the regional scale because they require the intensive collection of local scale data. In the case of stream sediment supply, studies in recent decades (Wallbrink et al., 2003, Lu et al., 2001a) have used variations on the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1960, Wischmeier and Smith, 1978) to estimate the sediment supply from sheet erosion across...
Australia. The USLE and its variants have the advantage of being constructed from data sets that can be developed at the broader region using remote sensing technologies. Inputs for a national exploration of sheet erosion were developed in this way as part of the National Land and Water Resources Audit, and the technique applied at the national scale (Lu et al., 2001a).

1.3 What does water quality mean? How does the social-cultural perspective shape the assessment of water quality?

It is not enough, however, to know the regional flux of environmental condition. Any assessment of water quality must also be made with reference to some kind of environmental value. The assumption made in an assessment of quality is that there is a normative state and that the relationship between a measured value and the normative state is known.

The factors that influence the distribution of water quality in Victoria are very complex. According to the National Water Quality Guidelines ‘Water quality, ecosystem health and the surrounding environment are all intimately connected’ (ANZECC & ARMCANZ, 2000). That is, if water quality deteriorates, essential biophysical attributes of water and its surrounding environment are also altered from their original state.

1.4 The use of GIS technologies to investigate regional scale data.

The need to acknowledge the regional perspective of environmental resources has arisen at the same time as new technologies are allowing us to examine the regional characteristics of the environment. The developing sophistication of remote sensing has made the acquisition of global and regional environmental data inexpensive and widely available. When scientists talk about global warming and the thinning ozone layer, the science is based on global scale data, on digital data provided by satellites and the information is communicated by maps of distribution on the global scale.

The technology of Geographic Information Systems (GIS) is central to an understanding this regional data. GIS are specific class of computer software, ideally suited to manipulating large spatial data sets and analysing spatial patterns and relationships among environmental phenomena.
1.5 Research objective
The objective of this thesis, then, is to investigate the distribution and significance of stream turbidity in Victoria. Specifically, the thesis will explore the factors that may have influenced the pattern of regional variation and factors that give it significance in the social, cultural and environmental context. The thesis will then report on the development of a regional spatial model of stream turbidity for Victoria to be used as a tool to explore the regional variation and provide predictions of stream turbidity at ungauged locations.

1.6 Research outline
The thesis will specifically investigate four key questions.

- What factors can explain the distribution of water quality and, specifically, stream turbidity in Victoria?
- What is the social-cultural context in which water quality assessment is made?
- Can stream turbidity be used as a metric for assessing the health of water resources?
- How can spatial models be employed to explore the variation and significance of stream turbidity at the regional scale?

1.6.1 What factors have influenced the distribution of water quality and, specifically, stream turbidity in Victoria?
It will be shown that water quality is determined by a complex interaction between the biological, physical and chemical characteristics of a streams catchment. However, equally significant in determining water quality is the human intervention in those processes within a catchment. Chapter 2 of this thesis will outline the history of water resource development in Victoria. It will show how the pattern of human settlement over time combined with a unique physical environment and created a distinctive pattern of resource use and management in Victoria. Chapter 3 will further explore the way in which direct water management further complicated this already complex pattern.
1.6.2 What is the social-cultural context in which water quality assessment is made?

Chapters 2 and 3 will also show how the distribution of water resources has been fundamental to the development of the rural and urban landscapes in Victoria and how the community perception of water distribution has guided and informed that development. Chapter 4 of the thesis will, specifically, investigate the history and characteristics of sustainability and explore current areas of debate and then examine how the concept of sustainability applies to water resources in Victoria. Chapter 4 will also outline the development of complexity theory and system theory and show how these developments represent new ways of thinking about the environment.

1.6.3 Can stream turbidity be used for assessing the health of water resources?

New advances in aggregated metrics such as the Index of Stream Condition (Ladson et al., 1999c) and biological measures of water quality such as AUSRIVAS (Simpson et al., 1997) are providing new opportunities to assess the degree and direction of change in regional environmental condition, while traditional chemical and physical measures of water quality offer the advantage of significant temporal data sets. Chapter 5 will explore a number of these methods for assessing and understanding the concept of environmental health and, in that context, explore the utility of using stream turbidity as an indicator of catchment health. Together chapters 5 and 6 will describe the characteristics of stream turbidity and outline its relationship to stream and catchment health.

1.6.4 How can spatial models be used to assess the health of water resources at the regional scale?

The spatial distribution of water in Victoria can be viewed in the global, national, regional and local context. This new understanding of the global system has been augmented by the development of spatial techniques and the availability of new kinds of spatial information at the regional, national and global scales. Early settlers in Victoria could not begin to visualise their own impact on the greater region, however, the development of regional spatial information means that modern Australians not only understand their impact on the greater region but they can visualise that impact.
Chapters 7 and 8 of this thesis will investigate the use of this new spatial information in the context of sustainability. GIS will be used to manipulate the data at the regional scale and provide analysis of complex spatial relationships. GIS are described by Maguire (1991) as a special case of information systems that focus on spatial entities and relationships. According to Maguire, they consist of a series of views; a map view, a database view and a spatial analysis view. They have the unique ability to organize and integrate apparently disparate data sets together by geography (Maguire, 1991, p17). GIS enables the representation of water, not just as a simple resource, but in its more complex regional, spatial, environmental context.

Chapter 7 will specifically develop a novel spatial method, based on readily available GIS hydrological capabilities, and explore a regional model of stream turbidity for Victoria. In chapter 8 the outputs from this modelling will be critically examined and, based on this analysis, chapter 9 will summarise the findings of the research and make recommendations as to how future research should proceed.

1.7 Project methodology

1.7.1 Phase 1 Literature survey
At the core of the model development will be a wide-ranging literature survey. The literature survey will interrogate published literature and other sources directly related to the questions posed in 1.2.1 – 1.2.4. Several bodies of literature will be targeted. Specifically, the survey will interrogate appropriate works that might shed light on the history of land use and settlement in Victoria and elements of that history that may help explain the regional distribution of stream turbidity.

While the philosophical underpinning of the approach will form a large section of the thesis, the model building phase is central to the investigation of stream turbidity in Victoria.

1.7.2 Phase 2 Data collection
After establishing relevant model criteria, the project will seek to identify potential regional-scale environmental characteristics that may serve as criteria for indicating levels of stream turbidity and, based on availability,
identify available spatial data sets of sufficient reliability and coverage. In particular, large regional-scale data sets will be sourced from the National Land and Water Resources Audit Data Library.

1.7.3 Phase 3 Statistical model
Using statistical techniques, including stepwise regression and correlation, a process will be undertaken to develop a statistical model of stream turbidity based on coincidence between catchment characteristics, represented by regional digital data, and stream turbidity measurements recorded by the Victorian Water Quality Monitoring Network.

1.7.4 Phase 4 GIS construction
Data sets representing key variables and relationships developed by the statistical modelling will be manipulated to produce modelled stream turbidity values for Victoria. The process will consist of:

- identifying appropriate software for spatial model construction;
- construction of appropriate data layers within the GIS;
- utilising spatial analysis tools to generate derived data layers; and
- transforming outputs from a statistical model of stream turbidity into a spatially distributed model and produce raster based outputs.

1.7.5 Phase 5 Analysis
In the analysis phase the model results will be discussed and the model’s adequacy to perform its intended function assessed. Critical observations will be made, especially in regards to model uncertainty, and recommendations made for future research.

1.8 Conclusion
The objective of this thesis, then, is to investigate the distribution and significance of stream turbidity in Victoria. Specifically, the thesis will explore the factors that may have influenced the pattern of regional variation and factors that give it significance in the social, cultural and environmental context. The early chapters, 1-3 will provide a philosophical, biophysical, historical and cultural context for the assessment of water quality in Victoria.
Chapter 4 will provide a broader philosophical context by outlining the concept of sustainability and its implications for water quality assessment, while chapters 5 and 6 will explore the meanings of environmental health and the use of stream turbidity as an indicator of catchment and stream condition.

Chapter 7 will then report on the development of a regional spatial model of stream turbidity for Victoria to be used as a tool to explore the regional variation in stream turbidity and provide predictions of turbidity at ungauged locations. Chapter 8 will provide a critical analysis of the modelling approach and chapter 9 will summarise the model and provide some direction for future research.

Chapter 2 will begin the investigation by describing Victoria, its geography and climate, and the way in which these factors influence the management of water resources. It will then go on to describe the National and global context in which water in Victoria is managed.
CHAPTER 2. A GEOGRAPHY OF LAND MANAGEMENT IN VICTORIA

2.1 Introduction
This chapter will provide some background information about the State of Victoria, its geography, its climate and how surface water is distributed. It will outline how the process of European settlement of Victoria interacted with the prevailing geography to produce the current pattern of water resource use and land management. This pattern provides the context in which to interpret the current regional flux of stream turbidity.

It will be shown that the landscape of Victoria was significantly altered by the arrival of European colonists. These colonists removed vast areas of native vegetation, built a web of earthen channels across the northern plains, constructed massive dams, and harvested water from pristine mountain streams.

Evidence will be presented to show that while these new water developers saw their resource as almost endlessly resilient, in recent times it is increasingly evident that deteriorating environmental conditions present a
finite limit to the use of natural resources. It will be shown that land
degradation, in the form of soil erosion and deposition, soil degradation and
ecosystem change are processes that have significantly changed the basic
natural infrastructure responsible for maintaining the physico-chemical
equilibrium of water quality over large areas of Victoria. The aim of this
analysis is to show that the significance of current water quality values,
including stream turbidity, must be interpreted in the context of a complex
interaction between pre-colonial environmental conditions and historical
settlement patterns.

2.2 Victoria - location
Victoria is located between latitudes 34 and 39 degrees south and longitudes
141 and 150 degrees west. Located on the south-eastern margin of Australia,
it is bounded by the Murray River to the north and northeast, by the 141st
(actually 141°00′30″) meridian of longitude to the west and by Bass Strait and
the Southern Ocean to the south and comprises approximately 3% of the total
landmass of Australia.

In 2003 Victoria had a population of 4.9 million people and, of those, 3.3
million lived in the city of Melbourne and 1.6 million lived in provincial centres

Total precipitation for Victoria amounts to 150 gigalitres per annum.
Approximately 84% of the precipitation evaporates or is taken up by plants and then returned to the atmosphere. About 1% percolates through the soil and adds to the groundwater and 15% finds its way into rivers and streams (Environment and Natural Resources Committee, 2001b). About a third of the 15% that enters Victorian streams, or 6500 gigalitres, is extracted for use in irrigation, industry and domestic and urban purposes (Department of Sustainability and Environment, 2003).

Of the 6500 gigalitres, 77% is used in irrigated farming, 9% is used in regional urban centres, 8% is used by urban Melbourne and 6% is used for rural domestic and stock purposes (see Figure 2-2).

![Figure 2-2 Consumptive uses of water in Victoria 1996/1997](image)

**Figure 2-2** Consumptive uses of water in Victoria 1996/1997
(Department of Sustainability and Environment, 2003)

### 2.3 Victoria – settlement

The exploitation of water resources in Victoria has been intrinsically linked to the pattern of human settlement. In turn, the pattern of settlement is a product of history and geography; including the location of water resources.

The first Australians probably arrived 45,000 years ago (Flannery, 2001), and by 1788, when the first Europeans arrived and established a permanent settlement at Sydney, it is estimated there were between 300,000 and 1,000,000 Aboriginal Australians leading semi-nomadic lives (Smith, 1980).

A large number of these were probably resident in Victoria’s fertile valleys when the first European explorers followed the coastline from Sydney, south through Bass Strait. Between 1798 and 1802 George Bass and Matthew
Flinders explored the coastline and during 1800 and 1801 the survey ship the Lady Nelson mapped the Victorian coastline.

Following this exploration, the first attempt at permanent settlement by Europeans was near Sorrento on the Mornington Peninsula in 1803 and ended in failure due to the lack of permanent water and poor prospects for farming. Unofficial settlements by whalers and sealers on the Victorian coastline had been established for some time, including a substantial settlement at Portland by the Henty family established in 1833. However, it was not until 1835 that the first major successful settlement was established at Port Phillip (modern day Melbourne) by a private group from Van Diemans Land (modern day Tasmania) called the Port Phillip Association (Priestly, 1984).

The government of the day, which was centred in Sydney, wanted to control the spread of settlement in an orderly fashion, but the unofficial spread of settlement was uncontrollable. They quickly sent troops and a police magistrate to the new settlement and by 1839 had appointed a Crown Lands Commissioner to control the distribution of land (Kiddle, 1961). These first few settlements were to be the vanguard for a large numbers of settlers who came; at first from Van Diemans Land, and then later, cross-country from Sydney.

They brought with them the farming methods and attitudes toward water that they had known in well watered Scotland, Ireland and England. They brought with them the knowledge from a region where seasons were predictable, soil was mostly fertile and where water was plentiful and the supply reliable.

The history of early farming in Victoria is, essentially, the story of how those European style methods persisted and adapted in the face of a completely different geography, where extreme climatic variability, low nutrient soils and low water availability led to a rapidly changing and significantly changed landscape (Australian Science and Technology Heritage Centre, 2000).

These new settlers came to Victoria because they saw an opportunity to establish new lives and new identities far from their home countries. Europe was ostensibly overcrowded; disease, and grinding poverty were
commonplace and it was a common view that class distinctions and the weight of history restricted opportunity. Kiddle (1961) describes the conditions in which Scots, English and Irish immigrants had left their native homes. The late eighteenth century had seen the arrival of an agrarian revolution in Britain. Open fields, commons and wastes were enclosed. Farming was transformed with the creation of vast estates and large farms and there had been great technical improvements in agriculture and animal husbandry. Poor economic conditions had been caused by a depression following the Napoleonic wars and rents for farming land had skyrocketed. Coupled with this, population in Britain was also booming; the population of England and Wales rose from 8.9 million in 1801 to 13.9 million in 1831 (Kiddle, 1961). The result was that it was increasingly hard for small landholders to make a living, and it was increasingly difficult for the poor classes to access land.

### 2.4 The pattern of settlement

These first settlers in Victoria arrived as pastoralists from Van Dieman’s Land; they brought sheep by boat from northern Tasmania and swelled the new settlements at Port Phillip and Portland, further to the west. These two locations (see Figure 2-4) were the only adequate safe harbours on what was an uncompromising coastline. Of the two, Melbourne was thought more attractive to settlers because its deep indentation led ships right up to ‘wide open pastoral spaces’ (Kiddle, 1961).

In 1835, John Batman sailed from Hobart and landed in Port Phillip Bay. His small group which included six Aborigines from Sydney then moved to the north of present day Melbourne. He organised an ineffective treaty with the local Dutagala Aboriginal tribe and purchased 600,000 acres of land for substantial quantity of trinkets. Batman divided the land closest to Port Phillip into seventeen sheep runs and posted guards to protect his domain. Soon more settlers arrived, spurred on by Batman’s success. When they arrived, they and their sheep were merely herded further and further into the unmapped bush.

Inspired also by the reports of Batman’s intended occupation, John Pascoe Fawkner’s party arrived soon after and took up occupation on the site of
present day Melbourne. According to Blainey (1955), with Batman’s party came the birth of the pastoral occupation of Victoria and with Fawkner’s party came the birth of the settlement of Port Phillip (now Melbourne).

At Portland, Edward Henty had already arrived in 1833 and had set up a whaling enterprise. While the Henty family ran a business supplying sealers with provision, they were also involved in sheep grazing; attracted by the nearby open eucalypt woodland with its abundance of grass (Blainey, 1955). This settlement became the nucleus for further development in the west.

When these colonists looked inland they saw a vast land covered, for the most part, in a dry sclerophyll forest of eucalypt, acacia and melaleuca. To the west of Melbourne they saw tussock grassland, to the north they saw rolling, lightly timbered hills, and to the east of Melbourne they saw mountainous country, covered in dense eucalypt forest (Figure 2-6). This mountainous country where relief rises to 1,900 metres, with extensive areas over 300 metres (see Figure 2-5) remained a substantial barrier: tree clearing would be difficult, and the rugged terrain would make it hard for pastoral activities. According to Frost (1997), before the turn of the twentieth century, the costs of settlement in these areas, including clearing the heavy forest, inadequate transport and government opposition, outweighed the financial return from

![Figure 2-3 Landforms of Victoria (Department of Primary Industries, 2003)](image-url)
farming. As the pastoral settlement progressed inland, it also ran up against the mallee scrublands in the northwest with their sand dunes and concomitant low soil fertility. It was the open eucalypt woodland to the north and the grasslands to the west that initially attracted pastoralists coming from Melbourne. These were areas where the task of clearing land would be easiest.

**Figure 2-4 Pre-European major vegetation groups in Victoria**

(National Land and Water Resources Audit, 2004)

### 2.5 Australia Felix

During the 1830’s information about the coast of Victoria abounded, information about the interior was lacking. The future of settlement in the west of the state was set, when in 1836, Major Thomas Mitchell, on his expedition from Sydney to explore the western part of what is now Victoria reported the
apparent fertility of the soil and the mild climate. As Mitchell left St Arnard in
the north west of Victoria and entered the Donald Plains he commented:

*July 13.–We had at length discovered a country ready for the immediate
reception of civilised man; and destined perhaps to become eventually a
portion of a great empire. Unencumbered by too much wood, it yet
possessed enough for all purposes; its soil was exuberant, and its climate
temperate; it was bounded on three sides by the ocean; and it was
traversed by mighty rivers, and watered by streams innumerable. Of this
Eden I was the first European to explore its mountains and streams--to
behold its scenery--to investigate its geological character--and, by my
survey, to develop those natural advantages, certain to become, at no distant date, of vast importance to a new people. (Mitchell, 1839)*

Mitchell had arrived in a time of plenty, 1836 was a wet year (Powell, 1970b). He famously christened it Australia Felix, which translates from the Latin as ‘fortunate Australia’. Many settlers were encouraged by Mitchell’s description and, on his return, followed the wheel marks left by his wagon on the return journey and settled in Port Phillip (Priestly, 1984).

While the early colonies at Sydney and Van Diemans Land had been established as penal colonies, the government in England also wanted to settle the new land with ordinary free settlers. Ostensibly they wanted to use the new colonies as an outlet for excess population from Britain, and conveniently use this to soak up excess industrial output. However, a growing need for wool in British mills encouraged settlers to establish pastoral activities (Powell, 1970b).

### 2.6 Squatting

Consequently, in these early years agricultural activity was dominated by the grazing of sheep for wool production. Huge sheep runs were established, fanning out from the settlements established at Melbourne and Portland. In 1850, it is estimated that in Victoria there were 76,000 people and six million sheep (Blainey, 1955).

The nature of farming in Victoria was characterised for all time by this initial period of colonisation. The pastoralists, who occupied areas outside the settled districts against government command, built homesteads and ran
sheep in unfenced country. These ‘squatters’, especially those in the Western District, where relatively rich soils and high rainfall combined with natural grasslands to make farming easier and more profitable, grew to be the most influential and wealthy colonists.

2.7 Exploitation
While the soil may have been relatively rich in the Western District, overall, Victoria is an area of poor soil fertility, when compared to England, Scotland or Ireland. Settlers who did not have a large sheep run were forced by the lack of capital and the general lack of infrastructure to farm in coastal areas, and then only as a kind of mining activity, where mainly wheat was planted and cropped for a few seasons, till the naturally low nutrient soil was depleted (Blainey, 1955). These settlers then often moved further north into Mitchell’s Australia Felix. In the early stages of colonization, soil fertility was a major limiting factor on the distribution of agriculture in Victoria (Blainey, 1955).

The further spread of farming had to wait until the development of railways, roads and water supply, and the much later discovery that fertiliser and chemical additives could improve the productivity of poor soils (Wadham, 1955).

After the Gold Rush of the 1850’s the new burgeoning population had become wealthier and the colony was awash with money from British investors. The government ploughed investment into new settlements in the north and north-west of the state, connecting them with roads and railways. In particular Wadham (1955) suggests it was the development of railways to Bendigo and Ballarat in 1862, Echuca in 1864 and Horsham in the west in 1878, that initiated the extension of farming in the north of the State.

While the post Gold Rush development of infrastructure represents a significant turning point in rural Victoria, Wadham (1955), from his mid twentieth century point of view, describes two phases of Victorian agriculture. During the first ‘Exploitative’ phase of settlement, squatters naturally picked the land where water was available, and had a vegetative cover that could easily be replaced by grass. The second phase which Wadham calls ‘Progress through Technical Developments’ had its beginning in 1920. In this
phase, the limitations imposed by the natural, environmental conditions of Victorian soils and climate had been overcome by technical and scientific achievements. Wadham was Professor of Agriculture at the University of Melbourne in the nineteen fifties, and he was also on the Commonwealth Migration Planning Council. He was a popular academic and media personality and his views were influential in agricultural circles in the mid twentieth century (Falvey and Bardsley, 2004).

From a twenty-first century perspective, however, Wadham’s ‘Progress through Technical Developments’, might be considered yet another phase of exploitation. During the early years of the twentieth century, settlements were pushed even further into areas in the north-west which were previously thought of as too poor. Government policies of closer settlement and the establishment of post war soldier settlements intensified farming in many parts of the state. An enthusiasm for the possibilities of technical developments in agriculture led to better management of marginal land overall, but the increased intensification and smaller farm sizes continued the pressure on natural resources (Keneley, 1999).

2.8 Land degradation
This pressure on natural resources resulted in significant land degradation. According to Boucher (2003), land degradation can be classified into three main types; ecosystem change (degradation of vegetation), soil erosion and deposition (water and wind erosion) and soil degradation (soil salinity and degradation of soil structure).

2.8.1 Ecosystem change
On arrival, colonial Australians had a huge impact on the vegetation of their new land. While the pastoralists initially, cleared only a small plot for their homestead, once it became possible to acquire leasehold and title to properties, the clearing of vegetation began on a large scale. While, at present forest covers approximately 35% of Victoria’s area, in 1869 forest covered around 88% (Glaznig, 1995).
Figure 2-6 shows the extent and composition of current vegetation in Victoria. The white areas on the map represent the area of vegetation cleared since 1836. Initially, natural vegetation was cleared to make way for pastoral activities. This clearing was, therefore, concentrated on the plains to the north and northwest of Melbourne, coastal Gippsland and in the relatively flat, fertile valleys that extend into the highlands (Glanznig, 1995). Examination of Figure 2-6 shows that clearing of vegetation has since spread into the north-west, where mallee predominates, and into parts of Gippsland where tall eucalypt forests have now made way for farming.

At the same time that large areas of Victoria have been deforested, large areas have been invaded by weed species. According to a Environment and Natural Resources Committee report (2002), in 1993, there were 1221 naturalised, introduced taxa in Victoria. Naturalised populations are those said to be self-sustaining. Consequently, more than 65% of the area of the State carries ‘wholly or predominantly exotic vegetation and every terrestrial and wetland vegetation community in Victoria has been affected by weeds as well as a significant proportion of marine environments’ (Environment and Natural Resources Committee, 2002).
2.8.2 Soil erosion and deposition

In the years since initial European colonisation, significant areas of Victoria have been affected by soil erosion and deposition. In particular, gully erosion,
sheet erosion and rill erosion have reduced the extent of potential farmland and contributed vast amounts of sediment to streams.

According to Boucher (2003) ‘…gullies are open erosion channels at least 30 cm deep which conduct ephemeral runoff and are frequently characterized by steep sidewalls and a lack of vegetation’. Milton (1971) identifies the reduction of deep rooting native grasses under grazing pressure, the compaction of soils and removal of ground cover on steep slopes as the cause of accelerated gully erosion. As Figure 2-7 shows, this gully erosion affects a significant area of the state, especially in the centre of the state, where historical vegetation removal coincides with increased gradients.

Early colonists occupied and cleared the land close to streams and rivers first and there is some evidence that this initial rush of land clearance lead to an enormous acceleration of sediment movement within Victorian rivers. Scott (2001), for instance, quotes a letter from John Robertson, a settler in the Portland District in a letter he wrote to Governor Latrobe in 1853. Robertson describes how the rapid appearance of land degradation in the first thirteen years of occupation of his farm, lead to a massive movement of soil into streams.

Figure 2-7  Victoria - gully erosion density, 1982 (Department of Primary Industries, 2003)
“….One day all the creeks and little watercourses were covered with a large tussocky grass, with other grasses and plants, to the middle of every watercourse but the Glenelg and Wannon, and in many places of these rivers; now that the only soil is getting trodden hard with stock, springs of salt water are bursting out in every hollow or watercourse, and as it trickles down the watercourse in summer, the strong tussocky grasses die before it, with all others. The clay is left perfectly bare in summer. The strong clay cracks; the winter rain washes out the clay; now mostly every little gully has a deep rut; when rain falls it runs off the hard ground, rushes down these ruts, runs into larger creeks, and is carrying earth, trees, and all before it. Over Wannon country is now as difficult a ride as if it were fenced. Ruts, seven, eight and ten feet deep, and as wide, are found for miles, where two years ago it was covered with tussocky grass like a land marsh. ” Robertson, J. (1853) in a letter to Governor Latrobe (Scott, 2001)

One result of this land degradation is that river sediment loads in Australia are generally 10 to 50 times greater than pre-European loads in intensively used river basins (Land & Water Australia, 2002). A report by Land & Water Australia cited the Glenelg region in Victoria and the Murray Darling Basin (part of which is in Victoria) as amongst those areas in Australia with the highest level of sediment deposition within streams (Land & Water Australia, 2002).

According to Scott (2001) stream sediment loads in the Murray Darling Basin were at their peak in the latter half of the nineteenth century and the first half of the twentieth century. Scott argues that a growing awareness of the problem from the 1940’s onward has resulted in a gradual adjustment towards a new ‘equilibrium’ where the rates of erosion are slowly declining.
2.8.3 **Soil degradation.**

Along with elevated sediment transport and a significant reduction in the area of natural forest, the expansion of intensive farming has brought with it significant areas of dryland and irrigation salinity. Figure 2-8 shows the density of sites in Victoria that have been identified as having symptoms of dryland salinity. Dryland salinity has affected 260,000 hectares of Victorian farming land, and of this, 140,000 hectares is concentrated in the northern irrigation districts and 120,000 hectares is scattered throughout the dryland (grazing & cropping) areas of Victoria (Department of Sustainability and Environment, 2001).

Dryland salinity is a symptom of rising water tables. Rising water tables are mainly caused by the removal of deep rooted plants, perennial trees, shrubs and grasses and their replacement with annual crops and pastures that do not need much water. Salts within the underlying material are brought to the surface and accumulate, making soils unsuitable for agriculture (National Action Plan for Salinity and Water Quality, 2004). The salt has its origin, either in the marine origin of underlying sediments, or in saltfall. Saltfall is the natural
precipitation of salt from rainfall. Plants take in the natural rainfall and concentrate the salts in their root zone, while evaporating pure water. (National Land and Water Resources Audit, 2001a). Common problems associated with dryland salinity include soil erosion, eutrophication of streams and the loss of riparian zone vegetation (National Land and Water Resources Audit, 2001a).

Irrigation salinity is similar to Dryland salinity and threatens 74% of Victoria’s irrigated land. With irrigation salinity, a ground water mound forms under irrigation areas where irrigation can amount to four times the natural precipitation. While the rising groundwater forces salt further toward the surface, increased groundwater flows leads to increased salt inputs to streams (Environment and Natural Resources Committee, 2001b).

2.9 Mining
It is not only the pastoral occupation and agricultural practices that have degraded the natural landscape and effected water quality. Water was in great demand in the goldfields in the latter half of the nineteenth century. Mining techniques that included using large pumps to spray soil, break it apart and separate out the gold, caused sediment transport on a massive scale in those areas (see Figure 2-9). Garden (2001) describes the main effects of gold mining as localised damage from digging, the spread of subsoils as mullock or tailings, the clearing and consumption of timber and the degradation of water systems.

The result is that substantial areas of Victoria were completely changed by mining practices. Garden (2001) claims that these areas, not only have a changed landscape, but also have substantially reduced biodiversity.
Ladson (2000) surveys estimates of the impact of mining on the delivery of sediment to Victorian streams and estimates that, between 1900 and 1908, over 109,000,000 cubic yards \[83.3 \times 10^6 \text{ m}^3\] of material worked by bucket dredging and hydraulic sluicing were added to Victorian streams.

### 2.10 River navigation and de-snagging

According to a survey by Ladson (2000) an increase in settlement in Victoria and New South Wales, especially following the Gold Rush, increased demand for transport, including river navigation. While Australian rivers were regarded as being unsuitable for extensive river navigation, the high cost of land transport encouraged a number of schemes aimed at altering the characteristics of larger streams to enable the passage of steamers and their barges. In particular, large scale de-snagging was carried out in a number of streams in Victoria, including the Goulburn and Murray Rivers (technically, the Murray actually belongs in NSW).

Snags, are described as ‘sticks, branches, trunks and whole trees that fall into rivers and streams’ (Treadwell, 2000). According to Treadwell (2000) this debris is important in supporting the ecology and geomorphology of streams and rivers. Snags themselves provide habitat for aquatic animals and stable sites for the processing of carbon and nutrients. They can also influence the
flow and channel structure and create habitat such as scour pools (Treadwell, 2000).

The impact of de-snagging has been significant loss of habitat for fish and other aquatic and terrestrial organisms and a general simplification of channel morphology (Treadwell, 2000). While evidence exists for the extent of this operation in the Murray and Goulbourn Rivers, rivers such as the Snowy, Glenelg, Hopkins, and Werribee Rivers, as well the Gippsland Lakes and associated navigable waterways (Ladson, 2000) are also thought to have been significantly effected.

2.11 Water quality

Water quality in Victoria has then been significantly changed by land use practices that have mobilised sediments and released excess nutrients. High nutrient concentrations can lead to accelerated growth of aquatic plants, algal blooms (Tiller and Newall, 2003). In particular, algal blooms have been identified as a continual problem in Victorian water bodies. Algal blooms are the visible appearance of free floating algae or distinct discolouration of surface water or an algal cell count greater than 2,000 cells/ml of water, (Perry, 2003). While the exact cause of algal blooms is unknown they have been linked to, among other factors, high nutrient concentrations and eutrophication (Perry, 2003).

Eutrophication is the increase in the nutrient content, including phosphorous and nitrogen, of a body of water resulting in oxygen depletion (Department of Natural Resources and Environment, 1997). Eutrophication has become a major concern in streams and lakes that drain catchments with intensive farming. For instance, the Gippsland Lakes region is especially prone (Webster et al., 2001)

In intensively farmed catchments, water quality has also been adversely influenced by chemicals and pollutants used in farming, including fertilisers and insecticides, and in highly urbanised catchments, urban and industrial wastes have led to an increase in water borne pollutants, including heavy metals.
2.12 Victoria’s climate

Strikingly, Victoria’s weather is dominated by a west to east progression of high pressure systems across southern Australia; especially from April to November. Dispersed among these high pressure systems are low pressure systems which bring marked cold fronts and their rain laden air. In Spring the location of these cells is more unpredictable and from September to November, especially, Victoria’s weather is highly variable. In summer the systems move further south and warmer conditions caused by stable high pressure system in the centre of the continent dominate.

An examination of a map showing average annual rainfall for Victoria, (see Figure 2-10) shows how the climatological variation from north western Victoria towards the coastal margin represents a shift from the influence of the continental high pressure cell to the increasing influence of coastal or maritime geography.

In the west of the state most rainfall occurs in the winter months and in the east of the state rainfall is even throughout the year. Coastal climatology is influenced by the march of low-pressure cells from west to east in the southern ocean during winter. Frontal precipitation is augmented by local orographic rainfall and moist maritime air to produce locally high rates of annual rainfall, especially on the southern slopes of the Great Dividing Range.

This gradient from the coastal fringe to the north west of the state can be seen in maps of average maximum temperature (see Figure 2-11), and importantly, for water quality and availability, it can be seen in the pattern of median annual runoff (see Figure 2-12).

While the most attractive areas for farming, lightly treed land with good rainfall, had been taken up fairly early after colonization began, it was in the marginal areas where rainfall was low and where runoff was low that colonists encountered the dominant feature of Victorian climate; variability.
Figure 2-10  Victoria - Average annual rainfall (Commonwealth Bureau of Meteorology, 2004)

Figure 2-11 Victoria - average annual maximum temperature (Commonwealth Bureau of Meteorology, 2004)
Figure 2-13 shows a graph of estimated total rainfall for Victoria for the years 1910 to 1996. The striking characteristic is the considerable range in annual rainfall values and apparent oscillations within that range. The eleven-year running mean indicates oscillations of between ten and twenty years. The considerable range varies from around 300 mm per year to over 900 mm per year.

An examination of the two rainfall variability maps, rainfall variability for January to March, (see Figure 2-14) and rainfall variability for June to August (see Figure 2-15) shows that in the winter months variability across Victoria is lower than in summer. In the winter months, variability in parts of Victoria can be low to moderate, while in the summer months rainfall variability, especially in the north west of the state can be very high. The implications of this variability for water management are clear. To sustain human habitation or farming activity in such a climate, water needs to be harvested in times of plenty and distributed in times of abundance.

2.13 Victoria – the distribution of water.

This climatic variability has had a profound affect on the distribution of water in Victoria and just as Victoria is a region of immense variety; climatic variety, physiographic variety and ecological variety; the distribution of water is also immensely varied. The central highlands produce clear mountain streams; the Mallee is streaked with ephemeral creeks and areas of internal drainage, while the northern plains are crossed by slow moving turbid rivers.
Figure 2-12 Victoria - median annual runoff (Department of Primary Industries, 2003)

Figure 2-13 Annual total rainfall for Victoria (CSIRO Atmospheric Research, 2000)
Figure 2-14 Australia - rainfall variability, January to March. (Commonwealth Bureau of Meteorology, 2004)

Figure 2-15 Australia - rainfall variability, June to August. (Commonwealth Bureau of Meteorology, 2004)
2.14 **Victoria’s rivers and lakes**

There are 3820 named watercourses in Victoria, with a total length of 56,000 kilometres. In addition there are numerous un-named streams that are mainly smaller tributaries of named watercourses (Natural Resources & Environment, 2001). Victoria is divided by two distinct large river basins; the Murray Darling to the north and the South-east Coast to the south (Figure 2-17). The drainage divide is the southern extension of the Great Dividing Range that runs from Victoria, all the way up into southern Queensland.

Most of the main river systems to the north of the Great Dividing Range, like the Goulburn and the Loddon, rise in the Victorian Alps or the Victorian Midlands and flow down onto wide riverine plains. While rivers that rise on the southern slopes of the Great Dividing Range tend to flow more directly to the sea. Figure 2-18 is a map of important Victorian streams showing their status during the 1968 drought. Clearly many streams in Victoria can only loosely be called permanent. While streams in the Victorian Alps, the Otway Ranges, in Gippsland and in the north of the state were still flowing, in the west and north-west of the state most streams had ceased to flow during the 1968 drought.
While many rivers have been drained, dredged and channelled, and about 35% of the State’s wetlands have been drained (Natural Resources & Environment, 2001), eighteen river segments with special scenic, recreational, cultural or ecological values have been declared Heritage Rivers under the Heritage Rivers Act 1992 (Parliament of Victoria, 1999) (see Table 2-1). The Act introduces special conditions aimed at protecting perceived environmental value. As can be seen from Table 2-1, conditions include the protection of rivers from further impoundments, diversions, timber harvesting and any water diversion that might impair the ‘attributes’ of the area.

Because the supply of artesian water is limited, significant development of groundwater resources in Victoria had to wait until the early twentieth century when small pumps to bring sub-artesian water to the surface were readily available (Department of Conservation and Environment - Victoria, 1991, p30).

![Victorian Drainage Basins](image)

Figure 2-17 Victorian drainage basins. Subdivisions are main river basins
Figure 2-18 Streams flowing during severe drought –1968
(Department of Primary Industries, 2003)

Table 2-1 Heritage rivers and special conditions under the Heritage Rivers Act (Parliament of Victoria, 1999)

<table>
<thead>
<tr>
<th>No Impoundments artificial barriers or structures are to be constructed</th>
<th>No new water diversions</th>
<th>New Water diversions not to significantly impair attributes of area</th>
<th>No timber harvesting</th>
</tr>
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<tbody>
<tr>
<td>Mitta Mitta River</td>
<td>Genoa River</td>
<td>Mitta Mitta River</td>
<td>Mitta Mitta River</td>
</tr>
<tr>
<td>Ovens River</td>
<td>Suggan Buggan</td>
<td>Ovens River</td>
<td>Big River</td>
</tr>
<tr>
<td>Howqua River</td>
<td>Berrima River</td>
<td>Howqua River</td>
<td>Wimmera River</td>
</tr>
<tr>
<td>Goulburn River</td>
<td>Thomson River</td>
<td>Goulburn River</td>
<td>Genoa River</td>
</tr>
<tr>
<td>Genoa River Bemm, Goolengook, Arte and Errinundra River</td>
<td></td>
<td>Bemm, Goolengook, Arte and Errinundra River</td>
<td>Bemm, Goolengook, Arte and Errinundra River</td>
</tr>
<tr>
<td>Snowy River</td>
<td></td>
<td>Snowy River</td>
<td>Suggan Buggan and Berrima River</td>
</tr>
<tr>
<td>Suggan Buggan and Berrima River</td>
<td></td>
<td>Upper Buchan River</td>
<td>Upper Buchan River</td>
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<td>Upper Buchan River</td>
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<td>Mitchell and Wonnangatta River</td>
<td>Mitchell and Wonnangatta River</td>
</tr>
<tr>
<td>Mitchell and Wonnangatta River</td>
<td></td>
<td>Yarra River</td>
<td>Thomson River</td>
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<tr>
<td>Thomson River</td>
<td></td>
<td>Lederderg River</td>
<td>Yarra River</td>
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<tr>
<td>Aire River</td>
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<td>Lederderg River</td>
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<td>Glenelg River</td>
<td>Glenelg River</td>
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<td>Aire River</td>
</tr>
<tr>
<td>Aberfeldy River</td>
<td>Aberfeldy River</td>
<td></td>
<td>Glenelg River</td>
</tr>
</tbody>
</table>
2.15 Victoria’s Groundwater

While for the most part this thesis deals with surface water, a significant quantity of Victoria’s water comes from artesian and sub-artesian water. Victoria is not endowed with substantial quantities of groundwater when compared to other eastern states that take water from the Great Artesian Basin, but, there are 74,250 groundwater bores in Victoria that extract over 250,000 megalitres of water per year (see Figure 2-19). One out of every ten people in the state use groundwater in some form (Nott, 2002).

Figure 2-19 shows that private bores are concentrated in the Otway region and in the north central part of the state and in Gippsland. Extraction of groundwater is limited in the north west of the state where, salinity levels are high (see Figure 2-20) and where the map of beneficial use indicates the groundwater is not suitable for farming application (see Figure 2-21). Figure 2-20 also shows that the aquifers in the eastern highlands are little used but have high quality water that is suitable for drinking (see Figure 2-21).

2.16 Victoria water storage and diversions

In Victoria, the distribution of major dams and storages has been influenced by topography, rainfall, catchment area, evaporation, catchment vegetation, proximity to urban areas, geology, politics and individual enthusiasm. The first water storages were built to provide reticulated water to growing population centres. Melbourne, with its burgeoning population in the 1850’s stimulated the construction of Yan Yean (Department of Conservation and Environment - Victoria, 1991).

At the time, the technology needed to build dams was low, and economic resources were limited, locations for water storage needed to take advantage, as far as possible, of natural water storages. Yan Yean, for instance, was built on the site of a natural swamp; a low earth wall constructed across the valley (Department of Conservation and Environment - Victoria, 1991).
Figure 2-19 Victoria – groundwater extraction bores (Department of Primary Industries, 2003)

Figure 2-20 Victoria - groundwater salinity (Department of Primary Industries, 2003)
In general, deep-water storages are more efficient; they have lower evaporation rates and are less prone to algal growth. However, in northern Victoria, where relief is low, only wide shallow storages are possible (Australian Water Resources Council, 1976). In these areas, however, as can
be seen from Figure 2-23 and Error! Reference source not found. evaporation is high and natural rainfall is low.

The Gold Rush saw the first major development of dams and water storages. These were concentrated in central Victoria; at Spring Gully, Malmsbury, Crusoe and Campaspe near Bendigo; and for Geelong, at Upper Stoney Creek and Bostock.

With the twentieth century and the transition from a pastoral to an agricultural economy, large water storages were built on the Murray River and on the Goulburn River. Significant milestones in the development of water storages in Victoria during this period, include the construction of the Hume Dam in 1936, the first large dam to be built in Victoria with a capacity of 1,542,000 megalitres; the building of Lake Eildon in 1955 with a capacity of 3,390,000 megalitres and the construction of Dartmouth dam in 1978 with a capacity of 4 million megalitres (Department of Conservation and Environment - Victoria, 1991).

During the twentieth century Victoria’s water storage grew significantly. The Thomson dam built by the Melbourne Metropolitan Board of Works is the most significant urban storage in Victoria, at 1125 gigalitres, but it is dwarfed by the large storages built for irrigation (Department of Conservation and Environment - Victoria, 1991).

Following the Second World War, continued expansion of irrigated farming led to the enlargement of the Hume Dam to 3.1 million megalitres, the construction of the Snowy Mountains Hydro-electric Scheme and the construction of the Dartmouth Dam, built by the River Murray Commission.

The Snowy Mountains Scheme, began in 1949 and completed in 1974, captures and diverts the waters of 12 rivers and 71 creeks. It includes 16 dams, 18 aqueducts, 19 trans-mountain tunnels, 7 power stations and 2 pumping stations. Approximately 99% of the Snowy River’s natural flow is diverted below the Jindabyne Dam. The scheme has historically provided, on average, an annual diversion of 1.2 gigalitres of water into the Murray and 1.21 gigalitres into the Murrumbidgee (Smith, 2000). Some indication of the scale of this development can be gained by a consideration of the figures: the
Snowy scheme is responsible for approximately 25% of flows in the Murrumbidgee, rising to 60% in drought years, and 10% of flows in the Murray, rising to 33% in drought years. Approximately half of these flows are sourced from the Snowy River catchment while the remaining is water that would naturally have flowed into those catchments but is regulated by the scheme (Smith, 2000).

Additional to large impoundments are the hundreds of thousands of small farm dams in Victoria. As yet there has been no accurate census of farm dams, but according to the Australian Water Resources Assessment 2000 (National Land and Water Resources Audit, 2001b), farm dams in Australia account for an estimated 9% of the total water stored.

![Average Rainfall Annual](image)

**Figure 2-23 Australia: average annual rainfall (Commonwealth Bureau of Meteorology, 2004)**

### 2.17 Conclusion

The pattern and progress of the European colonisation of Victoria established a unique distribution of water resource use in Victoria. Early settlers brought with them farming techniques and water management techniques that were
often inappropriate for the conditions in Victoria and completely change the character of the landscape in a matter of a few decades. As a result of this environmental pressure, modern Victorians can look back and catalogue significant ecosystem change, the effects of widespread soil erosion and deposition, and the prevalent symptoms of soil degradation.
CHAPTER 3. WATER USE AND MANAGEMENT IN VICTORIA

3.1 Introduction

Chapter 2 outlined the way in which human settlement in Victoria interacted with the prevailing geography to create the present pattern of resource distribution. Importantly, the chapter showed that, in the past, the development of water resources in Victoria often proceeded without reference to the environmental limitations of the land itself. Unlike their predecessors, through the development of global and regional environmental data and remote sensing technologies, Victorians are now able to see their natural resources from a wider, regional and global perspective.

This chapter will further that investigation, from the perspective of water management and it will show how the sense of regional and global environmental responsibility has, over time, been reflected in the management of water resources. The chapter will begin by defining the concept of water use and then go on to comment on relevant issues of water management in the global context. It will then continue by specifically outlining the use and management of water in Victoria and the development of the current water management policies.
Importantly, the chapter addresses the key question “What is the social-cultural context in which water quality assessment is made?”. The assessment of water quality is not made in isolation; it is carried out within a complex historical and social context. Information presented in this chapter provides some important indicators of the context in which past and recent resource management decisions have been made.

The chapter will argue that the development of agriculture in Victoria was directed by intense idealism and not by the agricultural potential of the State’s soils or the potential impact of agriculture on those soils or, in the long term on water quality. The large scale land degradation which led to increased sediment supply to streams was impelled by social forces, not just natural forces. Early Victorian farmers were not looking to the future consequences of the agrarian myth which motivated much of the intensive agricultural development. This development was, instead, fuelled by a view of nature as a limitless resource.

### 3.2 Management and use of water by Aborigines

Before the Europeans arrived in Victoria, Aboriginal people, who themselves probably arrived around 40 - 60 thousand years ago (Flannery, 2001), employed unique methods to manage their, often unreliable, water resources.

Most evidence suggests that Aboriginal Australians moved from water source to water source to maintain reliable food supplies and camped where water was plentiful. Rivers provided them with an artery for transport and trade and a source of food (Powell 1991). But other techniques were used as well. At Lake Condah in western Victoria evidence indicates that the Gunditjmara people modified the natural flow of a grassy wetland over 8,000 years ago. They built weirs, channels and dams to create a substantial eel farm that may have supported up to 10,000 people (Builth, 1996).

In western Victoria, McNiven (1998) describes yet another technique for managing water used by Aborigines. The author describes a possible pulsation settlement pattern at Lake Corangamite, where Aborigines moved out from sources of freshwater in response to the winter – spring wet season, to take advantage of ephemeral water sources and their food resources.
During times of low rainfall the Aborigines would then contract back to permanent freshwater as ephemeral streams dried up.

Not only was water important for Aboriginal survival, but McKay (2002) suggests that there is evidence that before European contact Victorian Aborigines defined their territory in terms of the water features. They would speak of their country as a land of water holes, creeks and rivers. Water, was for Aborigines ‘a source of both subsistence and cultural inspiration’ (McKay, 2002).

Clearly water was important to Aboriginal people, and they employed a variety of techniques to manage the variability in its supply. It was inevitable that as Europeans arrived they would come into conflict with Aborigines over access to water. Aborigines were driven from places with easy access to water. It is even reported that some Aborigines were taken prisoner and used by European travellers to secure fresh water (McKay, 2002).

While direct water use before European colonisation appears to have had little impact on stream flow, it is possible that the use of fire and the control of larger animal species attributed to Aborigines might have had a significant impact on catchment vegetation. Flannery (2001) argues that the arrival of
Aborigines and the use of fire as a tool to manage local vegetation and animal populations brought with it a massive change in the landscape of Australia.

3.3 Colonisation and exploration
During 1830’s and 1850’s as the new European wave of immigrants arrived in Victoria, settlement closely hugged the main watercourses: venturing too far from reliable water could mean agricultural ruin (Priestly, 1984). In this initial period of colonisation, the water for human settlements was obtained from streams, springs and some newly dug storage wells. In the country areas new settlers jostled for positions around creeks and water holes. But the lack of tenure meant there was little investment in wells or dams (Priestly, 1984).

3.4 Urban water management
In early colonial Melbourne it was a common part of daily life to bucket water out the Yarra. The site for the new settlement had been partly chosen because a rock shelf across the Yarra prevented salt water from penetrating any further inland. The pool behind the rock shelf was a convenient place to take water (Department of Conservation and Environment - Victoria, 1991).

Between 1839 and 1841 works were carried out to raise the rock shelf and provide greater storage. During this time, private contractors supplied household water in water carts. Near the corner of Flinders Lane and Elizabeth Street, tanks were built and water was pumped from the Yarra in 1850 to supply drinking water (Horsfall, 1962).

The quality of this water was considered quite poor, and because of this, a small private water company was established in 1849 to sell filtered water. This company represented the birth of water planning in Victoria. The company hired James Blackburn, an ex-convict, engineer and architect who had designed Hobart’s water supply system. The company lobbied the Melbourne City Council to protect its business from other river users but the failure to secure guaranteed access to the river water led to the company’s demise. When it was finally wound up, the government stepped in to guarantee the supply of water (Department of Conservation and Environment - Victoria, 1991).
As a result, the City Council hired Blackburn to investigate the establishment of an adequate supply of water and sewage disposal. In 1853 a free settler, Matthew Bullock Jackson was appointed to head an independent Commission of Sewers and Water Supply. The members of the commission included the Mayor of Melbourne and the Town Clerk; Blackburn was appointed as a consulting engineer. The formation of the Commission was seen as a compromise between the City Council who wanted control over its own water supply, and the State Government who were uneasy about letting the Council levy water rates to raise its own revenue (Department of Conservation and Environment - Victoria, 1991).

By 1852 Blackburn had completed a survey of all possible sites to develop a water supply, and had recommended a marsh at Yan Yean, 30 kilometres from Melbourne. Yan Yean reservoir would take water from the Plenty River and deliver it to Melbourne in steel pipes. During the 1880’s these pipes were replaced with an open channel. In December 1857 a ceremony was held on the corner of Elizabeth and Flinders Streets in Melbourne; water sprayed onto a waiting crowd (Priestly, 1984).

As the population of Melbourne grew rapidly during the Gold Rush, waste disposal became an urgent problem. Melbourne was a very unhealthy place to be. Typhoid, cholera and dysentery were commonplace (Department of Conservation and Environment - Victoria, 1991). While the supply of fresh water was seen as an antidote to poor health conditions, the increase in available water after the introduction of Yan Yean, initially, however, did little to stop a rising death toll from disease. More water supplied, meant more polluted water to dispose of. It also meant that polluted water became more mobile, and as can be seen in Figure 3-2, community concern about the spread of disease through the water supply was high (Department of Conservation and Environment - Victoria, 1991).
The development of sewerage did not, however, keep pace with the development of urban sprawl, or the provision of reticulated water. In early Melbourne sewage disposal was a constant problem. It was not until the Melbourne and Metropolitan Board of Works was established in 1891, following a Royal Commission into Sanitation in 1889, that a co-ordinated system of sewage disposal was begun (Department of Conservation and Environment - Victoria, 1991).

### 3.5 The squatters and selectors

In country Victoria, the early years of land ownership set the pattern for water use for all time. The politics of early Victoria created two distinct classes of land ownership, squatters and the selectors. The squatters, who traced their rights to land from the original pastoral occupation, were a distinct and very powerful group. In the 1850’s they occupied thirty-five percent of seats in the Legislative Assembly and two thirds of seats in the Legislative Council. During the early phase of colonisation, squatters had simply, and illegally, occupied vast areas of land. This land was the easiest land to turn to pastoral activities;
the lightly timbered plains and low hills to the west of Melbourne. The squatters, initially at least, paid nothing to occupy their properties. When the government finally stepped in, rather than evict them, it demanded peppercorn rents for their, sometimes substantial, properties (Kiddle, 1961).

Selectors came after the original squatter expansion, and their access to land was controlled more closely by government policy. They waged a continuous battle with successive governments to open up land that had been locked up by the squatters and allow a greater number of people to own their own land. Squatters fought back, using their considerable influence in government. Kiddle’s (1961) view is that the bitter battle for land selection had engendered a public suspicion in squatter motives, which united all opposing forces with a common scapegoat.

The squatters land holdings in the Western District were large. In June 1893 the Age newspaper listed seventeen squatting families who, between them, owned two million acres (Kiddle, 1961).

While the squatters held onto their estates and those opposing the squatters argued for free selection (for all land to be opened up so that individuals could purchase freehold land) government edicts from London via Sydney pressed for the closer concentration of settlement and the taming and colonizing of the wilderness in an orderly and profitable fashion.

It is this three cornered battle over land selection (squatters, selectors and government) that has left a distinct mark on the development of agriculture and the development of water resources in Victoria. At all turns the squatters resisted the pressure toward closer settlement and, because of this, new agriculture development encouraged by London, and later by Melbourne and Canberra, would be forced to the north and northeast of the western district, into less fertile land with lower rainfall.

3.6 Changes brought on by gold mining

Large-scale management of water supply in country Victoria had its genesis in the need to provide water to the burgeoning mining settlements on the Victorian goldfields. Water for mining activities and to service stock was, at
this time, obtained directly from streams. When gold was discovered in 1851, the first public water schemes were developed soon after.

The earliest reticulated supplies were at Bendigo (1858-1859) and Ballarat (1860-1862) and Geelong (late 1860's) (Priestly, 1984). North of Melbourne, Yan Yean reservoir was completed in 1857 (Archive@Victoria, 2003). In 1860 the government agreed to spend £50,000 for the construction of reservoirs on the goldfields; according to Priestly (1984) thirty-five small reservoirs were quickly built.

The discovery of gold led to an enormous expansion of Victoria’s population, the population grew from 76,162 in 1850, to 537,847 in 1860 (Laughton, 1914) that is, the numbers of people grew sevenfold in ten years. In this context it does not seem unusual, then, that the Victorian Water Supply Department (VWSD) was established in 1865 as a sub-department of the Department of Mines; water and mining were inextricably linked.

3.7 A growing need for farming after the Gold Rush
With the expanding economy and a growing population came a growing need for water to supply agriculture. As gold mining declined, the newly arrived population needed something else to do. In the 1850's, bread in the new colony was still baked in South Australia from Californian and Chilean flour (Blainey, 1955). There was increasing pressure for the government to act and provide the infrastructure for the expansion of agriculture. In the 1860’s and 1870’s farming expanded rapidly. Railways were constructed, roads were built and water schemes were developed.

3.8 Water Conservation Act 1881 and 1883
By the 1880’s the need for better central regulation and co-ordination of rural water supplies led to an inquiry by the Water Conservancy Board, and resulted in the Water Conservation Acts 1881 and 1883 which gave the VWSD power to appoint Commissioners for local Waterworks Trusts and Districts and control the supply and sale of water.

During this time the State began to construct publicly owned water storages. The Goulburn Weir on the Goulburn River near Nagambie and the Laanecoorie Weir on the Loddon were both completed around 1891. The
Goulburn Weir (Figure 3-3) raised water levels on the Goulburn River and diverted it via an earthen channel 32 km to the Waranga Reservoir (Australian Science and Technology Heritage Centre, 2000).

![Figure 3-3 Goulburn Weir at Nagambie](Australian Science and Technology Heritage Centre, 2000)

3.9 The irrigation movement

With Alfred Deakin as a major driving force, a movement began in the late 1800’s to intensify government support for the development of Victoria’s water resources. Between 1884 and 1885 a Royal Commission was held, headed by Alfred Deakin. As President, the future Prime Minister zealously pushed an investigation that would provide a basis for future development of the agriculture sector (Department of Conservation and Environment - Victoria, 1991).

During 1885 Deakin travelled to the United States and studied their irrigation practices. In California he met two Canadians, George and William Benjamin Chaffey, and invited them to visit Victoria. The Chaffey brothers were enthusiastic proponents of irrigation and had developed irrigation areas in California and Canada. The Chaffeys took control of the development of an irrigation area around Mildura after the Government provided inexpensive land (Department of Conservation and Environment - Victoria, 1991).
3.10 The Irrigation Act 1886: end of the Riparian Act

To enable the kind of large-scale development that the Chaffeys envisioned, changes were needed. The Irrigation Act 1886, which was a direct result of the Royal Commission, radically vested water rights in surface water in the Crown; ownership of water was effectively nationalized. Before this time the Riparian Act inherited from English common law applied in Victoria.

Under the Riparian Act, rights to water belonged to properties that were adjacent to waterways and they could use as much as they liked as long as they did not substantially effect water quality for downstream users (Tan, 2001). It was argued at the time that the Riparian Act was inappropriate in a country that had relatively few streams, and where government control and establishment of large scale irrigation schemes was going to be essential to the future economic success of Victoria.

The Water Conservation Act had enabled the establishment of local irrigation trusts; the Irrigation Act built on this and allowed the formation of large-scale water trusts and irrigation schemes. The Act also properly defined the rights of water users and entrusted the supreme power over water to the state (Department of Conservation and Environment - Victoria, 1991).

A few years after the Irrigation Act was passed there had been ninety trusts formed and hundreds of kilometres of channels constructed.
3.11 The failure of initial developments
This initial bloom of water trusts and irrigation schemes was universally unsuccessful (Bellanta, 2002). The Chaffey brothers in Mildura filed for bankruptcy in December 1895 (East, 1955). According to East (1955) this lack of success was due to two main reasons. Firstly, the schemes often had too optimistic a view of available water and no resources to construct storages: projected water yields were based on inadequately short stream flow records. The second reason for failure was that the trusts revenues relied too much on the sale of water. Farming methods were often inappropriate; holdings were too large, farmers did not use the water when it was available and soil was inadequately prepared so that after a few years of watering the land became infertile. Compounding this, the local trusts did not have the power to compel water regimes that might provide reliable revenue.

3.12 The optimism of the 1880’s
According to Bellanta (2002), the 1880’s were a period of intense optimism in Australian society. It was a boom time and economic prosperity was everywhere. During this time the pursuit of irrigation was the pursuit of an ideal, an Eden (Bellanta, 2002). The development of irrigation, it was thought, would foster a ‘haven of egalitarian plenty and liberty’ (Bellanta, 2002). There was an overwhelming desire at the time to develop agricultural potential to its maximum. This was further increased by a popular sentiment that all people had a right to own land in the colony. Not only did they have a right to the land, the possession of such land, enabled individuals to be independent and reach their full potential. This notion, often referred to as an agrarian myth, is outlined in detail by Powell (1970b), and is often embodied in the concept of the Yeoman farmer.

3.13 The yeoman farmer
Powell (1970b) outlines a view that radical immigrants who came into Victoria as part of the population influx during the Gold Rush added to a general radicalism amongst the population. This radicalism led to a common view that land reform was at the heart of political reform. At this time (1850’s and 60’s) land reform meant opportunities for individuals to select and purchase freehold land and an end to government controls on what land could be
selected. The result was that free selection became an aspiration allied to political freedom.

The concept of the yeoman farmer, common during the late part of the nineteenth century, had survived and was still active during the early phase of the twentieth century. Powell (1970a) describes the yeoman farmer as ‘a prosperous and independent small landholder imbued with high moral standards which set the tone for the rest of society to follow’. The yeoman farmer was economically independent and received the direct rewards from his (women were not included) own toil. Figure 3-5 shows a cartoon used to encourage settlers in Victoria. The yeoman farmer was going to provide the basis of agricultural progress.

Figure 3-5  "The Man that carries the others" from New Settlers’ Handbook to Victoria, 1924. (Department of Primary Industries, 2004)

This agrarian ideal was further encouraged in the twentieth century when technological advances in farming provided the impression that an individual could easily prosper on small landholdings. Keneley (2000) quotes Thomas Cherry, the Director of Agriculture in 1913, who proclaimed ‘...the limit to
production,... provided there is sufficient moisture to bring crops to maturity, is not yet in sight'.

The yeoman farmer was not looking to the future consequences of his ambition and the agrarian myth but was motivated by a view of nature as a limitless resource. This idealism propelled the intensity of agricultural development well beyond the limitations of the land itself and became the catalyst for large scale land degradation.

3.14 Closer settlement
In the nineteenth century, Victoria was still mostly a wilderness, and while in the twenty-first century context wilderness is a valuable commodity itself, in the nineteenth century, wilderness had to be conquered and tamed. Just as government policy in the twenty-first century protects wilderness from those base instincts, in the nineteenth and early twentieth century government policy sought to encourage the taming of the wilderness.

In fact, it was thought every true colonial’s duty to contribute to the extension of agriculture into the wilds. The Western District squatters were accused of putting themselves in the way of proper development of the land and its resources. Opposing forces rallied around the cry for closer settlement (Priestly, 1984).

3.15 The fight for closer settlement
As population grew, the pressure increased on the holders of these original lands, the squatters, to break them up for closer settlement. According to Priestly (1984), there was a growing public conviction that large areas of land owned by a few squatter families could be put to more intense use.

The Land Act 1846 and the subsequent Order in Council 1847 provided for a fourteen year tenure for squatters and the pre-emptive right to purchase the land at the end of the lease (Kiddle, 1961). The Order in Council stipulated that the squatters could graze livestock but they could not be involved in other farming activities, other than those for home use (Foster, 1998).

The Land Act was not successful, however, in solving the problem of squatter’s tenure. Intense political argument over the meaning of the Order in
Council continued throughout the 1850’s. Further Land Acts of 1860, 1862 and 1865 were similar attempts to find a solution to the land dispute. However, the loose phrasing of the Acts enabled squatter families to purchase any number of adjacent blocks (Kiddle, 1961).

The Land Act 1880 imposed a land tax on properties over 640 acres. Squatters were in uproar, and a barrage of applications for special consideration paralysed the process and delayed the taxation for some time.

The Closer Settlement Act of 1898 enabled the government to acquire large estates by agreement with the owner, and then subdivide them into smaller blocks for sale. However, by 1904, just 34,000 acres had been purchased. Two thirds of that consisted of just two properties. The Act was further amended in 1906, 1907 and 1909 to include provision for compulsory acquisition. By June 1917 the Closer Settlement Board had increased the resident population of the countryside by about thirteen thousand (Priestly, 1984).

At the beginning of the twentieth century, Victorian governments continued a policy of closer settlement in western Victoria. Land was purchased after the first and second World Wars, subdivided and offered to soldier settlers.

The pattern of agricultural development in Victoria was, then, critically drawn by this interaction between those who had large land holdings and those who promoted closer settlement.

### 3.16 Wimmera – Mallee Stock and Domestic Supply Scheme

Running parallel to the push for closer settlement was the construction of infrastructure. Between 1890 and 1940, 16,000 km of channels were constructed to carry 'domestic and stock' water to the Mallee and Wimmera (Environment and Natural Resources Committee, 2001b).

The Wimmera Mallee Stock and Domestic Supply Scheme (see Figure 3-9) takes water from the Glenelg and Wimmera rivers and sends it to twenty thousand farms, fifty towns and three thousand hectares of irrigation near Horsham and Murtoa (Wimmera-Mallee Water Entitlements Project Group, 2002).
3.17 The twentieth century
A second major stage in development of Victoria’s water resources began early in the twentieth century. In 1905 the Swinburne Water Act took away local control of irrigation and abolished the irrigation trusts. Control of water policy fell to a new body, and in fact an entirely new form of government agency; the State Rivers and Water Supply Commission (SRWS). The SRWS is thought to be the first corporate entity in the world given the task of developing a major regional natural resource (East, 1955).

While Alfred Deakin had left his mark as the father of Victorian irrigation, the first chairman of the SRWS; Elwood Mead might be seen as the father of the large-scale water development that characterized the first half of the twentieth century. Mead was an American, and a recognized expert in irrigation development. In the face of the extensive failure of irrigation developments, Mead convinced the government that the key to successful irrigation was closer settlement and intensive water use (East, 1955). As part of this policy, in 1909, compulsory water rights were applied. That is, farmers were forced to pay for allotted water even if they didn’t use it (East, 1955). In 1912 the Closer Settlement Act gave the SRWC the power to purchase, dispose and administer lands in irrigation areas or on land that was only suitable for settlement under irrigation (Archive@Victoria).

3.18 Soldier settlers
In 1917 the Discharged Soldier’s Settlement Act gave the Commission control of the settlement of returned servicemen men and women on irrigable lands, and in 1922 these powers to determine the pattern of settlement in irrigation districts were used to encourage the settlement of British immigrants. In the post second world war period these powers were again used to facilitate the settlement of returned soldiers (Archive@Victoria, 2003).

While some soldier settlements were successful, a great number were not. Many of the soldier settlers had little agricultural experience. Great optimism had surrounded their potential. But often the agricultural potential of these new subdivisions had been overestimated.
Keneley (2000) suggests the foundations of the Victorian soldier settlement scheme were ‘based on flawed perceptions of rural life’, of an agrarian myth.

Figure 3-6 Constructing an irrigation channel early in the twentieth century (Department of Primary Industries, 2004)

3.19 More developments
The next major stage in water management in Victoria was the passage of The River Murray Waters Act of 1915. The Act ratified an agreement between the governments of the Commonwealth, New South Wales, Victoria and South Australia for the construction of water supply works, the allocation of Murray waters and appointed the River Murray Commission to oversee its implementation (Australian Science and Technology Heritage Centre, 2000).

And, perhaps as the final blow to the irrigation trusts, in 1937 an act of parliament transferred almost the entire cost of irrigation and water supply works from the water user to the general tax payer (East, 1955).
Figure 3-7 Ruined farmland south of Torrita in the Mallee, April 1944. A block of soil is marooned as the surrounding ground eroded. A combination of drought and cultivation techniques destroyed the structure of the soil. Wind whipped the sand up and the ground literally disappeared beneath the feet of the farmers’ (Department of Primary Industries, 2004)

3.20 Stages in water conservation

Speedie (1962) describes three distinct stages of water planning in Victoria.

1. Diversion of stream flow by channel or pumping without the use of storage.

2. Conservation of winter flows for use in the succeeding summer months.

3. Conservation of flows of wetter years for use in future dry years.

Stage 1 refers to the initial stage adopted by pioneers and in areas where local stream-flow is sufficient. Stage 2 is the provision of small local storages for local diversion and Stage 3 is the provision of large-scale storage projects necessary for irrigation projects.

These stages neatly outline the progress of water management in its early years. Initially colonists tried to live with what they had. They inhabited areas where water was plentiful. As population pressure grew, and competition for these water-rich lands also grew, early farmers and city planners began to build small storages, based on their understanding of European practices; winter flows were stored for summer use.
The need to supply water to water-poor land, to advance the march of agriculture and to support gold mining activities, hastened the third stage. When economic means were available larger storages were built to buffer farmers from Victoria’s unreliable rainfall pattern; wet year rain was stored for dry year supply. In 1955, Ronald East, who was Chief Executive Officer of the State Rivers and Water Supply Commission at the time wrote that Victoria was just entering the third stage (East, 1955).

3.21 The Murray

The Murray River catchment covers about 14% of the Australian continent and covers approximately 50% of Victoria (Department of Conservation and Environment - Victoria, 1991). In the early days of settlement, the Murray River became an important transport artery but water was also, increasingly, demanded for irrigation.

A Premiers Conference in 1911 recommended that the competing claims be investigated by a team of engineers (Department of Conservation and Environment - Victoria, 1991). The engineers report formed the basis of the Murray Waters Agreement 1914. In the Murray Waters Agreement Victoria, New South Wales and South Australia agreed on a system of water allocation from the Murray. The chief concern at the time was navigability. The quantity of water allocated to South Australia was to be enough so that paddle steamers didn’t run aground (Blanch, 2002).

At the time the South Australian Government was concerned that the two, more prosperous states were going to take all the water from the Murray for their new irrigation developments. The agreement provided for the construction of twenty-six weirs to be built on the Murray to provide for navigable water, even if large amounts of flow were diverted (Blanch, 2002). Effectively the Murray became a very long series of pools.

3.22 Current water management practices

In “Water Victoria – The Next 100 Years” (Department of Conservation and Environment - Victoria, 1991), the authors outline a political divide that contributed in no small way to the development of water resource management in Victoria. Henry Bolte, who was Minister for Mines and Water
Resource during the 1940’s and 50’s and then Premier in 1955, was an ardent supporter of water resource development in Victoria. He championed the development of some of the largest water storages in the state, including: Cairn Curran, Eppalock, Rocklands and Upper Yarra. Bolte was a Liberal Conservative, with a support base among the rural community. As part of his government’s policy, not only were there massive subsidies toward the construction of water infrastructure, there was also a clear commitment to protect water that flowed north of the Great Dividing Range from the clutches of the, then, Melbourne Metropolitan Board of Works (MMBW).

Bolte proclaimed that not one drop of water was to be taken from north of the divide to augment Melbourne’s water supplies. He had developed a close relationship with Ronald East and sought to reassure the State Rivers and Water Supply Commission (SRWSC) that their irrigation water was safe (Department of Conservation and Environment - Victoria, 1991). The development of Melbourne’s water supplies was forced to the south, with the construction of the Thomson Dam in the early seventies, rather than to a proposed reservoir on the Big River, in the Goulburn Catchment.

In 1975 the Water Resources Act created a new Ministry of Water Resources and Water Supply and the Water Resources Council. The aim of this new legislation was to bring the MMBW and SRWSC under the same Minister. Up until that time the MMBW had been under the control of the Minister for Local Government.

During the 1980’s, there was significant reform of water resource management in Victoria. Two main themes arose out of a number of enquiries and reports. Firstly, the need for an integrated, whole of catchment approach to water management, and, secondly, a need to simplify legislation dealing with water, which was recognized, universally, as being too complex (Tan, 2001). In 1980 the Government established a joint parliamentary committee called the Public Bodies Review Committee. Although the MMBW was outside its brief, the Review Committee recommended the reorganisation of rural water management.
The State Water Supply Commission was abolished in 1984 by the Water Act. Its responsibilities, assets and powers passed to the Rural Water Commission (RWC). The Department of Water Resources (DWR) took over the Commission’s role in the development of rural water resource policy (Archive@Victoria, 2003).

3.23 Water reform

The characteristics of current water management in Australia have been overwhelmingly influenced by the push for reform of the water industry. This reform has at its roots two major forces: continuing, global concern for environmental health and continuing signs of pressure on the environmental health of Australia. In the early 1990’s when the United Nations held its Conference on Environment and Development (UNCED Earth Summit) in Rio de Janeiro, in Australia a giant algal bloom a thousand kilometres long developed in the Darling River.

The ramifications of this algal bloom considerably changed the course of water management in Australia. Following the bloom, but not until 1995, an audit was carried out on water use within the Murray Darling Basin. The audit found that continued diversions from the Murray would result in further river health problems, reduce the security of water supply for irrigators and reduce the reliability water supply during droughts (Independent Audit Group, 1995).

Following the audit a limit was established on the volume of water that could be taken from the Murray-Darling system. This limit, often referred to as the ‘Cap’, was a radical step. For probably the first time in Australia, the environmental health of a significant river was used as part of the reason for limiting the further allocation of water (Independent Audit Group, 1996).

At the conclusion of the Earth Summit, Australia and 177 other countries signed the Agenda 21 agreement (United Nations Department of Economic and Social Affairs, 1992). This document offered specific mechanisms for governments to incorporate the concept of sustainable development in their policy framework. Australia’s Federal Government eagerly accepted the requirements of Agenda 21, labelling their own take on it ESD. ESD has a more distinctly environmental flavour than Sustainable Development.
According to the Australian Federal Government ESD is

‘…using, conserving and enhancing the community’s resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased’ (Environment Australia, 1992a).

Agenda 21 specifically calls on countries to pursue water reform and integrated catchment management.

Coincident with the development of global environmental concern, was a push for national microeconomic reform in Australia. These two forces coalesced with the establishment of the Federal Government’s Strategic Framework for Water Reform.

3.24 National competition policy

At the core of the Federal Government’s water reform agenda was the implementation of the 1994 Council Of Australian Governments (COAG) agreement Strategic Framework for Water Reform, through the mechanism of National Competition Policy (NCP). National Competition Policy is a set of agreements endorsed by state governments in 1995. The agreement also established the National Competition Council, a body charged with the task of monitoring state performance against the objectives and timelines of National competition Policy (Marsden Jacob and Associates, 2000).

Philosophically, National Competition Policy assumes that economic competition is the best way to promote efficiency in government business, and seeks to promote the conditions where competition can function. Competition policy aims to implement microeconomic reform and to encourage the most efficient use of government resources. Marsden et al. (2000), define the overall objectives of competition policy as an attempt to:

- Grow the overall size of the economy;
- Generate more jobs and higher wages; and
- Increase the range and quality of products and services that are available.
Although not explicitly outlined in the objectives of competition policy, the policy gave the governments the ability to balance the achievement of these aims with other considerations such as ‘social-welfare and equity issues, the interests of consumers, ecological sustainability and the efficient allocation of resources’ (2000). Consequently, National Competition Policy has been a vehicle for considerable environmental reform.

Where governments can demonstrate that they have met reform objectives outlined in the agreement, they become eligible for competition payments from the Federal Government. These payments form instalments of agreed annual Federal funding to the states and are often referred to as tranche payments.

Critical elements of the water reform framework include:

- All water pricing is to be based on the principles of full cost recovery and transparency of cross-subsidies;
- Any future new investment in irrigation schemes, or extensions to existing schemes, are to be undertaken only after appraisal indicates it is economically viable and ecologically sustainable;
- States and Territory Governments, through relevant agencies, are to implement comprehensive systems of water allocations or entitlements, which are to be backed by the separation of water property rights from land and include clear specification of entitlements in terms of ownership, volume, reliability, transferability and, if appropriate, quality;
- The formal determination of water allocations or entitlements, including allocations for the environment as a legitimate user of water;
- Trading, including cross border sales, of water allocations and entitlements within the social or physical and ecological constraints of catchments;
- An integrated catchment management approach to water resource management be adopted;
- The separation, as far as possible, of resource management and regulatory roles of government from water service provision;
• Greater responsibility at the local level for the management of water resources;
• Greater public education about water use and consultation in the implementation of water reforms; and
• Appropriate research into water use, efficiency technologies and related areas.

(Department of Agriculture Fisheries and Forestry, 2003)

3.25 National Water Initiative
At its meeting in 2003, the Council of Australian Governments (COAG) agreed to augment the water reform process with a National Water Initiative (NWI). The NWI aims to:

• Improve the security of water access entitlements, including by clear assignment of risks of reductions in future water availability and by returning over allocated systems to sustainable allocation levels;

• Ensure ecosystem health by implementing regimes to protect environmental assets at a whole-of-basin, aquifer or catchment scale;

• Ensure water is put to best use by encouraging the expansion of water markets and trading across and between districts and States (where water systems are physically shared), involving clear rules for trading, robust water accounting arrangements and pricing based on full cost recovery principles; and

• Encourage water conservation in our cities, including better use of stormwater and recycled water.

(Department of Prime Minister and Cabinet, 2003)

3.26 Water reform in Victoria
In 2003 the National Competition Council (NCC) reported that Victoria had satisfactorily addressed its urban water and waste-water pricing obligations under the reform process (National Competition Council, 2003). The Council found that Victoria had, in the main, addressed concerns about full cost recovery in the urban water sector through the adoption of a two-part tariff and that prices for water achieved at least the floor price for full cost recovery in
2002-2003. It had also increased cost transparency by reducing free water allowances, and had ensured water users across the state have a strong incentive to use water efficiently.

Full cost recovery, in regional-urban and rural areas was still to be adequately achieved; the Council found that rural water supply services are still progressing to full cost recovery.

In the north-west of Victoria, Wimmera Mallee Water has commenced two programs to replace the open channel system with pipelines. The aim is to reduce evaporation losses, freeing up water for other uses such as environmental flows. The Northern Mallee Pipeline Project, when completed, will free up almost 35,000 megalitres for the environment, while the proposed Wimmera-Mallee Pipeline Project could free up as much as 83,000 megalitres. (Wimmera-Mallee Water Entitlements Project Group, 2002).

As a component of water reform the Victorian government has undertaken to draw up water management plans for individual streams throughout the state. To this end the state has instituted a system of bulk entitlements, stream-flow management plans and groundwater management plans. Bulk entitlements are contracts with water authorities for the supply of water from regulated streams (streams in which flow is modified by releases from dams). Stream-flow management plans are agreements developed with stakeholder participation to manage flow in unregulated streams and groundwater management plans are being developed to manage regional groundwater supplies.

While the Bulk entitlements process is nearly complete for regulated streams in Victoria, only three stream-flow management plans have, so far, been completed out of the thirty-three plans that have been commenced or are still to be commenced (National Competition Council, 2003).

In its 2003 assessment, the NCC cited its satisfaction with the Victorian government’s then, recently published green paper (Department of Sustainability and Environment, 2003), which outlined the direction of water reform in Victoria.
‘Securing Our Water Future Together’ (Department of Sustainability and Environment, 2004c), otherwise known as the white paper, builds on the green paper and outlines the Victorian government’s direction for the future of water use in Victoria; specifically, the future of urban water, irrigation water and water for the environment. The white paper institutes a raft of relatively radical changes to water management in Victoria; including the establishment of an environmental reserve; that is a portion of the flow of all rivers in Victoria, which the government will manage, through the Catchment Management Authorities, on behalf of the environment.

Although the white paper contains a great deal of inexact language, such as ‘improve’, ‘investigate’ and ‘develop’, its direction is basically that determined by the federal government’s water reform agenda. That is, the main points of the white paper address full cost recovery, environmental water allocations, water rights, water trading, institutional reform, legislation reform, education and consultation.

Figure 3-8 Surface water development status (National Land and Water Resources Audit, 2001c)
Figure 3-9 Rural Water Authorities (Department of Primary Industries, 2003)

Figure 3-10 Groundwater management areas (Department of Primary Industries, 2003)
3.27 Current extent of surface water commitment

Figure 3-8 is a map produce by the National Land and Water Resources Audit in 2001 showing the development status of Victoria’s water supply (National Land and Water Resources Audit, 2001c). The classification can be considered as a general indication of the level of water commitment.

The areas of higher rainfall and lower evaporation south of the divide are generally assessed as having low to medium development status. In the southeast these areas correlate with areas of forest cover. These areas acted as a deterrent to original colonisation and, later, to efforts at closer settlement. In the west areas of low commitment correlate with the sparsely treed plains taken up by squatters in the 1830’s and fiercely held against the movement for closer settlement.

North of the divide the commitment level is assessed as fully developed. This is because, as part of the Murray Darling Basin area, it is subject to the so-called ‘Cap’ and it is assumed that no more water can be taken. This area includes the Goulburn Valley, the Murray Valley and other areas where soldier settlement schemes were most successful.

In the northwest, however, the Wimmera is given a special rating because of its extreme commitment. This is an area of huge success for the closer settlement movement. It is an area where massive expenditure created the Wimmera – Mallee Stock and Domestic Water Supply and brought water from the slopes of the Grampians north to where rainfall is low, precipitation is high and soil fertility is low.

3.28 Conclusion

The development of water management in Victoria was, then, the result of a complex chain of decisions taken in their social and political context. Important currents in the history of water resource development in Victoria include the desire for closer settlement, the political power of early squatters, the driving notion of the yeoman farmer, and, in recent times, the development of a global and regional perspective on resource development.

This management response to Victoria’s distinctive environment and historical development produced a unique pattern of resource development at the
regional scale. A network of open channels weaves its way through some of
the most arid parts of Victoria, huge reservoirs control the flow on the largest
rivers and irrigation channels pour water on land where salt sits ominously
below the surface.

In this context it is clear that management of water resources has not always
been conducted in the pursuit of the best environmental outcomes. When
water resource managers interpret measured water quality values, knowledge
of the history of management impacts at that location is essential.
CHAPTER 4. SUSTAINABLE WATER USE

4.1 Introduction
Chapter 3 outlined the way in which water management in Victoria developed as a result of decisions taken in the prevailing social and political context. However, at the core of current management decisions in Victoria is the consideration of sustainability. This chapter will address the water resources in Victoria from the broader perspective of sustainability. It will describe the development of the concepts that are at its basis, and outline how it applies to water and water quality in Victoria. Essentially, this chapter is addressing the fundamental question, what is sustainability, and how has it influenced our understanding of stream turbidity. This chapter will provide a backdrop for chapter 5, which will then specifically outline methods for measuring environmental health.

The concept of sustainable management of water resources has developed a new complexion in the last few decades. It will be shown in this chapter that in the past the management of water meant having enough water left from winter rains to supplement summer supply and in recent years it has begun to have more complex associations. Sustainable water use is now, almost universally considered to include maintenance of the environmental health of waterways, and by implication, the environmental health of the whole catchment.
This broadening definition of sustainable supply has ramifications for how water availability and quality are measured. The allocation of water for human use must now take into account sustainable management of water resources. The Australian Federal Government has adopted a policy of Ecologically Sustainable Development (ESD) (Environment Australia, 2001). Measuring water quality, which in past decades was a test of its fitness for particular human uses, such as irrigation and potable supply, is now entering a new phase where it is expected to reflect the wider concerns of ESD.

Within the framework of ESD, water quality and water availability are intrinsically linked. The question “how much water can be used?” must have the same answer as, “what level of water quality is acceptable?”. Any amount of water can be used, as long as the water quality, and by inference, the biological health of the catchment is acceptable.

Acceptable levels of stream turbidity in Victorian streams exist in a complex political and cultural context, not only, as shown in the previous chapter, does our understanding of water quality have a particularly Victorian context, but there is a national and global context that shapes the way we evaluate the quality of or water.

Before the thesis discusses methods for measuring environmental health in chapter 5, the following section will examine the complexity of meanings associated with this new national and global context and discuss how sustainability applies to measuring water quality and availability in Victoria.

4.2 What is sustainability?

The notion of sustainable development was first popularised in Our Common Future, a report to the World Commission on Environment and Development by Gro Harlem Brundtland in 1987. The report defined Sustainable Development as:

‘...development that meets the needs of the present without compromising the ability of future generations to meet their own needs.’

(Brundtland et al., 1990b, p87).

There are three key elements to this definition. It is focussed on the beneficial aspects of economic development. It defines the key objective of
intergeneration equity (natural resources must be left for future generations),
and it highlights a need for development to include a social dimension. The
report comments that:

“For far from requiring the cessation of economic growth, it [the report]
recognises that the problems of poverty and underdevelopment cannot
be solved unless we have a new era of growth in which developing
countries play a large role and reap large benefits” p84

The Brundtland report recognised the global importance of sustainable
resource use. It recognised the global responsibility for environmental
management and it recognised the need for global management of natural
resources. The report also underlined a view that sustainable development
must provide for the basic needs of people in developing countries; equity
must not only be intergenerational but intra-generational.

Dalal-Clayton (2000) asserts that the ideas behind sustainable development
began with the work of Malthus on population growth in the late eighteenth
century. The author traces the emergence of the concept of sustainable
development to the 1970s, with the publication of several important
documents including:

• How to be a Survivor: A Plan to Save Spaceship Earth (Paul Erlich
1971);
• The Limits to Growth (Meadows et al. 1972) by the Club of Rome;
• A Blueprint for Survival (The Ecologist, 1972) promoting a movement
for man to live with’ nature and calling for a stable (and sustainable)
society with a diversity of physical and social environments;
• Only One Earth (Barbara Ward and Rene Dubos, 1972) for the UN
Conference on the Human Environment in Stockholm in that year;
and
• Small is Beautiful (Schumacher 1973).

Rachel Carson’s 1962 book Silent Spring could also be added to this list.
There is one clear similarity between all these publications; they all take a
global perspective on the distribution and condition of natural resources and
the natural environment. The 1960s and 1970s represents a time when there was a growing awareness of environmental issues and a growing awareness of the complexity of the environment itself.

Dalal-Clayton (2000) suggests that prior to the articulation of sustainable development, global environmental concerns were focussed on the limits to resources; population, waste, energy; issues that surrounded industrial development and the rapid growth in resource consumption. Sustainable development, however, included a wider concern for the protection of fundamental human needs.

The foundations for this new way of looking at environmental management had been laid down in previous decades, but four developments, in particular, are fundamental to the articulation of Sustainable Development, the construction of a systems view of environmental connectivity, the discovery of complexity science, the growth of a global view of world resources and the increasing value placed on the intrinsic nature of the natural environment.

4.3 Complexity and systems thinking

As with other natural resources, the management of water resources occurs within a complex system of interdependent, and competing, ecological, economic and social forces. Water does not exist in isolation. When it is removed from the environment, or its flow modified, a complex array of ancillary effects is created.

Ludwig von Bertalanffy, considered the father of complex systems theory, outlined the developing General Systems Theory in 1950. In Bertalanffy’s (1950) view, many facets of biological, ecological and social activity could be explained as the interaction of systems and sub-systems. Bertalanffy’s aim in formulating General Systems Theory was to create a paradigm that could, according to Naveh (2000a), “create a unified scientific theory of integrative systems thinking’ and

‘provide a transdisciplinary view of the world that integrates and links cultural and ideological barriers, quantitative and normative approaches, and qualitative and descriptive approaches by cutting across narrowly
defined borders separated in traditional scientific disciplines’ (Naveh, 2000b).

In this way general systems theory offers the commonality of approach that enables the linking of ecological, economic and social systems. Unlike simple systems, complex systems are adaptive, contain non-linear relationships and contain feedback mechanisms. According to Costanza et al. (1993) ecological and economic systems are both complex systems. Costanza quotes von Bertalanffy (1968) and describes these complex systems as being characterised by:

‘Strong (usually non-linear) interactions between the parts; complex feedback loops which make it difficult to distinguish cause from effect; significant time and space lags; discontinuities, thresholds and limits; all resulting in the inability to simply add-up or aggregate small scale behaviour to arrive at large-scale results’ (Costanza et al., 1993).

From this perspective, the simple mechanistic relationships that are a hallmark of Newtonian, reductionist, approaches cannot begin to describe the system, in which the whole is more than the sum of its parts (Capra, 1997).

Doug Cocks (1999) draws a further distinction between complex adaptive systems and complex deterministic systems. In deterministic systems, interactions are linear rather that non-linear. Cocks reminds us that the distinctions between complex and simple or deterministic and non-linear are essentially open to interpretation. This is important because any model or measure of the natural world is an attempt to gather the important characteristics of a system and provide them in a form that is understandable. In deterministic systems the simplification is aimed at the mechanistic relationships between entities. In a complex, adaptive system the simplification is aimed at clarifying, what Capra (1997) calls ‘pattern, structure, and process’. There is always a level of simplification, and there is always some information obscured by aggregation and reduction. Complex systems theory is itself a simplification of what is really happening.

The system in which we interpret the significance of stream turbidity is one such complex system. The evaluation of turbidity is influenced by the
complexities of its ecological and geochemical context as well as its historical, social-cultural context.

In the measurement of water quality, traditional water quality measures including the measurement of turbidity were developed using a simple system approach. Assessing water quality based on potable supply, for instance, follows a deterministic understanding of water as either fit or unfit for its intended purpose. A complex systems view would see water quality in its wider context. A more complex understanding might try to understand the significance of turbidity in its ecological or geochemical context.

From the perspective of complexity, the first aim is to identify those structures that describe the system that provides the potable supply. Thus, the system might be divided into physical processes and biological processes, and important structures within those processes might be identified as the groundwater zone, the riparian zone, the wider catchment, the stream itself, the management regime and the pattern of use. A complex model could also be seen to model the linear and non-linear relationships between these components and show how the feedback from one component affects the initial state of the process, and how these relationships adapt over time to changing states. Measuring water quality from the complex perspective would, initially, require a qualitative assessment of some or all of the significant components in that system.

While water quality in Victoria continues to be monitored using the traditional physico-chemical measures of water quality, such as nitrogen, phosphorous, turbidity and electro-conductivity, there is some recognition of this more complex context, with the introduction of routine assessment of water quality using biological indicators (ANZECC & ARMCANZ, 2000). In particular, water quality is now regularly assessed in Victoria using the AUSRIVAS biological protocol (Metzeling, 2001). AUSRIVAS seeks to measure the intactness of macro-invertebrate communities within streams, when compared to pristine reference sites.

This kind of monitoring is a direct response to the newly developed appreciation of complex systems. The relationship between macro-
invertebrate communities and water quality is not deterministic: insects do not make potable water. However, they are an important component of the complex system that makes potable water.

Even though pattern, structure and process provide more information about complex systems than the mechanistic relationships, they are still only simplified representations. A model of an ecosystem which reflected the true level of complexity would probably be so complex that interpretation would be difficult. However, a model that attempted to capture only the important patterns, structures, and processes would need to sacrifice much detail.

The choice of a system description must suit the purpose of the modelling. Identified most often in the literature at the global scale is the broad separation of social, economic and environmental systems. The basis for their use can be seen in their distinguishing sets of values. In economic systems value is expressed in monetary terms. In social systems value is expressed in terms of welfare or standard of living, and in environmental systems, ecological health and biophysical integrity are the currency.

### 4.4 Complexity and environmental health

Historically, water resources in Victoria, as in many other places, were managed, predominantly, as a simple system. In this simple system, the available water was assessed with reference to the concept of divertible yield. Divertible yield is a simple-system concept based on the idea that the availability of a water resource can be determined as a product of mechanistic relationships between hydrological variables.

The Australian Water Resources Assessment 2001 (National Land a Water Resources Audit, 2001b) describes divertible yield as the:

‘…average annual volume (ML) that could be diverted using both existing and potential infrastructure and under an ultimate level of infrastructure development scenario - making no allowance for environmental water requirements.’ (National Land a Water Resources Audit, 2001b)

It is common now to differentiate between divertible yield and sustainable yield. The Australian Water Resources Assessment 2001 makes it clear that sustainable yield of water resources is the:
‘...average annual volume that can be abstracted for use, taking account of environmental water provisions’ (National Land a Water Resources Audit, 2001b)

In 1992 that Council of Australian Governments (COAG), for the first time, required formal allocations of water to the environment. In 1962 Speedie (1962), however, had only one concept for describing potential water resources:

‘The total supply available … is the capacity of the storage, plus river flow during the period, less evaporation loss during the period.’ (Speedie, 1962)

From the perspective of Speedie the limiting factors on water use are the amount and variability of rainfall, evaporation, storage capacity and the distribution cost. From the simple system perspective environmental health is not a limiting factor but, purely, a determinant of water quality.

From the complex perspective, no water can be used without influencing or being influenced by other components in the system. While water managers strive to meet community demands for the welfare provided by water, the limits of environmental health are commonly reached well before either the welfare is reduced or the increasing marginal price of water forces the user to seek alternatives. Traditionally, the availability of water has not been linked to changes in environmental health. And, until the recent arrival of metrics such as AUSRIVAS, there has been little scientific research to provide the link between water use and environmental outcomes.

The limits to acceptable environmental health were reached in 1991 with the, now infamous 1000km long algal bloom in the Murray–Darling River basin (see figure 4-1 and Figure 4-2). Water allocation in the Murray–Darling had been increasing rapidly in recent years, almost doubling between 1960 and 1994 (Figure 4-2). It seems that water allocations had been made with little or no assessment of the capacity of the river system to cope with these massive withdrawals. Allocations had been made assuming that the quantitative measure of resource availability represented the limit to water availability; there was still water in the rivers. When community and scientific uproar led to the Cap on water diversions from the Murray-Darling, it was clear that an
environmental limit had been reached. Importantly, the wider community were exposed to the idea that environmental health, and not flow volume, represented the finite limits of water use in the Murray-Darling system. Although algal blooms are a natural part of the Murray–Darling ecology, the scale of the 1991 bloom prompted a massive rethink of environmental management in the catchment and throughout Australia. In 2001 an inquiry into the allocation of water resources in Victoria found that, although the finite nature of water resources represents a limit to water use:

`Before these limits to consumptive use are reached, other limitations in the form of environmental degradation and excessive conflict between competing uses will be evident. …Victoria cannot continue to increase its consumptive use of water indefinitely. It would “hit a brick wall” if development of water use continued along past lines, with: “social conflict occurring because of high financial costs and extensive environmental damage.” (Environment and Natural Resources Committee, 2002, chapter 2.52).`

If environmental damage poses a significant limit to water use, then environmental health could also be used as an important indicator of water availability. Clearly, system components that control environmental health are important indicators of system structure, and the integrity of their pattern and processes are important indicators of sustainability.

The health of a waterway is not only influenced by water abstraction or modification to flow, it is also affected by land use within the stream’s catchment. There are indications, discussed earlier, that historical changes in land use within Victoria’s catchments caused massive changes to water quality. While algal blooms can be one symptom of environmental pressure on water resources, changes in stream turbidity can also be caused by increased pressure on water resources. However, unlike algal blooms turbidity is directly related to land use within the catchment.
Toxic algae: a 1000km disaster in our rivers

by ASA WAHLQUIST
Rural Reporter

An immense algal bloom, believed to be the biggest recorded in Australia, if not the world, has exploded along the Darling/Barwon River System. The bloom, which started to form about a month ago, is toxic in pockets and stretches 1,000 km from Mungindi on the Queensland border to Wilcannia. The Minister for Natural Resources, Mr. Causley, said the bloom was a national disaster and the army might have to be called in to help ship water to isolated areas. The Department of Water Resources issued a warning to residents along the river yesterday to avoid contact, drinking or cooking with the water. Scientists were flown over the length of the bloom at the weekend. Dr. Lee Bowling was shocked at the colour of the river which is normally turbid and a milky tea colour. "Most of the way it looked like an emerald green river running through dry landscape. I've never seen anything like it," he said. The colour was produced by giant blooms of the blue green algae Anabaena. The algae can produce a toxin that kills stock and is believed to attack the human nervous system, causing respiratory distress and death by suffocation, skin problems and gastroenteritis. It can also affect the liver. (Sydney Morning Herald, 22.11.91)

Figure 4-1 Toxic algae: a 1000km disaster in our rivers. From Environmental Education As a Weapon: The Importance of Contextual Knowledge in a Rural Community (Mahony, 1996)

Figure 4-2 Annual water diversions from the Murray River (Environment and Natural Resources Committee, 2001a)
4.5 The global view

With or without the formalised concept of sustainability, there have been two major developments in the way wealthy western communities view the environment. Firstly, there has been a growing awareness of the potential global environmental implications of the local use of natural resources. Secondly, there has been a growing sense that the intrinsic value of the environment to the community is growing in relation to the value placed on economic growth.

The State of the Environment Report of 1996 made the new global perspective clear when it states that:

‘We now recognize that we are part of a global ecosystem and an increasingly integrated global economy. This poses a new set of questions for sustainable development. Issues such as ozone depletion and climate change demand global responses. International action is succeeding in reducing the use of ozone-depleting substances.’ (State of the Environment Advisory Council, 1996)

As Schmidheiny (1992) comments, ‘During the first great wave of environmental concern in the late 1960’s and early 1970s’, most of the problems seemed local’ but ‘When the environment re-emerged on the political agenda in the 1980’s, the main concerns had become international: acid rain, depletion of the ozone layer and global warming’.

4.6 Instrumental and intrinsic environmental values

Simultaneous with this increased globalisation of environmental concern has been the rising consideration of environmental value in wealthy nations. Economists have traditionally described environmental value as either instrumental, that is, value assigned to economic services provided by the environment or, so called intrinsic values, existence value, option values and bequest values. These values, described by Thomas (2001) and Postel and Carpenter (1997) attempt to ascribe economic value to non-market environmental values. While instrumental values might include the value of irrigated crop production or the provision of clean drinking water, intrinsic values might reflect the value placed on the existence of an ecosystem, the option to enjoy that ecosystem or knowing that future generations will have
access to that ecosystem. Because intrinsic value can be based on the perception of environmental intactness, they may be reduced even if the instrumental function is still fulfilled. Intrinsic environmental values can only really be explained with reference to the metaphysical or aesthetic properties ascribed to environmental phenomena.

There has been a clear growth in the view that the natural environment has intrinsic value. The State of the Environment Report 1996 comments that ‘Environmental awareness has increased dramatically in the past decade, penetrating all sections of the community’ (1996). While the State of the Environment Report 2001 concludes that

‘It is only in the last 30 years that many Australians have developed a renewed commitment to a conservation ethic. Yet what has emerged is a very complex and contradictory set of attitudes and processes … there is a powerful and growing desire to pass on to the next generation a land in better shape than was inherited ‘(Australian State of the Environment Committee, 2001, p4).

On their Biodiversity website (2004a) the Department of Environment Heritage state that ‘Many Australians place a high value on native plants and animals, which contribute to a sense of cultural identity, spiritual enrichment and recreation’.

While methods such as opportunity cost and contingent valuation are commonly used to measure intrinsic values (Beder, 1997), change on the scale of decades is difficult to measure in any empirical sense. However, an increase in intrinsic environmental valuation is evident throughout the 20th century, not only through the development of phenomena, such as the Green Movement, but in the characteristics of broader public policy.

Geoffrey Blainey (2001) identifies the decade of the sixties as the turning point in Australia, with the appearance of the so-called green agenda. He points to the 1972 election of Gough Whitlam as a starting point from where environmental issues began to enter the political sphere. This enabled intense battles over
‘...the endangered Lake Pedder in Tasmania, the sand dunes of Fraser Island in Queensland, the wetlands around Kakadu in the Northern Territory, and the wild and tumbling Franklin River in Tasmania. As a result of these debates, large areas of Australia were protected as national parks and nature areas.’ (Blainey, 2001)

While Blainey identifies ‘natural beauty’ as the intrinsic environmental value at the source of these battles, instrumental valuation has also been used to offer a defence against exploitation of environmental resources. In particular, recent claims have been made that environment may be given instrumental value by calculating the contribution to human welfare in the form of ecosystem services (Daily, 1997b).

It is through the concept of systems theory and complexity that intrinsic valuation of the environment becomes indistinguishable from instrumental valuation. In this complex view, the existence of the environment can have value because it provides services that are necessary to the survival of humanity. Complexity links the local to the global. This linking has helped blur the boundaries between intrinsic and instrumental value allowing environmentalists to use rational arguments to support irrational, intrinsic, value.

Gretchen Daily’s (1997a) ecosystem services approach, for instance, argues that instrumental values can account for environmental losses. The ecosystem services approach attributes economic value to environmental phenomena based on the value of their replacement costs.

4.7 How is sustainability measured in Australia?

Sustainable Development is, fundamentally, a measure of future resource availability. It is a new form of measurement that takes into account the ramifications of resource use in the global context. And, as has been discussed, it takes into account a systems view of environmental connectivity, the perspectives of complexity science, and the intrinsic value of the natural environment.

From a simplistic point of view, resource use is either sustainable or not sustainable. Logically, a resource cannot be partly sustainable. In the real
world, however, resource availability is a decision problem that requires the balancing of a multitude of competing perspectives, and requires tradeoffs between environmental integrity and social and economic imperatives. While, it is unlikely that in such complex decision problems all stakeholders could agree totally, management decisions must still be made. A strict application of sustainable resource use would mean that use that alters the ongoing state of natural resources cannot be sustainable. However, declining environmental conditions demand a management response that considers the real world. A management response that sought to stop all modifications of the natural environment would not get far.

One response to this dilemma is the pressure-state-response (PSR) model adopted for State to the Environment Reporting (Department of the Environment and Heritage, 2001). This method, developed by the Organization for Economic Co-operation and Development (OECD) seeks to identify environmental pressures which result from human activities, assess the current state of the environment and document responses to those pressures (OECD, 2003). The PSR method has been widely used to structure assessment of environmental phenomena by identifying key indicators, which in turn can be measured to assess the relative quality of environmental sustainability (Vitalis, 2001). Critically, this method avoids classification of resource condition as sustainable or not sustainable; however, it still remains necessary at some point to make quantitative assessment of resource condition.

Many would argue that sustainability is a rubbery term for which there are innumerable meanings. It is not the intention of this thesis to discuss at length the varied understandings of sustainability. Many authors, for example Holdren et al. (1995), Sutton (2000) have discussed, at length, definitions of sustainability. In fact, the nature of sustainability seems to leave a host of questions that need to be answered, and which, in the eyes of some, are its weakest point. At what temporal scale should sustainability be assessed; is short-term depletion acceptable? Should resource managers wait for the symptoms of un-sustainability before they act? Does sustainability mean that no resources should be degraded over time, or does it mean that future
generations should have the same opportunities, regardless of resource condition? What scale should sustainability be measured at; is local depletion acceptable amidst regional abundance? Should sustainability be measured at catchment, political boundary or some other scale? Who should decide when something is sustainable?

These questions reflect the fact that sustainability is specific to its cultural, environmental and economic context. In the Australian context, the adoption of ESD has attempted to provide guidelines to answer some of these questions. The National Strategy for ESD describes ecologically sustainable development as:

'using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased' (Environment Australia, 2001).

The ESD process began in Australia in 1989 as a formal government initiative aimed at bringing the question of sustainable development into institutional decision making. Nine working groups were established after a summit of industry, union and conservation groups. The working groups identified key problem areas and attempted to find solutions that would meet environmental, economic and social goals. In 1992, the year of UNCED and the year of the 1000 km algal bloom, the work of the ESD process was presented as the National Strategy for Ecologically Sustainable Development (NSESD) (Department of Environment and Heritage, 2002). The NSESD outlines seven guiding principles:

1. Decision making processes should effectively integrate both long and short-term economic, environmental, social and equity considerations.

This is recognition that temporal and systems complexity are to be important elements in any resource decision. In fact, this first principle represents a radical approach to natural resource management. Bradbury (2000) considers Complex Systems Science to be a Trojan horse for a subversive new scientific understanding of the world. To Bradbury (2000), Sustainable Development is really about finding a palatable way to get a hearing for some
very subversive ideas. Considering resource use in the economic, environmental and social milieux is a subversive idea from complexity science.

2. *Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.*

Sometimes called the precautionary principle, this is recognition that lack of knowledge of a system should not be used as an excuse that sanctions long term degradation of resources. This approach has been criticised for being too fuzzy and undefined. Chase (1997), for instance, criticises the approach because acting with uncertainty can have uncertain outcomes. Chase (1997) gave some examples from the US where the precautionary principle has been applied and unexpected consequences have ensued.

3. *The global dimension of environmental impacts of actions and policies should be recognised and considered*

This is clear acknowledgment that local resource use has global implications; the Australian environment cannot be considered as detached from the global environment.

4. *The need to develop a strong, growing and diversified economy which can enhance the capacity for environmental protection should be recognised.*

With parentage that can be traced back to the Brundtland report this principle makes it clear that economic growth is to be considered the cornerstone of sustainable resource use. This is, perhaps, the one point that has enabled Sustainable Development to become such a powerful concept.

5. *The need to maintain and enhance international competitiveness in an environmentally sound manner should be recognised.*

6. *Cost effective and flexible policy instruments should be adopted, such as improved valuation, pricing and incentive mechanisms*
This is recognition that the global marketplace is not necessarily a fair marketplace. While sustainability might require higher valuation of environmental assets, it shouldn’t prevent tariffs and subsidies being used to maintain international markets.

7. Decisions and actions should provide for broad community involvement on issues which affect them.

This is recognition that the appropriate balance between social, environmental and economic values is dependent upon the local cultural, historical and political context.

4.8 What is being sustained?
As discussed in chapters 2 and 3, the Australian and Victorian landscapes are, to a large extent, modified from their state before European colonisation. The stated aim of ESD, which includes ‘conserving our ecosystems for the benefit of future generations’, (Department of Environment and Heritage, 2004b) seems to be too late for most of Australia and Victoria. This highlights what is a clear divergence between the policy of ESD and the Australian experience.

The State of Environment 1996 clarifies the aim of ESD and elaborates saying that:

‘Sustainable development requires the maintenance of the following three key components of the environment:

- Biodiversity: the variety of species, populations, habitats and ecosystems
- Ecological integrity: the general health and resilience of natural life-support systems, including their ability to assimilate wastes and withstand stresses such as climate change and ozone depletion
- Natural capital: the stock of productive soil, fresh water, forests, clean air, ocean, and other renewable resources that underpin the survival, health and prosperity of human communities.’

(State of the Environment Advisory Council, 1996)
These components represent global or regional scale environmental attributes. However, in Australia it is more common to assess the relative health of environmental phenomena at the local scale by comparison to pristine natural environments that resemble states prior to European colonization. Dostine (2002), for instance, describes ecological health as ‘similarity to a pristine, undisturbed state’.

Evaluating turbidity in this context would require some knowledge of turbidity levels prior to European intervention in catchment processes.

The Brundtland report accepted that not all parts of the landscape could be preserved in pristine condition. The report states that ‘A forest may be depleted in one part of a watershed and extended elsewhere’ (Brundtland et al., 1990a p89). However, pristine environments cannot be extended. This represents an unresolved issue in environmental management in Australia. Biodiversity, ecosystem integrity and natural capital can each be described in ways that enable economic growth to contribute to their extent; but economic growth cannot bring back pristine environmental values.

The pursuit of ESD has clear consequences for the measurement of water quality, availability and water management. An assessment of quality must take into account complexity, it must take into account the global and regional perspective, and it must consider the likely ramifications on intrinsic environmental value.

4.9 Communicating spatial distribution

It is apparent; with this amazing complexity, that water quality and availability have a substantial spatial distribution. Indications of water availability commonly used, including the level of water in impoundments, for instance, are generalisations of complex ecological, social and economic criteria that allow a quantity of water to be removed from the natural environment and impounded. These criteria, however, have a distribution throughout the catchment and, in some cases, external to the catchment and not just at the source of extraction.

The terrestrial stage of the water cycle can be described in terms of flow, storage and water quality. The flow of water can be parameterised by
characteristics of overland flow, groundwater flow and in-stream flow. Storage can be described by the characteristics of groundwater storage, in-stream storage and impoundment. In each of these phases water can, then, be described in terms of human intervention: intervention in patterns of flow, storage and water quality.

Using this descriptive paradigm, the term ‘user’ can be seen to include those involved in any pattern of land use that impinges on water availability by altering flow, storage or water quality. Use is any activity that materially alters the natural qualities of flow, storage or impoundment. Effectively, land use is water use.

Clear terminology is needed because terms like ‘consumer’ that are commonly used in relation to water are not adequate. Water is not consumed. When it is taken from a stream or bore it does not become invisible. Its location changes, its flow and storage and quality are modified.

It follows, then, that any space that can be described by land use can be described by its contribution to sustainable water use. Economic, social and environmental forces influence the flow of water at all places within a catchment. Any location within a catchment can, then, be assigned a state of environmental health based on the level of human intervention in water flow, storage and quality.

4.10 Conclusion

Where once sustainable management of water meant having enough water left from winter rains to supplement summer supply, in recent years it has begun to have more complex associations. Sustainable water use is now almost universally considered to include maintenance of the environmental health of waterways, and by implication, the environmental health of the whole catchment. Measuring water quality, which in past decades was a test of its fitness for particular human uses, such as irrigation and potable supply, is now entering a new phase where it is expected to reflect the wider concerns of ESD.

The new concepts that sustainability brings with it include, the global importance of sustainable resource use, the global responsibility for
environmental management and the need for global management of natural resources. Four developments, in particular are fundamental to the coming of ESD: the development of a systems view of environmental connectivity, the discovery of complexity science, the growth of a global view of world resources and the increasing value placed on the intrinsic nature of the natural environment.
5.1 Introduction

Chapter 4 outlined the development of sustainability as a concept. It argued that sustainability is founded on an increasing global perspective of the natural world. Coupled with this growing global perspective, has been the development of a systems view of environmental connectedness, the growth of complexity science, and an increase in the intrinsic valuation of environment by major western societies. Chapter 4 also outlined how the measurement of available water is interdependent with the assessment of environmental health. This has significant consequences for the measurement of future water resource availability.

This chapter will begin by discussing how environmental health is increasingly being considered as the determinant of water availability. It will then define terms that are associated with environmental health and survey various methods for defining environmental health relevant to water resources. The objective is to identify those attributes of environmental health that best suit the measurement of sustainable water resources at the regional scale and against this examine the efficacy of stream turbidity as an indicator of stream and catchment health.
5.2 Environmental health – the limit to water use.

An outline of Victoria's water resources in 1962, 'Water Resources of Victoria', made no mention of the environmental consequences of water supply development (East, 1962). To the authors of this report, the difficulties of providing adequate water storage were purely the economic difficulties imposed by rainfall variability and the challenge of calculating potential catchment yield.

Apart from the economic considerations, Horsfall (1962) in the same report, describes the aim of water management as water conservation. That is, conservation of excess water from times of plenty to augment water needs in times of drought. Horsfall describes the total supply available for use as a proportion of the total storage (over an unspecified 'prolonged dry period') plus river flow during the period, less evaporation loss.

Thirteen years later, a report in 1975, 'Review of Australia’s Water Resources' claimed that Australian attitude to water resources management had changed in the preceding two decades. Water management was no longer just to be seen as storing water and regulating streams, but was now to be seen as

‘…conserving unregulated streams in an unmodified landscape for wildlife preservation or recreation purposes, or for possible social or economic use by future generations’ (Australian Water Resources Council, 1976).

The report also claimed that there was an increased public awareness of 'non-consumptive and on-site uses of water' in environmental inquiries associated with major water storage projects in Australia.

This report states that only 24% of potential divertible yield had been committed up to the report publication. Three reasons are given for the low commitment of water resources. Firstly, the economic resources of the country were not yet fully developed, secondly, many potential developments were too expensive and, thirdly, the bulk of potential developments were remote from population centres in the tropical north and Tasmania. Environmental considerations were not mentioned as a brake on available water.
A report in 1991, ‘Water Victoria: The Next 100 Years’ (Department of Conservation and Environment - Victoria, 1991), recommends that water resource use should be managed to attain sustainable development. To do this there has to be a balance struck between economic, hydrologic, and environmental values. In this report, the environment is to be considered as a competing value on an equal footing with economic considerations.

By 1992 a report into potential storage sites in northern Victoria concluded that all 26 sites considered were perceived to have environmental problems (Department of Water Resources, 1992). The report ominously concludes that further environmental studies were needed before any further development of water resources should take place, and that these studies would, most likely, increase previously identified costs, and that before any development takes place these costs should reach the market price of water. The inference was that the price of water was far too low. However, not only was the price too low, there were potentially high environmental costs that would somehow have to be factored into the cost benefit analysis of any new water developments.

In 2001 the Australian Water Resources Assessment (National Land and Water Resources Audit, 2001b) concluded that ‘26% of Australia’s 325 surface water management areas are either close to or overused when compared with sustainable flow regime requirements’.

These reports represent the outline of a trend, from colonial times, through the post war boom in resource development, to the modern era of water reform. In colonial times, environmental problems were largely ignored as an element in water resource management, then in the late 60’s and 70’s the notion of environmental value crept into water resource planning: the environment had to be considered. The intactness of an unmodified landscape was seen as having premium environmental value. However, the environment was still only one of many competing elements in water resource planning, even up until the early 1990’s. Following the early 1990’s, the environment became the major consideration in water resource planning and, in particular, environmental health became the major determinant of water availability. When the Australian Water Resource Assessment concluded that a large number of
surface water areas were overused, it did not mean that water had stopped flowing, it meant that environmental condition had declined or was declining. The report clearly states that a sustainable flow regime is:

‘The limit on potentially divertible water that will be allowed to be diverted from a resource after taking account of environmental values and making provision for environmental water needs.’ (National Land and Water Resources Audit, 2001b)

From this view, environmental values must precede the satisfaction of other uses of water. A specific portion of the water resource must now be allocated to the environment.

5.3 Environmental flows
The establishment of environmental flows is an area that seeks management solutions to the problem of poor environmental condition. Environmental flows are solutions mostly aimed at regulated streams, where the natural pattern of flow is extensively controlled by upstream diversions, and impoundments. Ladson (2002) defines environmental flows as water managed specifically to meet environmental needs, while Dyson et al. (2003) describe an environmental flow as:

‘… the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated.’ (Dyson et al., 2003 p3).

Methods aimed at identifying environmental flows attempt to find a relationship between the flow of a river and some component of the stream supported ecosystem. Schofield et al. (2003) categorise methodologies for establishing environmental flows into four categories: hydrology based approaches, hydraulic rating methodologies, habitat simulation methodologies and holistic methodologies. Figure 5-1 contains general descriptions of these methodologies.
**Environmental Flow Methodologies**

**Hydrology-based approaches** usually rely on the use of historical hydrological data, and are often referred to as fixed percentage or standard-setting methodologies. They assume that the provision of some proportion of the natural flow regime will maintain sufficient of the required hydraulic habitats, and therefore the fishery or other desired ecological feature. They frequently attempt to define a ‘minimum flow’. Expert judgment is often incorporated to increase the quality of the assessment.

**Hydraulic rating methodologies** use rated river cross-sections to measure changes in hydraulic parameters such as depth or wetted perimeter with changing flow, and relate these changes to increased or decreased habitat availability.

**Habitat simulation methodologies** use multiple cross-sections to model habitat changes, usually in terms of depth, velocity and substratum types, and may be linked to habitat preference measures for selected biota.

**Holistic methodologies** are designed to evaluate ecosystem requirements, in contrast to most of the environmental-flow-assessment methodologies described above which aim to assess the flow requirements of individual species or ecological components. Holistic methodologies employ groups of specialists from different disciplines (e.g. fish, invertebrate and riparian vegetation biologists, social scientists, geomorphologists and hydrologists) and the final assessment is a consensus view of the flows that are needed to meet the requirements of a variety of critical species and components.

Figure 5-1 Environmental flow methodologies: after Schofield et al. (2003)

In the Australian context, Arthington (1998), in particular has described the need for an holistic approach to environmental flows. According to Arthington, a holistic approach aims:

‘...to assess the water requirements of the complete ecosystem, including such components as the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary, as well as any particularly important features such as rare and endangered species.’ (Arthington, 1998)

It is not the intention of this thesis to survey the complex area of environmental flow methodologies in any more depth. The point to be made here is that to establish environmental flow methodologies, a decision still has to be made about the relative environmental health of a particular stream.

Schofield et al. (2003) comment that:

‘...the consequences of flow reduction for a fish community can be assessed by scientific investigation but the decision as to whether those impacts are acceptable is one for society. ... At some stage, someone or some group has to decide which option will be implemented.’ (Schofield et al., 2003)
At some stage, someone has to decide which state of flow is qualitatively better than another.

5.4 What is environmental health?
Water quality is inextricably linked with measures of environmental health, and acceptable levels of environmental health, both socially acceptable and economically acceptable, dictate water availability. But what is environmental health? A quick survey of situations in which degrees of environmental health are articulated reveals that its meanings are heavily context dependent. A number of terms have been used to identify specific system structures that suit the needs of the studies at hand. At its core, however, environmental health is a generic term for the qualitative state of those parts of the biogeophysical world that are external to the human cultural world. The term ‘health’ implies a qualitative measurement, metaphorically suggesting that environmental states can be compared to states describing human health. Karr (1999) surveys literature in this area and comments that there are some who would argue that health was an inappropriate metaphor for environmental condition. In particular, Scrimgeour and Wicklum (1996) believe that health is an inappropriate term because no objective ecosystem state can be stated as better than any other. Karr (1999) claims, however, that health is a useful term because it is a concept that all people are familiar with. This means, as a policy goal, it has ‘at least some chance in engaging public interest’ (Karr, 1999 p223). In the Australian context it is common to describe ecosystem health in terms of the difference between current states and a state prior to European colonisation. The argument that no ecosystem state can be seen as better than any other can only be carried if there were no commonly held natural states for comparison.

5.5 Measuring environmental health
Fundamental to measures of environmental health is the need to make judgements about the level of human interference with the workings of the environment. The term, environmental health, presupposes that changed environments are unhealthy and that human interaction with the environment is pathological.
The need for measures of environmental health is, more practically, driven by the requirement for managers of the environment to make qualitative judgments based on quantitative data. Quantitative measurements of environmental condition assist with the management of this human-environment interaction by providing descriptions of optimal conditions, or baselines, and enabling the degree of change over time to be stated.

However, to complicate this situation, regardless of the nature of quantitative data available, there is little common agreement on what constitutes good environmental health, and the criteria for the assessment of environmental health have changed in recent times. In regards to water, Schofield and Davies (1996b) comment that changing community perceptions of the values and appropriate uses of rivers have meant that concepts such as biodiversity and wilderness have been added to traditional values such as navigation, drinking water, irrigation, effluent disposal and recreation.

These new values, encapsulated in the Australian Government’s policy of ESD (Environment Australia, 2001), have given birth to a plethora of measures of environmental health that seek to include environmental values into assessment of water quality and seek to broaden the assessment of water quality to include the wider biophysical context.

Where, appropriate chemical and physical measures of water for drinking can be stated as absolute values of bacterial counts or suspended solids, absolute values for what constitute appropriate levels of environmental health are not so easy to quantify. Commonly, biological and physical assessment of appropriate conditions is given as rankings of comparative health when compared to some idealized environmental condition. There are a number of these measures and they each have a different focus depending on their management purposes.

5.6 Ecological health

Ecological health, for instance, focuses on the biotic component of the environment. In this context, the physical environment is seen as habitat. Dostine (2002) describes ecological health as ‘…similarity to a pristine
undisturbed state' and considers measures of in-stream biota as relevant to the ecological health of rivers.

According to Deeley and Paling (1999) ‘ecological health can be defined as the maintenance of the structural and functional attributes including natural variability and succession, of a particular ecosystem’.

5.7 Ecosystem health

Central to the meaning of ecosystem health is a focus on a systems view of ecology. Ecosystem health clearly relates to the integrity of relationships within the system and includes relationships to other systems. The origin of the term ‘ecosystem’ has been attributed to Tansley (1935). Tansley commented that:

‘...the whole system (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome. . . . It is the systems so formed, which, from the point of view of the ecologist, are the basic units of nature on the face of the earth.... These ecosystems, as we may call them, are of the most various kinds and sizes. They form one category of the multitudinous physical systems of the universe, which range from the universe as a whole down to the atom.’ (after (Lindeman, 1942)).

As Tansley suggests, systems thinking was first borrowed from physics and then applied to the biological world. It is this linking of the language of traditional science with the language of ecology that is the ecosystem approach. Lindeman (1942) described an ecosystem as:

‘...all those physical, chemical, and biological processes in a space-time continuum of any magnitude.’ (Lindeman, 1942)

An ecosystem, in this context, integrates, not only the language of traditional science, but it integrates realms of the biotic with the abiotic and it integrates these phenomena at any scale. Ecosystems can be thought of as nested systems that can be viewed at a range of scales.

The ecosystems approach has in recent times more comprehensively borrowed its language from systems thinking and, specifically, from the
theories of thermodynamics. Odum’s 1971 definition of ecosystem includes a much more specific reference to energy flows and material cycles:

‘Living organisms and their nonliving (abiotic) environment are inseparably interrelated and interact upon each other. Any unit that includes all of the organisms (i.e., the "community") in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (i.e., exchange of materials between living and nonliving parts) within the system is an ecological system or ecosystem.’ (Odum, 1971).

A measure of ecosystem health would then attempt to establish a qualitative assessment of the mechanistic function of ecosystems.

## 5.8 Measuring ecosystem health

While the theory of ecosystems is well advanced, the science of how ecosystems function is at a primitive stage, and establishing levels of health based on measurable system function is also at a primitive stage. Costanza (1992) surveys definitions of ecosystem health and summarizes them as:

- Health as homeostasis – (Maintenance of steady state in living organisms by use of feedback control processes.)
- Health as the absence of disease
- Health as diversity or complexity
- Health as stability or resilience
- Health as vigour or scope for growth
- Health as balance between system components

(Costanza, 1992)

In this seminal paper, ‘Toward an operational definition of ecosystem health’, Costanza examines these differing perceptions of ecosystem health and concludes that a healthy ecosystem can be defined according to system vigour, organization and resilience.

According to Costanza, vigour is the measure of system activity, metabolism, or primary productivity, while organisation is the relative degree of the systems organisation, including diversity and connectivity, and resilience is
‘the ability of the system to maintain its structure and patterns of behaviour in the face of disturbance’ (Costanza, 1992).

Implicit in the meaning of system resilience is a preferred state, or normative condition. Therefore, the first question to be asked in any assessment of system resilience must be ‘what is the normative condition?’ and from a management perspective, ‘what is the environmental goal?’ Hannon (1992) believes that to gain any consensus on ecological health, it must be assumed that the ecosystem has a preferred state.

From a practical perspective, to know how a system is organised, managers need to know the normative state and how the system is responding to perturbation, and to know about system resilience, managers, again, need to know the normative state, degree of system perturbation and the trend in system change.

Indicators, on their own, provide little without reference to a normative state. While an understanding of current conditions is not meaningful without reference to a normative state, while any trend in ecological change must be placed in the context of a normative state to assess the relative importance of that change.

Figure 5-2, from Costanza (1992), provides an example of how measures of environmental condition can include direct indicators of environmental condition, endpoints, or composites of these indicators, or measures of health based on multimetric values of environmental health (Costanza, 1992). The figure shows how the progression toward a values-based measure of health produces increasing difficulty, but is increasingly comprehensive and increasingly relevant when compared to simpler indicators and endpoints. A values based assessment of health implies a normative state. While Costanza (1992) points to an increasing relevance of these overall health values, one thing is being told the environment is sick, but these multimetric approaches do not explain why the environment is sick.
5.9 Ecosystem integrity

De Leo and Levin (1997) outline the advantages of focusing on levels of ecosystem integrity. In particular, the authors eschew the health metaphor because they feel that it reflects a simplistic approach to ecosystems, first articulated by Frederick Clements at the beginning of the 20th century. This Clementsian view sees individual biological organisms as a blueprint for the function of individual biological communities; that is, the biological organism and the biological community are both constantly striving for an equilibrium state. However, the authors point out that dynamic processes within ecological communities are in a constant state of change, and that a normative state is difficult to define. This is an echo of the earlier paper by Costanza (1992), who argues that it cannot be assumed that all change is bad, that nature is in a constant state of adjustment, change and succession and this state of flux is a normative state.
Ecosystem integrity supposes that ‘various genetic, competitive, and behavioural processes (rather than states) are responsible for maintaining the key features of observed ecosystems’ (De Leo and Levin, 1997). Measures of integrity must accept that ecosystem states are dynamic, and that the dynamics of those processes vary with scale.

5.10 Stream health and river health
Measures of stream health might contain aspects of both biotic and physical health. Measures of stream health focus on the stream separate from its catchment. According to Schofield and Davies (1996b) river health (stream health) ‘is the degree of similarity to an unimpacted river of the same type, particularly in terms of its biological diversity and ecological functioning’.

This methodology, commonly used for assessing relative environmental health is called referencing. Referencing uses ideal sites, or reference sites as they are called, to establish the normative state of environmental health. Sheldon and Thoms (2000), for example, describe a system of referencing applied to patterns of stream flow in large dryland rivers. Normative states of flow are deduced from least impacted rivers and compared to other, similar, streams. The AUSRIVAS index and other bioassessment tools detailed in section 5.17 also use reference conditions to measure the level of environmental health. According to Dallas (2000) an ecological reference condition is:

‘...the condition that is representative of a group of “least-impacted” or minimally-disturbed sites organised by selected physical, chemical and biological characteristics’

A limitation with river health is that it is focused so completely on the health of the riverine environment. It treats the river as an object that is separate from the catchment.

5.11 Catchment health and Integrated Catchment Management: the holistic approach.
Compared to river health, measures of catchment health offer a more holistic, integrated, assessment of environmental health. In measures of catchment health water is still the focus, but the emphasis is on catchment wide
conditions. These conditions, although indirectly related to the hydrological properties of the catchment, conceptually link the impact of all human activities within the catchment to their hydrological consequences.

Catchment health is closely linked to the concept of Integrated Catchment Management (ICM). Ewing et al. (1997) survey literature in the wider area of Integrated Environmental Management (IEM) and comment that:

“most of the conceptual development and experience with IEM relates to water and related land resources, in which catchments are used to define that ‘system’ in which integrated management is to occur”.

From this perspective, the catchment describes the boundary of the system of interest, and the hydrological elements, including the stream, are components of nested systems.

According to the NSW Catchment Management Act 1989, ‘Total Catchment Management’ (analogous to ICM) is ‘the coordinated and sustainable use and management of land, water, vegetation and other natural resources on a water catchment basis so as to balance resource utilization and conservation’ (Government of New South Wales, 1989).

This integrated approach is a direct heir to the Australian Government’s national strategy of Ecologically Sustainable Development (NSESD). The NSESD strategy specifies that governments should ‘continue to encourage and support actions to develop and adopt an integrated catchment management approach to water resources’ (Ecologically Sustainable Development Steering Committee, 1992).

ICM integrates the management of the environmental, social and economic aspects of the whole catchment, just as sustainability attempts to measure the social, economic and environmental consequences of human environmental interaction.

Measures of catchment health must be composed of a number of individual assessments of the ecological health of system components. The Catchment Condition Project, for instance, is a multimetric assessment of catchment condition (Department of Agriculture Fisheries and Forestry Australia, 2002). The catchment condition index is composed of three sub indices of water
condition, land condition and biota condition. Each of these sub-indices is, in turn, an aggregation of available data (see Table 5-1).

### 5.12 Landscape health

Related to the concept of catchment health is the concept of landscape health. In its introduction, a report for the National Land and Water Resources Audit (2000) entitled ‘Landscape Health In Australia’ described landscape health as:

‘...a scale of study and understanding beyond the paddock or the farm. A landscape includes the:

- underlying geology and hydrogeology;
- landforms and soils; and
- plants and animals.

A landscape may be drained by a number of catchments, and the characteristics of that landscape will apply to those parts of those catchments. While a catchment may contain many different geologies and associated landforms, soils and vegetation, a landscape has a characteristic suite and pattern of these, clearly differentiating it from adjacent landscapes.’

(National Land and Water Resources Audit, 2000)

The key to landscape health, then, is that it applies to the broad-scale landscape, unlike catchment health, its extent is not defined by catchments, and its components are not focused on hydrology. This view of landscape sees the visual ‘pattern’ of landscape components as the structure for assessing health. These components are disconnected from the structure and function of the constituent ecosystems. Rapport et al. (1998), discuss methods of evaluating landscape health. The authors claim that:

‘...landscapes are healthy when the cycling of energy and nutrients is not impaired, when the key ecological components are preserved e.g. wildlife, soil and microfauna, when the system is resistant and resilient to long-term effects of natural perturbations and ‘when the system does not have to be constantly doctored’, (Rapport et al., 1998)
This definition of landscape health is a regional ecosystem view, and it takes into consideration the regional flux of environmental condition.

The multimetric approach taken in the NLWRA study used a plethora of data sources, and the authors comment that the fundamental constraint to the study was the absence of appropriate data sets to determine current landscape health. Landscapes contain a multitude of nested ecosystems, and this can mean that measures of landscape health contain nested opportunities for data uncertainty to creep into the process of establishing baseline conditions.

The NLWRA study derived a classification based on a synthesis between landscape condition and the trend in condition of landscape attributes. This was deemed a measure of landscape stress (see Figure 5-3).
5.13 Measures of environmental health relevant to water management

Unlike the qualitative, multimetric approach of landscape health, water quality has traditionally been measured using quantitative metrics of chemical and physical characteristics. Table 5-2 on page 109 lists those chemical and physical characteristics commonly measured in Victoria.

In recent times, however, qualitative measures of environmental health have also been used to assess the consequences of water use. Physical and biological indicators have been developed to assess the relative environmental health of waterways. Biological indicators are now routinely used, and are an important part of the methodology recommended by the National Water Quality Management Strategy (ANZECC & ARMCANZ, 2000) Hart et al. (1999) consider these biological indicators as guidelines for ecosystem protection.

Figure 5-3 Australia - landscape stress (National Land and Water Resources Audit, 2000)
The fundamental difference between the physico-chemical approach and the biological, ecosystem protection approach is that the traditional approach sought to protect potential users from a particular chemical and physical quality of water, while the new approach seeks to protect the systems that produce the water. The National Water Quality Management Strategy (ANZECC & ARMCANZ, 2000) recommends an integrated approach where both the traditional methods and the newer biological methods combine to ‘enhance the confidence in correctly attributing causes’ to changed water quality.

While traditional methodologies are aimed at ‘indirectly estimating ecological impairment’, measures of environmental health aim to measure the relative level of environmental damage (ANZECC & ARMCANZ, 2000).

5.14 Chemical and physical water quality assessment

At the basis of all water quality analyses are effective and accurate data collection methodologies. For the most part, measures of water quality are based on a statistical assumption that the sampling of water from a single point within a stream can be extrapolated to the stream as a whole. Commonly, values at these point locations are extrapolated not only to the whole waterway at that point, but also to the whole reach, or catchment.

Historically, assessments of water quality were associated with the fitness of water for its intended purpose (see Table 6-2). The aim of individual chemical and physical water quality assessment is to indirectly estimate the level of ecological impairment. According to the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ, 2000) numerical guidelines are developed by assessing the response of biota from different taxa to individual chemicals. Single-stressor toxicity tests are carried out under controlled laboratory conditions.

The guidelines state that while there are some problems translating the laboratory measures into real world conditions, there are some advantages when using these physical and chemical water quality parameters as a surrogate for ecological health. The guidelines list the following advantages:

- Conceptual simplicity,
• Established technology,
• Explicit numerical objectives,
• The ability to acquire meaningful quantities of data relatively quickly
• Comparatively low costs

The disadvantage noted by the guidelines is that the laboratory conditions may not be relevant to the complexity of real world ecosystems.

These traditional methods, then, are aimed at assessing the relative ecological health of water. The normative, or reference conditions, are controlled laboratory conditions and do not relate to the real world conditions. The aim in these guidelines has been to produce global guideline values that indicate when ecological parameters are unacceptable. The particular ecology of interest, it could be argued, is primarily a human centred ecology. At the basis of water quality assessment is the understanding that the physical qualities and chemical composition of water indicate the fitness of water for its intended purpose.

Table 5-2 Parameters currently monitored as part of the VWQM N program (ECOscience, 2001).

<table>
<thead>
<tr>
<th>Field Parameters</th>
<th>Laboratory Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Conductivity (EC) (S/cm)</td>
<td>Colour (Filt.) (Pt/Co Units)</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>Filterable Reactive Phosphorus (FRP) (mg/L P)</td>
</tr>
<tr>
<td>pH (pH Units)</td>
<td>Total Phosphorus (TP) (mg/L P)</td>
</tr>
<tr>
<td>Water Temperature (°C)</td>
<td>Nitrates and Nitrates (NOx) (mg/L N)</td>
</tr>
<tr>
<td>Dissolved Oxygen (mg/L)</td>
<td>Total Kjeldahl Nitrogen (TKN) (mg/L N)</td>
</tr>
<tr>
<td>Gauge Height (m)</td>
<td>Suspended Solids (SS) (mg/L)</td>
</tr>
<tr>
<td>Discharge (ML/day)</td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>Major Ions</td>
</tr>
<tr>
<td>Arsenic (As) Lead (Pb)</td>
<td>Sodium (Na) Calcium (Ca)</td>
</tr>
<tr>
<td>Cadmium (Cd) Nickel (Ni)</td>
<td>Magnesium (Mg) Potassium (K)</td>
</tr>
<tr>
<td>Chromium (Cr) Zinc (Zn)</td>
<td>Alkalinity (CaCO3) Chloride (Cl)</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>Sulphate (SO4) pH</td>
</tr>
<tr>
<td></td>
<td>Electrical Conductivity (EC)</td>
</tr>
</tbody>
</table>
The fitness of water for a particular use is a statement of the normative condition, but the methodology involved in establishing those normative conditions does not indicate the health of the system.

5.15 Bioassessment

Biologically based assessment of environmental health, or bioassessment, can involve the consideration of a wide range of groups including macroinvertebrates (Chessman, 1995), fish (Kleynhans, 1999), algae (Benedetti-Cecchi et al., 2001), diatoms (John, 2000), micro-organisms and macrophytes (Schofield and Davies, 1996a).

According to Schofield and Davies (1996a), there are two reasons to use bioassessment techniques to measure river health:

- **assessing ecological values requires direct measurements of the system; and**
- **physico-chemical measurements alone are inadequate for assessing river health, as the processes linking changes in physical and chemical conditions in rivers and the ecological state are either poorly understood or too complex. They also do not take into account important changes to river habitat and are frequently instantaneous.**

(Schofield and Davies, 1996a)

Advantages of bioassessment techniques are also said to include the ability to provide an integrated assessment of stresses to river health, but also target specific stresses by identifying a particular group, taxon or species (Schofield and Davies, 1996a). A disadvantage of bioassessment is that it is difficult to relate the measured states to possible management actions. It can be one thing to know that there has been change to environmental health, but to know how to construct a management response to that change requires some indication of the relationship between management actions and biological condition.

5.16 RIVPACS

The River InVertebrate Prediction And Classification System, or RIVPACS approach is a bioassessment approach first developed at the River Laboratory
of the Institute of Freshwater Ecology, UK in 1977. According to Schofield and Davies (1996a), the objectives of RIVPACS were to:

- to develop a classification of unpolluted running water sites based on macroinvertebrate fauna
- to determine whether the fauna to be expected at an unstressed site could be predicted from physical and chemical features only.

The RIVPACS approach develops statistical relationships between the fauna and the environmental characteristics of a number of high quality reference sites which can be used to predict the macroinvertebrate fauna to be expected at any site in the absence of pollution or other environmental stress. The observed fauna at new test sites can then be compared with the expected fauna at that site to derive indices of ecological quality (Clarke et al., 2003).

In this approach, macroinvertebrates are used because they were considered to have almost universally moderate species richness and there is a significant body of literature describing the response of many taxa to a range of pollutants (Schofield and Davies, 1996a). The Department of Environment and Heritage (2004a) add that macroinvertebrates are visible to the eye, ‘easy to collect’, ‘relatively immobile’ and ‘reflect the aggregate of impacts of environmental change on the stream ecosystem’.

Variations of the RIVPACS approach have also been used in North America. The BEAST (Benthic Assessment of Sediment) model has been used to assess sediment quality in the Great Lakes, and in the Fraser River catchment in British Columbia (Clarke et al., 2003).

### 5.17 AUSRIVAS

In Australia, the Australian River Assessment System, or AUSRIVAS approach, based on the RIVPACS approach, was developed in 1994, under the aegis of the National River health Program (NRHP) (National River Health Program, 2000).

As in RIVPACS, AUSRIVAS consists of a series of mathematical models (one for each state) which use field collected data to predict the aquatic macroinvertebrate families that would be expected to be present in surveyed...
river sites in a reference condition. These models have been developed using habitat information and macroinvertebrate surveys at approximately 1500 selected reference sites (Department of the Environment and Heritage, 2004a).

Parsons et al. (2002) describe the development of a physical assessment protocol to extend the original concept of AUSRIVAS to include the prediction of physical and biological habitat. The protocol was developed after comparing existing physical assessment techniques, including the Index of Stream Condition (Ladson and White, 1999); (Ladson et al., 1999a); River Habitat Audit Procedure (Anderson, 1993), River Styles (Brierley et al., 1996) and Habitat Predictive Modelling (Davies et al., 2000).

Similar bioassessment methodologies, based on RIVPACS and AUSRIVAS have also been developed in South Africa as part of the South African River Health Programme (Dallas, 2000., Kleynhans, 1999).

5.18 SIGNAL
The 'Stream Invertebrate Grade Number - Average Level' or SIGNAL is a simple scoring system for macroinvertebrate samples which gives an indication of overall water quality (Chessman, 2003). The SIGNAL score is the average of pollution sensitivity values given at the family level for aquatic macroinvertebrates. SIGNAL was originally developed in 1993 to assess the impacts of sewage discharges into the Hawkesbury-Nepean River system near Sydney. SIGNAL scores reflect the changes in species composition that can be attributed to altered habitat characteristics, such as pollution (Chessman, 2003). High SIGNAL scores are likely to indicate low levels of salinity, low levels of turbidity and nutrients such as nitrogen and phosphorus and high levels of dissolved oxygen. The SIGNAL score can be calculated from AUSRIVAS data, but Chessman (2003) urges caution, because, as with the AUSRIVAS reference sites, baseline conditions are difficult to assess as pristine. There are few, if any, truly pristine streams in Australia.

5.19 Index of biological integrity (IBI)
In the United States Karr (1981) is considered the architect of an index of biological integrity (IBI) that uses fish assemblages to evaluate how water
environments reflect the physical (habitat), chemical, and biological conditions in streams. It was first developed in small mid-western streams. Between 1981 and 2002, 35 states in the USA have used the IBI as a means of bioassessment (An et al., 2002).

Like other bioassessment techniques, IBI is a rapid bioassessment method, designed to take a snapshot of conditions in a stream and infer stream condition spatially and temporally.

### 5.20 QBR: An index of riparian quality

While rapid bioassessment protocols like AUSRIVAS and RIVPACS deal with the ecological quality of the stream itself, a method has been developed by Munne et al. (2003) called the QBR (Qualitat del Bosc de Ribera) index. The QBR index uses simple measures of total vegetation cover and tree composition to define quality values in riparian habitat. It has the advantage of not needing reference conditions. According to Munne reference conditions can be difficult to identify, especially in lowland floodplain river systems because of the lack of pristine sites. This method was developed in rivers in Spain and on the Mediterranean coast but has also been applied by Bonada in the south west of Western Australia (Munne et al., 2003).

### 5.21 The Index of Stream Condition (ISC)

The Index of Stream Condition (ISC) is a multimetric index that aims to measure relative stream health (Ladson et al., 1999b, Ladson, 2000). It is intended for use by regional catchment managers and government agencies responsible for waterway management. The ISC aims to provide managers with a tool to benchmark stream condition and assist with the setting of priorities, the allocation of resources, and to assess the effectiveness of management strategies at the regional scale. Particular emphasis is placed on the use of the ISC to provide feedback and facilitate adaptive management of waterways.

The ISC gives a score for a particular river reach. Ladson, White et al. (1999b) describe a reach as ‘contiguous stretches of stream chosen so that they are approximately homogeneous in terms of the five components of stream condition’. The five components of stream condition are set out in Table 5-3.
5.22 Assessment of River Condition (ARC)

Similar to the index of stream condition, the Assessment of River Condition (ARC) is an integrated measure of river condition which relies on establishing reference conditions for all of its components. According to Norris (2001) the

Table 5-3 The five sub-indices of the Index of Stream Condition. (From Ladson, White et al. (1999b))

<table>
<thead>
<tr>
<th>Sub-index</th>
<th>Basis for subindex value</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrology</td>
<td>Comparison of the current flow regime with the flow regime existing under natural conditions.</td>
<td>Hydrologic deviation (comparison of monthly flows with those that would have existed under natural conditions)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percentage of catchment urbanized</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence of any hydropower stations that cause water surges</td>
</tr>
<tr>
<td>Physical form</td>
<td>Assessment of channel stability and amount of physical habitat</td>
<td>Bank stability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bed aggradation and degradation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence and influence of artificial barriers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density and origin (i.e. exotic or native species) of coarse woody debris (only assessed in plains streams)</td>
</tr>
<tr>
<td>Streamside zone</td>
<td>Assessment of quality and quantity of streamside vegetation</td>
<td>Width of vegetation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal continuity of vegetation (a measure of the number and significance of gaps in streamside vegetation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural intactness (comparison of overstorey, understorey and groundcover density with that existing under natural conditions)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proportion of cover that is indigenous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence of regeneration of indigenous species</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition of wetlands an billabongs (only assessed in plains streams)</td>
</tr>
<tr>
<td>Water quality</td>
<td>Assessment of key water quality parameters</td>
<td>Total phosphorus concentration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turbidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pH</td>
</tr>
<tr>
<td>Aquatic life</td>
<td>Presence of macroinvertebrate families</td>
<td>Presence of macroinvertebrate families using the SIGNAL index (Chessman, 1995)</td>
</tr>
</tbody>
</table>
Assessment of River Condition is based on the idea that ecological integrity, as assessed by the aquatic biota, is the fundamental measure of river health.

The ARC attempts to define a scalar approach to measuring river health (see Figure 5-4). In this approach, three levels of assessment; catchment condition, habitat condition and biological condition define the relationship between human activities and ecological conditions in rivers. Similar to the ISC, the ARC reports river condition at the scale of river reach. River reaches had a minimum length of 5km and maximum length of 183km.

5.23 Geomorphic river styles
It is the view of some that, while ecological, chemical, biological and physical indicators of ecosystem health are important, they are mostly ‘site specific, species-specific and restricted to one or a few aspects of aquatic ecosystems’ (Fryirs, 2003). The Geomorphic River Styles (GRS) approach aims to ‘provide a baseline survey of river character and behaviour, evaluating the physical controls on river structure at differing positions in catchments’ (Brierley et al., 1996). GRS begins by breaking rivers into contiguous sections based on similarity of geomorphological features.

Fundamental to GRS is the determination of river types. Fryirs (2003) considers that the determinants of river morphology are complex, both temporally and geographically, therefore simplification into types makes it possible to compare ‘like with like’. The authors note that bank erosion can be bad in some catchments but part of the natural sequence in other places. An approach is needed that develops meaningful reference conditions to make a qualitative assessment.

The GRS approach also requires that present river condition be assessed in its temporal context. Each river type is described in terms of river evolution (Fryirs, 2003). Brooksa and Brierley (2004) comment that ‘The geomorphic structure of alluvial rivers is now recognised as exerting a critical control on aquatic habitat, and by implication, aquatic ecosystem health’ p108.
Figure 5-4 Conceptual model of scales of factors related to river condition. This hierarchical model demonstrates catchment features such as longitudinal and lateral connectivity (dams and levees) and land use, which in turn have an effect on habitat features (riparian vegetation, snags, channel geomorphology), and these together affect the biotic components of the system (riparian vegetation, insects, fish, water birds). From Norris et al.(2001)

Table 5-1 ARC components and reference conditions From Norris et al (2001)

<table>
<thead>
<tr>
<th>ARC components</th>
<th>Reference condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrological index</td>
<td>All sub-indices were compared with pre-1750 flow regimes</td>
</tr>
<tr>
<td>Nutrient and Suspended sediment load index</td>
<td>All sub-indices were compared with nutrient and suspended sediment transport pre-1750 regimes</td>
</tr>
<tr>
<td>Habitat index</td>
<td></td>
</tr>
<tr>
<td>Bed condition sub-index</td>
<td>Stable bed of now net accumulation or degradation at century time scale</td>
</tr>
<tr>
<td>Riparian sub-index</td>
<td>Comparison with riparian vegetation coverage assumed to have existed under pre-1750 conditions</td>
</tr>
<tr>
<td>Connectivity sub index</td>
<td>Comparison with a no dam, no levee regime (pre-1750 conditions)</td>
</tr>
<tr>
<td>Catchment disturbance index</td>
<td>Comparison with a completely undeveloped catchment (pre-1750 conditions)</td>
</tr>
<tr>
<td>Biota index</td>
<td>Comparison with biota in a nearly pristine or minimally modified condition</td>
</tr>
</tbody>
</table>
Geomorphological characteristics are also considered as part of composite indices such as the Index of Stream Condition (Ladson et al., 1999b, Ladson, 2000).

5.24 USEPA rapid bioassessment protocol
The USEPA Rapid Bioassessment Protocol or HABSCORE is a multimetric developed by the United States Environmental Protection Agency (USEPA) (Barbour et al., 1999). HABSCORE uses Rapid Bioassessment Protocols (RBP) to assess stream condition based on fish, macroinvertebrate and periphyton assemblages.

The RBP uses visual judgement of ‘the structure of the surrounding physical habitat that influences the quality of the water resource and the condition of the resident aquatic community’ (Barbour et al., 1999). The habitat parameters assessed include, embeddedness, velocity / depth regime, sediment deposition, epifaunal (bottom) substrate / available cover, channel flow status, channel alteration, frequency of riffles (or bends), bank stability (score each bank), vegetative protection (score each bank) and riparian zone score (score each bank) (Parsons et al., 2000). HABSCORE provides a tool to assess the quality of in-stream and riparian habitat at a sampling site.

5.25 Assessment of environmental conditions of Victoria’s rivers and streams
The Environmental Protection Authority, Victoria (EPA), in its assessment of the environmental condition of rivers and streams in Victoria, uses a rapid bioassessment technique. The EPA’s rapid bioassessment aims to establish:

- **levels of attainment against established environmental quality objectives;**
- **progress towards meeting defined targets for improved environmental quality;**
- **potential risks to aquatic ecosystems from the impacts of human activities;** and
- **the environmental condition or health of aquatic ecosystems.**
In the field, two samples are collected. One from the streambed; the benthic sample, collected from the fast flowing waters and an edge or littoral sample, collected from the slow flowing habitat surrounding in stream vegetation. Additionally a suite of observations of stream condition are recorded.

In several reports on environmental condition in Victorian catchments, the EPA have used this data to develop seven indices of river condition, these include, AUSRIVAS, SIGNAL, Key Families, Number of Families, EPT (Ephemeroptera + Plecoptera + Trichoptera), ISC, and the USEPA Rapid Habitat Assessment (RHA) Protocol.

AUSRIVAS, SIGNAL and RHA are as described above. Key Families is a bioassessment method that attempts to identify the loss of taxa that indicate good habitat and water quality. Number of Families is a simple measure of the number of families to be found at any site, while EPT is a measure of the presence of insects of the orders Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies). Table 5- sets out the draft biological objectives for each of these seven indicators for the Latrobe, Thomson and Avon catchments.

Normative conditions in the Australian ecological context have been described as similar to a pristine state, however, when it comes to water quality, normative ecological conditions have only recently become the focus of water quality monitoring. Bioassessment has become a commonly applied methodology to describe the pristine state of streams with reference to similar unimpacted sites.
Table 5-2 Draft biological objectives and condition categories for each biological region in the Latrobe, Thomson and Avon catchments

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Highlands (Region 1) (edge/riffle)</th>
<th>Forests A (Region 2) (edge/riffle)</th>
<th>Forests B (Region 3) (edge/riffle)</th>
<th>Cleared Hills and Coastal Plains (Region 4) (edge/riffle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL/SRIVAS</td>
<td>N/A</td>
<td>Band A</td>
<td>Band A</td>
<td>Band A</td>
</tr>
<tr>
<td>SIGNAL</td>
<td>6/7/5/8</td>
<td>5/7/6/0</td>
<td>5/8/6/0</td>
<td>5/6/5</td>
</tr>
<tr>
<td>Number of Families</td>
<td>13/22</td>
<td>22/21</td>
<td>24/23</td>
<td>26/23</td>
</tr>
<tr>
<td>EPT Index score</td>
<td>4/50</td>
<td>7/9</td>
<td>9/50</td>
<td>N/A</td>
</tr>
<tr>
<td>Key Families</td>
<td>Combined habitat 18</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TSC/RHA Condition Rating</th>
<th>Excellent</th>
<th>Good</th>
<th>Marginal</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSC score</td>
<td>92-99</td>
<td>114-1</td>
<td>26-36</td>
<td>29-25</td>
<td>90-99</td>
</tr>
<tr>
<td>RHA score</td>
<td>350</td>
<td>350-500</td>
<td>130-140</td>
<td>120-130</td>
<td>920</td>
</tr>
</tbody>
</table>

N/A = not applicable

5.26 Modelling stream health

It is clear, then, that critical to measuring the health of streams in Victoria is consideration of the qualitative assessment of stream health and a quantitative assessment of system function. The system in which a stream operates is bounded by the catchment, and the qualitative assessment of catchment health is relative to the wider region in which the relative assessment is being made. For instance, an assessment may be made with reference to all the catchments in Victoria.

Complex multimetrics can provide a great deal of information about stream condition by providing a snapshot of condition for the locations measured; and with repeat measurement, they may be used to signify a general trend. They do not, however, allow us to understand the system functions that are at the heart of those of changing conditions. Because of the complex nature of these measures, such as the Catchment Condition Index, it is not possible to use their results to infer the likely condition at locations that were not sampled.

Because of the very limited amount of environmental information that is available over much of the Australian continent, it may be useful to make inferences of likely environmental condition at unsampled locations, based on their similarity to sampled locations. An as yet unpublished project recently carried out by the Department of Primary Industries in Victoria (see author for details), for instance, used regional environmental data to make inferences...
about the likely location of habitat for freshwater trout in Victoria. The data used included key data sets such as climate and fish catch, as well as estimates of likely stream turbidity values (produced as part of this study) for all streams in Victoria.

To make predictions of environmental health and help identify important system functions, an indicator is needed that clearly connects stream health with catchment land use: a measure of catchment condition that is not made up of multiple components, but has a clear impact on stream health.

Stream turbidity offers an ideal characteristic of water to establish a model of stream water quality. Turbidity is a characteristic of water that is tightly bound with catchment land use. It is a single measured quality of water that may possibly be used to establish normative states, current condition and establish trends and, unlike most indicators of environmental health, it may be possible to make predictions of environmental condition in locations where sampling has not occurred. Turbidity may also be modelled and examined to infer the likely mechanisms behind altered catchment condition. This will be discussed further in the next chapter.

5.27 Conclusion

In 1962 the limits to water availability were thought of as purely the quantitative limitations imposed by rainfall variability and catchment yield, however, by 2001 the environment had been established as the most important limiting factor on water availability.

From this view, water quality is inextricably linked with measures of environmental health, and acceptable levels of environmental health, both socially acceptable and economically acceptable, dictate water availability.

Where, appropriate chemical and physical measures of water for drinking can be stated as absolute values of bacterial counts or suspended solids, absolute values for what constitute appropriate levels of environmental health are not so easy to quantify. Commonly, biological and physical assessment of appropriate condition is given as a ranking of comparative health when compared to some idealised environmental condition. There are a number of
these measures and they each have a different focus depending on their management purposes.

Stream turbidity is a characteristic of water that is tightly bound with catchment land use and, as such, is an ideal indicator for exploring linkages between catchment land use and stream health, especially where that land use results in widespread mobilisation of soil. It is a single measured quality of water that can be analysed and manipulated statistically to establish normative states, current condition and establish trends; and unlike most indicators of environmental health, it can be used to make predictions into locations where sampling has not occurred.
CHAPTER 6. STREAM TURBIDITY AS AN INDICATOR OF CATCHMENT HEALTH

6.1 Introduction
While previous chapters established that the condition of Victoria’s natural environment has been significantly altered by the course of European colonisation, chapter 5 outlined different methods of measuring environmental health. Chapter 5 concluded that at the basis of common methods for identifying degrees of environmental health is the fundamental need to establish baseline conditions. This chapter will outline the attributes of stream turbidity, the history of its measurement and how it is related to overall catchment condition.

Turbidity is a quantifiable, optical quality of water. Commonly measured in Nephelometric Turbidity Units (NTU), it is a measure of the ability of particles within water to scatter light. Along with taste and odour it is a distinctive attribute of water that enables us to rapidly judge the quality of water for its intended purpose. Unlike odour and taste, turbidity is a quantifiable and comparable attribute of water and was amongst the first suite of water quality attributes routinely monitored by twentieth century water managers.
Over the course of European habitation in Australia, the significance of stream turbidity has been interpreted in varying ways. In its simplest interpretation, turbidity has been considered as a measure of the fitness of water for human consumption. Water suitable for drinking is, for instance, reported to be below 5 NTU’s (Nephelometric Turbidity Units) by the Victorian EPA (Environmental Protection Authority) standards.

In the nineteenth century, as vast tracts of land were cleared and radical agricultural practices transformed the landscape, what was once seen as a measure of potability also became a metaphor for the loss of agricultural potential. As enormous quantities of soil were washed into rivers turbidity became an important de-facto indicator of land management practices (Scott, 2001).

In recent times the measurement of turbidity has, with other indicators of water quality, turned another corner. Stream water quality is now assumed to be an indicator of the ecological health of the river and its catchment. Turbidity is now, increasingly, considered as an integral part of the natural river condition. It is no longer considered, exclusively, as something that makes water unfit to drink or, simply, as a waste of good topsoil; turbidity is taking its place as a natural characteristic of water, uniquely linked to the ecology of streams and catchments.

6.2 What is stream turbidity?

Turbidity is an optical quality of water caused by the scattering and absorption of light within a sample. The scattering and absorption is caused when undissolved particles interfere with the light passing through (Sadar, 1998). Humans have been developing measures to improve and assess water quality for over two thousand years (Montgomery, 1985), but it was not until the beginning of the twentieth century that a formal system of quantifying turbidity was first developed by Whipple and Jackson (1900) (see Sadar (1998) and United States Office of Water Environmental Protection Agency (1999)).

Whipple and Jackson developed a method using the Jackson candle turbidimeter. This device consisted of a candle and a special flat-bottomed glass tube and was calibrated in graduations equivalent to parts per million
(ppm) of suspended silica turbidity (see Figure 6-1). When the user looked into the tube and poured in a sample of water, at some point the amount of scattered light would equal the amount of transmitted light. At this point the image of the candle would be replaced by a diffused glow. The depth of the sample could then be read off a calibrated scale and the turbidity would be interpreted in ppm of silica, when compared to a standard composed of diatomaceous earth in suspension. These units were called Jackson Turbidity Units or JTU.

Figure 6-1 Jackson candle turbidimeter: from Sadar (1998)

Jackson turbidity units are now not commonly used and have been criticized because determination requires a subjective judgment of when the image of
the candle disappears. The Jackson turbidimeter is also unable to make reliable determinations below 25 JTU. In addition, the unit is cumbersome and because the light source was a candle flame, incident light emitted was in the long wavelength of the visible spectrum (Sadar, 1998).

The Jackson Candle Turbidimeter was originally calibrated using standards composed of natural materials such as Fuller's earth, kaolin and bed sediment. These standards were not easily repeatable and, generally, unreliable. In 1926, however, Kingsbury et al. (1926) developed formazin, a standard that offered a repeatable and reliable suspension for calibrating turbidimeters. Formazin is a solution of 5.00g of hydrazine sulfate and 50.0g of hexamethylenetetramine in one litre of distilled water. When left for 48 hours at 25 degrees Celsius the solution develops a white turbidity.

Formazin is particularly useful as a turbidity standard because it consists of polymer chains of several different lengths, which fold into random configurations. This results in a wide array of particle size and shape, from 0.1 to over 10 microns. This range fits well with particle size found in natural conditions (Sadar, 1998).

JTU are now not commonly used. The current standard is NTU or Nephelometric Turbidity Units. NTU are measured by Nephelometric turbidimeters. Nephelometric turbidimeters are instruments that measure light that scatters at an angle (usually 90 degrees) from a beam of light passing through a sample (see Figure 6-2). Nephelometric turbidimeters are accurate down to very low values of turbidity and up to very high values of turbidity.

Other units have been used to express a measure of turbidity: Formazin Turbidity Units (FTU), Formazin Attenuation Units (FAU) and Formazin Nephelometric Units (FNU). All these measures use formazin as a standard for calibration. The only difference is NTU and FNU are measures of scattered light and FTU and
FAU are measures of the attenuation of transmitted light. That is, they are measures of the decrease in light intensity caused by particles within a sample.

While NTU are calibrated against reproducible standards, the particles that make water turbid are not standardized; variation in the range of materials that make water turbid is significant. Further, the light scattering properties of particles in water depends on the size, shape and refractive index of the material. Small particles scatter light at the short wavelength end of the spectrum differently than light at the long wavelength end, while larger particles develop more complex patterns, scattering more light forward (see Figure 6-3).

Light scattering reduces inversely to the sixth power of the particle size. For this reason, colloidal silica suspensions almost approaching solids can appear transparent (Gregory, 1998). Consequently, the range of particles sizes that make up turbidity is important. Additionally, interferences, such as contamination, excessively coloured samples, stray light, accumulation of particles that absorb rather than scatter light or variation in particle density (see Table 6-1) can have a dramatic impact on turbidity readings (Sadar, 2002). For the purposes of measuring turbidity in excess of 5 NTU,
Figure 6-3 Scattering is a function of light wavelength and particles size. Assuming a wavelength of approximately 600 nm, the figure shows angular patterns of scattered light from particles of three relative sizes: A), 60nm, B) \(\approx 6000 \text{ nm} \). From Brumberger (1968) (Reproduced from Sadar (1998)).

colour, particle absorption and particle density are considered important interferences (Sadar, 2002).

Much debate has centred on the use of turbidity as a surrogate for suspended sediment load. Commonly, rating curves are developed through simple regression that correlate measured turbidity with measured levels of suspended sediment (Letcher et al., 1999). The difficulties in transmitting these regression models from one catchment to another are obvious. Particulates in suspension may have a totally different size distribution in different catchments and, perhaps, during different time periods and during flow events.
Table 6-1 Typical interferences associated with turbidity measurement. From Sadar (2002)

<table>
<thead>
<tr>
<th>Interference</th>
<th>Effect on the Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbing particles (coloured)</td>
<td>Negative bias (reported measurement is lower than actual turbidity)</td>
</tr>
<tr>
<td>Colour in the matrix</td>
<td>Negative if the incident light wavelengths overlap the absorptive spectra within the sample matrix.</td>
</tr>
<tr>
<td>Particle Size</td>
<td>Either positive or negative (wavelength dependent)</td>
</tr>
<tr>
<td></td>
<td>a) Large particles scatter long wavelengths of light more readily than small particles.</td>
</tr>
<tr>
<td></td>
<td>b) Small particles scatter short wavelengths of light more efficiently than long wavelengths</td>
</tr>
<tr>
<td>Stray light</td>
<td>Positive bias (reported measurement is higher than actual turbidity)</td>
</tr>
<tr>
<td>Particle Density</td>
<td>Negative bias (reported measurement is lower than actual turbidity)</td>
</tr>
<tr>
<td>Contamination</td>
<td>Positive bias (reported measurement is higher than actual turbidity)</td>
</tr>
</tbody>
</table>

Even though turbidity measurements are based upon formazin standards, there can be considerable difference between individual instruments. Gregory (1998) comments that measurement depends on the design of the instrument, the scattering angle and the acceptance angle of the detector and even different instruments from the same manufacture can give widely varying results.

Turbidity has also been measured using a turbidity fluctuation technique (Gregory, 1985) and particle counting techniques Gregory (1998). Instrument makers have modified traditional nephelometric techniques and various methods devised to reduce interference. Sadar (2002, 1998) surveys instrument designs that incorporate, among other innovations, the use of transmitted, forward scatter and back scatter methods to measure very high turbidity values.

Turbidity is also routinely measured using a Secchi disk. The Secchi disk is a black and white disk 20 cm in diameter attached to a long tape measure or cord marked in metres (see Figure 6-4).
The disk is lowered into water and an observation taken when the disk is no longer visible. The Secchi disk is named after Father Pietro Angelo Secchi, a scientific advisor to the Pope. He was the first to lower a new device used to test the transparency of water from a Papal naval vessel in April 1865 (Carlson, 2003). The Secchi disk is commonly used in volunteer or community monitoring programs (Carlson, 2003) and limnological studies (Holdren, 2002).

A device has also been developed in Australia called a "Morgan Bottle Turbidimeter" (White, 1994), in which a clear plastic bottle is calibrated by nephelometric measurement. A black symbol is drawn on the bottom of the bottle and a reading is taken when, as the bottle is filled, the mark on the bottom of the bottle becomes invisible. This device is similar to the original Jackson turbidimeter, while including some of the utility of the Secchi disk.
This method has the added advantage of being usable in shallow streams and fast flowing water.

The range of available instruments and technologies used to measure turbidity reflect a wide range of applications. Turbidity is used not only for assessment of natural streams and the quality of drinking water, but also in a host of other applications such as the assessment of the level of fat in milk (Sadar, 1998), the presence of Cryptosporidium oocysts (Gregory, 1998) and other pathogens in drinking water (United States Office of Water Environmental Protection Agency, 1999).

### 6.3 Turbidity: What does it mean?

Although stream turbidity is a universal characteristic of water, different users of water can interpret its significance in different ways. To the agriculture industry high levels of turbidity are an indicator of suspended particulate matter in streams, and, therefore, an indicator of soil erosion. The agricultural concern is for the loss of soil condition; soil degradation, soil movement and loss of nutrients (Freebairn, 2001).

From the ecological perspective changing turbidity values are an indicator of inappropriate land use and a threat to river health. Even though, instinctively, high levels of turbidity might be thought to represent poor levels of environmental health, natural levels of turbidity can be high and highly variable. Figure 6-5 shows the distribution of mean annual turbidity levels measured at 177 Victorian water-quality monitoring sites during 2001. Levels vary from 0.7 to 135 NTU’s.

Increased levels of turbidity can have a negative impact on ecological health. Research indicates that an increase in turbidity can limit light penetration and smother habitat (Environment Protection Authority Victoria, 2001). An increase in suspended sediment can also cause morbidity, decreased abundance and decreased diversity in macroinvertebrate communities. While increased levels of fine sediment can cause reduced feeding efficiency, decreased growth rates and increased disease amongst fish populations as
well as a general deterioration in habitat complexity (Prosser et al., 2001).

From the perspective of water quality regulation, acceptable levels of turbidity, relate to the beneficial use that an identifiable body of water is deemed to have. Beneficial uses include provision for domestic, industrial, cultural and ecological purposes (see Table 6-2). While high turbidity in water for industrial use may not be considered important, high levels of turbidity in drinking water, for instance, may decrease the efficiency of disinfection (chlorination). Particles associated with turbidity also provide a surface to which other pollutants may adsorb, and find refuge (Amirtharajah and Jones, 2000).

While, from the perspective of providing potable water, these adsorbed pollutants are malignant hitch hikers, from the ecological perspective these same pollutants, including carbon, nitrogen and phosphorus are interdependent with
Table 6-2 Beneficial uses of water in Victoria. Environment Protection Authority Victoria (2001)

<table>
<thead>
<tr>
<th>Beneficial uses of Water in Victoria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aquatic ecosystems:</strong></td>
</tr>
<tr>
<td>Largely unmodified ecosystems</td>
</tr>
<tr>
<td>Slightly to moderately modified ecosystems</td>
</tr>
<tr>
<td>Highly modified ecosystems</td>
</tr>
<tr>
<td><strong>Water suitable for:</strong></td>
</tr>
<tr>
<td>Primary contact recreation</td>
</tr>
<tr>
<td>Secondary contact recreation</td>
</tr>
<tr>
<td>Aesthetic enjoyment</td>
</tr>
<tr>
<td>Indigenous cultural and spiritual values</td>
</tr>
<tr>
<td>Non-indigenous cultural and spiritual values</td>
</tr>
<tr>
<td>Agriculture</td>
</tr>
<tr>
<td>Aquaculture</td>
</tr>
<tr>
<td>Industrial and commercial use</td>
</tr>
<tr>
<td>Human consumption after appropriate treatment</td>
</tr>
<tr>
<td>Consumption of fish, crustacea &amp; molluscs</td>
</tr>
</tbody>
</table>

the supply of organic and inorganic sediments (Drever, 1988) and, therefore essential to river health.

From the geomorphological and hydrological perspective, turbidity is a characteristic of water that relates to the transport of sediment by streams. Increased turbidity is, then, a function of increased sediment transport. The importance of increased sediment entrainment by streams is scale dependent. Short-term fluctuations in stream sediment loads may be related to an expected, episodic, regime of sediment transport. Long term changes to stream sediment loads, however, may represent considerable, physical
change to stream channels, wetlands and marine environments (Prosser et al., 2001).

The concept that comes most clearly from the literature is that turbidity can be considered closely bound with land use practice and is linked interdependently with the ecological health of catchments and streams. Freebairn (2001) makes it clear that, in the Australian context, turbidity can be considered a measure of the consequences of land management practices on soil erosion and run-off.

That is not to say that the level of stream turbidity is directly related to land use practice, but that changes in land use practice can alter the level of stream turbidity.

6.4 Water quality monitoring
While any estimate of the extent of streams in Victoria is doomed to fall into definitional problems, in 1999 the Department of Natural Resources assessed 18 thousand kilometres and 950 river reaches that covered the whole of Victoria (Environment and Natural Resources Committee, 2001a). In comparison, the Victorian Water Quality Monitoring Network (VWQMN) consists of around 200 fixed monitoring stations collecting instantaneous measures of physico-chemical indicators of pollution, on a monthly basis (Goudey, 1999).

While fixed site monitoring is commonly used to indicate the overall health of a waterway, inferences about the upstream source of changing health can only be made in a very general way. Water samples taken at fixed sites are subject to bias and uncertainty caused by the sampling methodology (Goudey and Lloyd-Smith, 1999). Bias due to the monitoring constraints may take a number of forms. Bias may be temporal or spatial in nature. For instance, monthly sampling means that daily or weekly variations are not considered. This temporal bias may be compounded when values that are measured at a single location are not representative of values at locations nearby. Surface sampling also means that surface values are extrapolated to the whole water column (Goudey and Lloyd-Smith, 1999).
While the objective of water quality sampling at fixed locations is to provide long term data on temporal fluctuations in water quality, another objective is also to determine whether there has been compliance with State Environment Protection Policy (SEPP) objectives (Goudey, 1999). The distribution of the monitoring network, however, is such that a tiny fraction of the stream network is sampled for a small fraction of time.

Continuous sampling at all locations on a stream network would enable an intimate knowledge of how water quality parameters change over time and react to changes in land use. However, the reality is that monitoring cannot be carried out on all reaches of all streams. There will always be a need to interpolate values between monitoring locations and extrapolate to the broader catchment area.

6.5 Water quality objectives

Historically, turbidity has been measured using a single, universal value to represent acceptable levels (Goudey, 2001). However, recent acknowledgment that natural levels of turbidity vary considerably has resulted in the establishment of localised water quality objectives. Victoria’s water quality objectives follow the lead of the ‘Australian and New Zealand
Guidelines for Fresh and Marine Water Quality’ (ANZECC & ARMCANZ, 2000). The EPA has developed water quality guidelines for rivers and streams that build on these guidelines and introduce water quality objectives for individual localities, based on a biological regionalisation developed through statistical analysis of biological data (see Figure 6-7) (Metzeling et al., 2001).

In Victoria, the EPA publishes water quality objectives in the State Environment Protection Policy (Environment Protection Authority Victoria, 2001). Appendix 3 is a table showing turbidity objectives for major biological regions in Victoria. The methodology used to establish these objectives is outlined by Goudey (2001).

![Figure 6-7 Turbidity objectives for Victoria (Environment Protection Authority Victoria, 2001)](image-url)
The objectives represent the 75th percentile of expected values with 95% confidence limits for discrete biological regions. The biological regions were developed by the EPA and represent areas of contiguous biological similarity, based on data gained from biological sampling.

This methodology is part of the EPA’s risk-based approach. Historically, water quality objectives were based on threshold values, above which, ecological health was likely to be jeopardised. The risk-based approach identifies ‘trigger values’ which indicate potential risk and initiate further management response (see Figure 6-8) (ANZECC & ARMCANZ, 2000, Environment Protection Authority Victoria, 2002). While the development of trigger values for different biological regions is an improvement over the previous method, considerable variation in turbidity levels is still to be found within those biological regions.
6.6 What are natural levels of turbidity?

In ‘Water erosion in the Murray-Darling Basin: Learning from the past’, Scott (2001) provides convincing evidence that changing land use after European settlement led to significant changes to levels of stream sediment supply.

Prosser et al. (2001), also survey research in this area and suggest that human activities have greatly increased the supply of sediment from agricultural hill slopes, leading to the rapid extension of gully networks and causing catastrophic widening of river channels.

Scott (2001) suggests that there has been dramatic change for a number of rivers that once formed chains of ponds, with marshland and swamps, to river beds characterised by steep sided continuous gullies. Scott also summarises historical evidence of river turbidity by concluding that rivers of the Murray-Darling, prior to settlement, contained less turbid water, due to the lower supply of sediment from the upper catchments. The water may have been less turbid, but high turbidity levels were still reported for some streams during high river flows. Scott also describes the sudden, and enormous, mobilisation of sediment by gold mining operations and the accelerated erosion caused by overgrazing and land clearing.

The main lesson from this research is that, currently, there are accelerated levels of sediment stored within stream channels, leading to a concurrent high level of suspended sediment in streams. The movement of this sediment may have no relationship to present land use regimes, but may be indicative of historical practices. Prosser (2001) comments that ‘major historical changes will continue to influence river behaviour for many decades to come’. The movement of large volumes of this sediment down river valleys can be very slow as it is deposited in slow flowing water and resuspended during periods of high velocity flow.

6.7 The source of sediments in streams

It is important to note that suspended sediment is not turbidity. Turbidity is a measure of the clarity of water, a distinctly optical, or aesthetic, quality. Measurements of suspended sediment or sediment yield are not measures that relate to aesthetic quality, but are quantitative measures of particle
transport. They express the work of rivers in moving quantities of particulate matter through a catchment. From the agricultural perspective this is the movement of valuable soil and nutrient, from the geomorphological perspective it is the transport of eroded material and from the ecological perspective it is a characteristic of habitat.

As mentioned earlier, there has been some debate around the use of turbidity as a surrogate for suspended sediment load. Extensive research has suggested that turbidity can be considered as a surrogate for suspended sediment (Gippel, 1995), (H. Sun et al., 2001), (R. B. Grayson et al., 1996). Although, there is also some research to show that this relationship is not always valid (Riley, 1997), the relationship would seem to hold true for a majority of rivers and streams. The measurement of suspended sediment is also more complex and more costly than the measurement of turbidity.

Much work has been also been carried out by CSIRO Land and Water on the dynamics of sediment supply to streams, mostly with an inherently agricultural focus. According to Moran et al. (2001), research has, consistently, shown that the majority of sediment is derived from subsoils (Wallbrink and Fogarty, 1998).

Scott (2001) outlines research done by Neil and Fogarty (1991) in which the volumes of sediment accumulating in 46 farm dams within the lower part of the Lake Burley Griffin catchment near Canberra were measured. The amount of sediment in each dam was measured by taking a series of core samples. The trap efficiency of each dam was also calculated so that the mean annual yield of sediment entering each dam could be calculated. The sediment yield for each catchment was grouped by the main land use, and the results obtained. These values are given in table 6-3.

It is clear that sediment yield varies with land use and is greatly accelerated by agriculture. The increased sediment yield from ‘Pine plantation’ is particularly noticeable. Sediment yield on these sites was recorded at 33 times the natural rate.
Table 6-3 Sediment yield of farm dams (Scott, 2001)

<table>
<thead>
<tr>
<th>Catchment class</th>
<th>Number of catchments</th>
<th>Mean area of catchments (ha)</th>
<th>Sediment yield (t/km²/yr)</th>
<th>Increase from 'natural' rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undisturbed native forest</td>
<td>4</td>
<td>88</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>Native pasture</td>
<td>13</td>
<td>60</td>
<td>9.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Improved pasture</td>
<td>3</td>
<td>401</td>
<td>13.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Overgrazed pasture</td>
<td>2</td>
<td>6.9</td>
<td>68</td>
<td>27</td>
</tr>
<tr>
<td>Winter cropping</td>
<td>5</td>
<td>21</td>
<td>52</td>
<td>21</td>
</tr>
<tr>
<td>Pine plantation</td>
<td>7</td>
<td>47</td>
<td>83</td>
<td>33</td>
</tr>
<tr>
<td>Discontinuous gullies</td>
<td>5</td>
<td>46</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>Continuous gullies</td>
<td>8</td>
<td>113</td>
<td>160</td>
<td>64</td>
</tr>
</tbody>
</table>

Land use is, however, not the only predictor of stream turbidity. In NSW it has been found that highly sodic soils result in turbidity problems. These high sodium levels prevent clay particles from binding and make them readily erodible. In yet other cases, calcium dominated soils have been shown to enable clay particles to bind tightly and reduce the ability of flowing water to dislodge them (Environment Protection Authority - NSW, 1997).

### 6.8 Conclusion

Turbidity is often considered by the agricultural community as a sign of soil erosion and a loss of agricultural potential, while from the ecological perspective it can be considered a sign of deteriorating river health.

Turbidity can be considered as a surrogate for suspended sediment, is closely bound with land use practice and, in the Australian context, can be considered a measure of the consequences of land management practices on soil erosion and run-off.

ESD requires us to consider the complex relationship between the stream and the catchment it drains. While, there is not a history of stream turbidity being used as a measure of environmental health, levels of turbidity are clearly related to the health of the whole catchment. Unlike biological measures of river health, stream turbidity can be mechanistically related to catchment processes. Turbidity is a characteristic of streams that is easily measured, has
a history of measurement and it is uniquely related to catchment land management.
CHAPTER 7. A REGIONAL MODEL OF STREAM TURBIDITY

7.1 Introduction
Chapter 6 described the main characteristics of stream turbidity, the history of its measurement, and how turbidity is related to overall catchment condition. Chapter 6 also argued that turbidity can be generally considered as a surrogate for suspended sediment and can be treated as a measure of the consequences of land management practices on soil erosion and run-off.

Chapter 7 describes a method used to construct a regional spatial model of stream turbidity for Victoria. The aim of the model is to establish probable turbidity values based on knowledge of catchment characteristics over the whole region. These modelled values may useful when compared to measured values and provide catchment managers with an initial assessment of whether measured values are similar to expected values. They may also be considered as baseline values, from which further modelling might infer a trend in water quality associated with catchment land use. Additionally, these values could be compared to reference conditions to infer a level of environmental health that connects water quality with catchment land use.
The chapter will begin with a discussion of why a modelling approach was chosen and what challenges are posed by the modelling approach. The chapter then continues with a detailed description of the modelling method.

### 7.2 Why a modelling approach?

While, the purpose of a measure of environmental health is to provide a qualitative ranking aimed primarily at prioritising remediation work, the purpose of a hydrological model is to understand the hydrological relationships between environmental phenomena, in an attempt to understand the processes that connect land use with environmental condition. A simple ranking of environmental measurements will not provide this information; neither will it tell us if the measurements should be expected at that location. Temporal and spatial associations established by a model can place measured data in context. The advantage then of a modelling approach, over a simple measuring approach is threefold. Associations found between model variables can provide context specific information to allow for informed ranking of environmental condition, a model can be used to investigate the causal relationships in hydrological systems and the model can use these relationships to predict environmental condition at locations that are not measured. The scope of this model is, initially, to provide the basis for an informed ranking of environmental condition. However, the use of a predictive approach alone would limit the opportunities to understand some of the drivers of turbidity at the regional scale. Therefore, the modelling approach must also investigate likely explanatory relationships between stream turbidity and catchment characteristics, but these relationships must be understood in the context of great uncertainty within the key data inputs to the model.

### 7.3 The challenges with this approach

This modelling approach brings with some considerable challenges. These include significant uncertainty caused by errors introduced with the model inputs, the modelling method and the model outputs. Regional spatial information describing catchment characteristics, for instance, is often of poor quality and low resolution. Mining this information for meaningful correlations
with environmental condition requires an explicit method to deal with multiple layers of uncertainty.

Even if techniques are developed to deal with this uncertainty, the difficulties involved in finding an explanatory relationship between turbidity and catchment characteristics are considerable. A major problem is that the relationship between measured turbidity levels and catchment characteristics involves many complex and non-linear interrelationships. Practitioners have some understanding of these relationships at the catchment level, but at the regional level, they are little understood. A study by Sadek (1998), for instance, used remotely sensed data and established a modelled relationship with turbidity in the Traralgon Creek catchment. The study found that peak stream flow, base stream flow, the density of river crossings, proximity to roads, proximity to steep terrain, and the incidence of landslides were important determinants of stream turbidity. Sadek’s model, which used linear regression, predicted up to 72% of variation within measured turbidity and concluded that turbidity was a good indicator of catchment condition and a useful surrogate for suspended solids concentration.

While Sadek’s work is useful at the catchment scale, it is not transferable to the regional context. The dataset was constructed for the catchment in question. How, for instance, could such a model be used to predict turbidity within a slow flowing regulated stream where there is little steep terrain and, few, if any, landslides?

Considerable work has been done to model hydrological processes at this catchment scale. A survey of scientists and researchers conducted by the Cooperative Research Centre for Catchment Hydrology in 2002 identified 36 commonly used catchment models in Australia (Marston F. et al., 2002). Catchment scale modelling aims to understand the contribution of physical catchment characteristics to the dynamics of the catchment scale water balance.

Given the complexity of catchment scale hydrological processes, the prediction of hydrological processes at a regional scale would seem impossible. However, some attempts have been made to do this. For instance
a study by Lu et al. (2001) in which the Revised Soil Loss Equation (RUSLE) (Renard et al. 1997) was used to predict soil erosion potential across over a large portion of the Australian continent. The RUSLE is based on an empirical model of soil erosion potential developed in the USA in the 1950’s (Wischmeier and Smith, 1978, Wischmeier and Smith, 1960) and then revised in the 1990’s. The model relationships were developed from specific experiments on a local plot scale. These relationships form the basis of an equation which is then often applied as a predictive model to broader regions (Wallbrink et al., 2003, Prosser et al., 2002).

7.4 Method
Rather than attempt to develop a model at the catchment scale and extrapolate to the region, the method developed for this project aims to discover a model from a number of locations across the region and interpolate to the sub-catchments within that region. Broadly, the model building process consists of three main phases: establishing the model parameters; establishing a statistical model of turbidity; and processing the model within the GIS to make regional scale predictions.

Before the final set of model parameters were established the full range of potential variables were examined for their inclusion. Potential variables were developed by examining multiple regional scale digital data sets for their relevance to stream catchment processes and for the availability of useful data sets. When this was completed, a further model selection process was guided by a stepwise regression procedure and augmented by statistical examination and expert opinion. The aim of the model selection process was to identify a set of catchment characteristics whose collective spatial distribution could be considered an indication of expected levels of stream turbidity.

When a final model was selected from the full range of available data sets, a multiple linear regression procedure was used to identify weights for each of the dependant variables. The GIS was then used to construct a raster in which the value of each cell is equivalent to solving the regression equation for that cell. The coefficients from the regression equation were substituted by
rasters in which values represent the numbers of cells of each independent variable that flow into that cell. The final product, created by solving the regression equation, was a raster of Victoria that indicates the spatial distribution of modelled turbidity values.

### 7.5 Establishing the potential variables

The aim of this study is not specifically to understand or explain the physical processes that govern the occurrence of turbidity, but to produce a predictive model based on statistical association. However, the variables chosen needed to be useful. They needed to reflect patterns of land use that will enable regulators and land managers to identify current land use characteristics and consider change. It will not be helpful to include model variables that have no, justifiable, explanatory purpose.

Potential data also had to be available at a national scale, or cover the broader south-eastern corner of Australia. Some catchments extended beyond the Victorian border and were out of reach for data sets that covered only to the state boundaries.

Additionally, potential data had to provide the highest possible resolution. The catchments used in this study were geographical areas where all surface runoff drained to the location of a specific water quality sampling site on a permanent stream. Some of these catchments were only as much as thirty square kilometres, so that data with a resolution of that magnitude was not considered. Even data with 5-kilometre grid resolution was reluctantly used.

While assembling the potential variables, two major sources of data emerged: the GEODATA 9 second Digital Elevation Model (DEM) and the National Land and Water Resources Audit (NLWRA), data library. The DEM would provide a model for establishing distributed hydrological parameters and the NLWRA data library could provide large amounts of national environmental data, much of it constructed using the 9-second DEM as a base. The 9-second DEM has a resolution equal to about 250 metres in Victoria.

The NLWRA is a program of the National Heritage Trust, which was set up in 1997 to provide detailed information on the distribution and condition of Australia’s natural resources at a national scale. The data library is the
repository of a large amount of spatial data, much of it available in digital formats appropriate for GIS. Within the data library, two sources of relevant data predominate. One is a collection of data produced for NLWRA as part of a project to predict mean annual sheet-wash and rill erosion potential (Lu et al., 2001b). These data sets were used to apply the Revised Universal Soil Loss Equation (RUSLE) at a national scale. Another major source of data was that collected for the Audit by a project entitled ‘Assessment of Catchment Condition in Australia’s Intensive Land use Zone: A biophysical assessment at the national scale’ (Department of Agriculture Fisheries and Forestry Australia, 2002).

This data was augmented by mean annual rainfall data from the Bureau of Meteorology and vector files showing the Interim Biogeographic Regionalisation from Environment Australia (2000). A complete list of potential variables and their sources is included as a data dictionary in Appendix 4.

To establish the distribution of potential variables, the spatial data needed to be expressed as a function of area within the VWQMN catchments. This was important because the model will report the expected turbidity levels at any location, based on the proportion of up-slope area populated by the model variables. The process consisted of identifying the catchment areas using the GIS, identifying all potential variables and then quantifying the area of each variable within each catchment.

7.6 Delineate catchments for VWQMN sites

Of the 200 VWQMN sites, 179 were chosen to include in this study (see Figure 6-6, page 134). The study sites represent water quality monitoring sites on perennial rivers and streams only. Sites on intermittent streams were rejected because turbidity values could not be compared where complimentary data could not be found. The result is that north-western Victoria is under represented in the spread of sites. While considerable data exists for water quality at other locations, this study was restricted to the fixed sites. The system of collecting water quality data in Victoria has been developing since 1975. Much of this developing record contains missing data. It was decided that five contiguous years of data from 1997 to 2001 would
provide the most reliable data set (see Figure 7-1 - Figure 7-5). The need for at least 5 years of monthly turbidity measurements precluded input from local or community based water quality monitoring.

The first challenge of the project was to delineate catchments for each of the 179 VWQM sites. Manually, delineating catchments from topographic data is a laborious task, and in areas of low relief, involves high levels of uncertainty. This process is one that is ideally suited to GIS. Commonly available GIS procedures can be used to process digital elevation models so that they become hydrologically sensible; that is, flow patterns derived from elevation data produce concentrations of flow similar to real world stream flow.

Figure 7-1 Median annual turbidity - 1997
Figure 7-2 Median annual turbidity - 1998

Figure 7-3 Median annual turbidity – 1999
Delineation of catchments requires the spatial modelling of flow over the elevation surface. The direction and accumulation of flow can be represented.
as rasters and used to produce modelled catchment boundaries. These modelled boundaries are subject to any errors in the initial DEM.

### 7.6.1 DEM selection

Several sources of digital elevation data in Victoria, suitable for GIS, are available. The VicMap elevation data from Land Victoria offers coverage of the whole state captured at 1:25000. While better resolution was possible using the 1:25000 elevation data, a number of data sets of catchment characteristics available through the NLWRA used the GEODATA 9-second DEM (Digital Elevation Model) by Geoscience Australia as a base. Very little could be gained from having flow information at better resolution than other catchment data. The coarsest resolution of the input data establishes the scale of the output maps. To use a fine resolution DEM would only produce a false accuracy in the outputs.

The data in the 9-second DEM seemed ideal. It was constructed using digitised contour information from the 1:100,000 spot height topographic maps, and river and water body information from the 1:25000 topographic maps. The ANUDEM algorithm (Hutchinson, 1996, Hutchinson, 1989, Hutchinson and...
Dowling, 1991) was used to interpolate the data into a regular grid space at 9 second intervals and enforce drainage and ridge information. That is, known stream locations and ridge information were enforced on the interpolated DEM.

As Figure 7-6 shows, this drainage was not enforced uniformly. The reds cells represent areas where drainage was enforced. Especially in the north-western areas of Victoria, relief is so low that stream catchments are nearly impossible to define. The ANUDEM algorithm applies a global drainage condition, attempting to fill small areas of internal drainage (sinks), which are not otherwise noted. Stream and water body data, sink data and elevation data are also conditionally enforced using the ANUDEM. The relevant tiles for South Eastern Australia; SJ54, SJ55, SI54, and SI55 were imported into ArcView 3.2 using the ArcView Import Utility.

Most of the work for this project, including processing the DEM, was carried out using ArcView 3.2, using the Spatial Analyst extension. A number of other extensions were also used. These were, either provided as sample extensions with ArcView, or provided by a third party. Particularly useful was the hydrology sample extension Hydrov11.avx, provided as a sample extension with ArcView.

While both ArcView 3.2 and ArcGIS 8.3 were used for different parts of this process, nearly all of the processing was done using both programs at different times. No significance should be seen in using one program or the other. The work took place during a transition period from ArcView to ArcGIS. ArcView 3.2 had had a longer history of development, so that many extensions exist to complete tasks that might otherwise demand much work. However, excellent sample extensions, enhanced cartographic display, and extended spatial analysis tools make ArcGIS a superior product.

7.6.2 Using Mosaic to join DEM tiles
The four tiles were stitched into one large grid using the mosaic function from USCLE grid utilities in ArcView (College of Liberal Arts Computing Lab, 2000). Figure 7-7 shows the DEM rendered in ArcScene with exaggerated elevation.
7.6.3 Filling areas of internal drainage

The ‘Fill sinks’ function from the hydrology sample extension was used to fill areas of internal drainage and small random errors in the DEM. The sink-filling algorithm uses the ArcView ZonalFill command available in the ArcView Spatial analyst extension. This command identifies areas of internal drainage by checking for flow direction out of a cell (see 7.6.4 Calculating flow direction). If there is no flow direction out of a cell, the ZonalFill command then gives that cell the value of an adjacent cell with the lowest value. If the wider zone of cells continues to lack flow out, the process is iterated until flow is achieved.

Although the DEM had previously been processed to remove spurious sinks, a large number of sinks still existed in the original data. For the purposes of this project these sinks, which included the position of lakes or areas of internal drainage were not deemed important. Areas of internal drainage confuse the 8-direction method of flow direction calculation and produce anomalies in the flow direction raster; cells flow back into themselves and create erroneous values. All areas of internal drainage, therefore, were filled, so that the later

Figure 7-7 Geodata 9-second DEM rendered in ArcScene (elevation is exaggerated approx. 1000 times)
catchment and vector stream network delineation could more easily determine the direction of flow through areas, such as lakes and very flat terrain.

Over 2000 small pits or sinks were identified and filled in the four tiles of the DEM. A number of these can be attributed to the coarse resolution of the DEM in areas of low relief and complex terrain. If data points used to construct the initial DEM are too far apart they may not register the outlet of small catchments.

### 7.6.4 Calculating flow direction

With the filled DEM as the active grid, the flow direction function from the hydrology sample extension in ArcGIS 8.3 was used to produce a grid showing direction of lowest down-slope cell. The function uses the 8-direction method (O'Callaghan and Mark, 1984), to assign one of eight numbers depending on the direction of the lowest down-slope cell (see Figure 7-8).

At the resolution of nine seconds (approximately 250m) a generalised flow model was thought adequate. The eight direction method has the advantage that it provides a clear decision model for the delineation of catchments and the delineation of stream channels.

The D8 method determines flow direction by first finding the maximum drop, that is, the direction of steepest descent from the cell of interest.

\[
\text{maximum drop} = \frac{\text{change in z value}}{\text{distance}}
\]
The distance value is determined as the distance between cell centres. The distance between two orthogonal cells is equal to the width of one cell and the distance between two diagonal cells is equal to 1.414216 cells (ESRI Arcobjects Online, 2003).

If all adjacent cells have the same descent, the neighbourhood is enlarged until the steepest descent is located. When the cell of greatest descent is found, the cell of interest is given a direction code.

If all surrounding cells are higher than the cell of interest, then the cell has an undefined flow direction. These undefined cells represent sinks or pits in the DEM. Sinks may represent areas of internal drainage, lakes or other water bodies. However, sinks can also be artefacts of the interpolation used to create the DEM.

### 7.6.5 Deriving flow accumulation

With the flow direction grid as the active grid, the ‘flow accumulation’ function from the hydrology extension was used to calculate the number of cells that flow into each individual cell.

![Flow Accumulation](image)

Figure 7-9 Flow accumulation of the DEM

Values in the flow direction grid represent the number of upslope cells that flow through an individual cell. Figure 7-9 shows the flow accumulation raster.
7.6.6 Deriving a vector stream network
With the flow accumulation grid active, the stream network function from the hydrology sample extension was used to derive a vector stream network from the DEM. This function creates a stream network based on a threshold value of accumulated cells. Varying thresholds were chosen to represent the number of accumulated cells that represent the start of modelled streams. 100 and 500 cells, in particular were chosen as useful values. The routine finds cells whose accumulated values meet the threshold and creates a vector network that generalizes a line connecting those cells to downstream cells.

7.6.7 Overlaying VWQMS locations
A vector point coverage of VWQMN sites was overlayed on the derived vector stream coverage to ascertain the coincidence between the geographic coordinates of the point data and the derived stream network. However, most of the point data was provided in degrees and minutes only. Given that sixty seconds of arc is equal to approximately 1 kilometre, some moving of points was going to be necessary.

The point data came in three groups. Group one contained a number of points with location available in latitude and longitude using the AGD 66 spheroid. Group two contained a number of points projected using the Australian Map Grid 55 coordinates, the Universal Transverse Mercator projection, on the AGD 66 spheroid. Group three containing two points in AMG used the Australian Map Grid 54 coordinates.

All three groups were imported into ArcView. Group two and three were saved as ArcView shape files and then converted from the AMG coordinates to the common format of latitude and longitude, using the ArcView projection utility.

The differing data sets reflect the fact that water quality monitoring in Victoria has been partly privatised and separate organizations were, during the initial stages of this project, responsible for reporting in separate regions.

7.6.8 Check point locations on stream network
Two issues were evident when the point theme was overlain on the stream network. Firstly, given that group one points did not have positions accurate to 60 seconds, a number of points had to be moved, up to one kilometre. This
discrepancy meant that at some stream locations, especially near the confluence of one or more streams, it was difficult to ascertain which stream the point belonged to. To rectify this problem the VicMap hydro theme was used to verify stream names and locations. The VicMap data was converted from VicGrid coordinates, using the Arc Toolbox projection wizard and converted to geographic coordinates.

A second issue was the 9-second resolution of the DEM. Although several regions in the DEM had had a stream network enforced, in most areas the hydrology at the valley bottom was not enforced. This meant that stream locations in areas of low relief were unreliable. Where a stream channel is the most significant change in terrain (e.g. areas of north-western Victoria) generalisation results in streams being located at a significant distance from true position. Where significant numbers of cells have the same elevation, the direction of flow takes a straight line to the nearest cell of lower elevation. This problem seemed particularly acute near the confluence of streams.

### 7.6.9 ‘Burning-in’ a more reliable stream network

The difficulty in identifying stream locations was tackled by enforcing drainage in the DEM using a vector coverage of streams that had been enhanced with information from topographic data. A stream network was acquired from the National Land and Water Resources Audit (NLWRA). The stream network entitled ‘Austreams’ was produced for a project of the NLWRA called the ‘Water-borne erosion and sediment transport project’ (see Figure 7-11). Austreams contains most of the larger streams in Victoria and achieved a better stream location for all but a few of the VWQMN sites. The need to use a simplified flow model is brought sharply into focus by the sheer density of streams shown in Figure 7-12.

The contrast between the stream network derived from the DEM and Austreams is illustrated in Figure 7-10. It shows differences of up to eight kilometres in stream position. The Horsham area has, generally, low relief and delineation of stream locations in this area from the DEM is unreliable. In such sites it was difficult to tell the actual location of the stream channel, or on which channel the site belonged.
To combat this problem, drainage was enforced through the use of an Avenue script in ArcView 3.2 from an extension called CRWR-PrePro (Hellwegner et al., 1997). This script, ‘txdot.burnstreams’ forces all cells that spatially coincide with the vector stream network to acquire a user defined elevation value. This value (in this case an arbitrary -50000 metres) is sufficiently low to make all adjacent cells higher. When the filling command is run and the flow direction command is run, adjacent cells are forced to flow into the enforced network. Figure 7-13 shows how the new DEM has a highly defined stream location. The burning-in only applies to cells that are coincident with the Austreams network, and when the filling command is run any new sinks caused by the new stream course are also filled.

Figure 7-10 Comparison between Austreams and DEM derived stream networks
Vicmap Hydro theme

Figure 7-12 Vicmap Hydro theme. The streams in this theme are so dense that a simplified stream network was necessary. The hydro theme contains transitory streams and streams that are closer together than the resolution of the DEM. That is, closer than 250 metres.
7.6.10 Adjusting points to locate them on the new stream network

The VWQMN points were edited within ArcView and manually moved onto stream locations. Although, the watershed function in ArcView lets the operator specify a threshold value to snap the pour points to the accumulation grid, this procedure can be arbitrary unless the data points are not first located within the snap distance. The points were moved to within one or two cells of a stream location; hence, within a zone of high-accumulated flow, and the snap distance set to three cells (approx. 750m).

Some data errors were identified in the location of points. These were rectified. A number of points were compared to the true position of streams using the VicMap hydro coverage, and relocated accordingly.

7.6.11 Delineate catchments

The catchments were constructed within ArcView 3.2 using ‘wshed_point.ave’ (Fridjof Schmidt, 2001). This is an Avenue script that delineates catchments using a point theme as the pour-point input. This script converts the point theme into a temporary grid and then runs the watershed function of the hydrology extension. The ‘watershed’ command converts the point theme to a
raster and uses the raster as a weight grid to determine the source of pour points for catchment delineation.

7.6.12 Checking catchment theme

The output from the watersheds script is a vector polygon coverage representing discrete catchments (Figure 7-14). The attribute data from the point coverage, which included data on turbidity and stream flow, was then joined to the polygon coverage.

The new catchments were then checked against vector catchment data available from the NLWRA; the coverage called ‘Surface Water Management Areas’ (Figure 7-15) and the coverage entitled ‘Nested catchments’ (Figure 7-16). The nested catchments and sub-catchments coverage from the NLWRA was determined from the latest 9-second DEM, with threshold values of 2.5km², 20km², 50km² and 500km². These catchments are defined by the

![VWQMN Catchments](image)

Figure 7-14 VWQMN catchments

area, or threshold values, but do not relate, specifically, to hydrologically meaningful areas (Hutchinson et al., 2001). Comparison between the VWQMS catchments and the nested catchments show a consistent similarity, especially in areas of complex relief. In a few areas, especially where relief is low, divergence is significant.
7.7 Identifying all potential data sets

The process of delineating catchments has been necessary for two reasons. Firstly, it has enabled the creation of spatially discrete areas that can be used to examine for biophysical characteristics. Just as water itself is, generally, accumulated to the lowest point in a catchment, this project is accepting that water quality variables are also accumulated to the lowest point in a catchment. The statistical model will seek to discover the relationship between the areal proportion of catchment characteristics and measured levels of stream turbidity. However, it is to be kept in mind that more complex rainfall runoff relationships may exist within a catchment.

The second reason for processing the DEM is to create a hydrologically sound model of the surface, so that a flow accumulation procedure can be used to model the effect of biophysical variables in the same way that the DEM can be used to model the movement of water.

Figure 7-15 Surface Water Management Areas (National Land and Water Resources Audit.)
7.8 Transform data sets into common format

All data sets that were to be included were transformed into a common format. While attempts have been made by organizations to standardize spheroids, datums and map projections, each project or organization has its own requirements. For instance, some digital data produced for the Department of Natural Resources and Environment is currently using VicGrid, which has, until recently, used a Lambert’s Conformal Conic projection using the AGD66 spheroid. However, most digital data produced for the NLWRA contained no projection information. These data sets were commonly in geographic coordinates, using the World Geodetic System 84 (WGS84), while other data sets used the new GDA94 spheroid.

For the purposes of this project, all vector data and raster data was stripped of projection information using the ArcGIS Toolbox. This enabled all data sets to occupy the same spatial extent based, purely, on latitude and longitude. It was necessary, however, to reproject all layers into Albers Equal Area projection to enable the calculation of area and the tabulation of area of each variable within each catchment.
7.9 Cross tabulate area of variable within the extent of catchments

Within ArcView, an Avenue script called Reproject was used to copy each raster to a new view. The new raster assumed the user-defined projection of the new view. Albers Equal Area projection was chosen to enable the area of each variable to be cross-tabulated within the area of each catchment using the ArcView tabulate function.

The output was a table in which rows represented the catchments; identified by their Gridcode number (a unique identifier), and columns represented a particular variable. Values in the table were the area, expressed in square kilometres, of each variable within a particular catchment. The cross tabulation was performed iteratively, and values were exported to Excel and copied into a single spreadsheet.

The result of this work was that the vector polygon coverage of VWQM sampling sites was attributed with values that represent the area of a number of catchment characteristics within each catchment.

The next phase involves discovering a model to summarize the relationship between those catchment characteristics and measured levels of stream turbidity.

7.10 Model selection

Models may be termed black box, grey box or white box (Lindskog, 1997). So-called, white-box models attempt to define processes within natural systems using purely mathematical relationships. These relationships may be arrived at through empirical experimentation, as in the case of the Universal Soil Loss Equation (Lu et al., 2001b), or they may used to test theoretical relationships. The presumption in a white box model is that interaction between variables in the model defines the model output. Physically based models are common in studies of catchment hydrology, for instance, see HSPF (Bicknell et al., 1997), SLURP (Kite and Droogers, 2000), Modflow (McDonald and Harbaugh, 1988), Topog (Vertessey et al., 1994), Topmodel (Beven et al., 1984) and many others. The US Geological Survey, alone, provides twenty-seven different catchment models.
These physically based process models require intense computational complexity, even at the scale of small catchments. Their application to regional hydrology is made difficult by the need for an enormous amount of data and by the need for that data to be locally based.

The concept of complex systems suggests that linkages between system components are both non-linear and tightly interrelated. This might suggest that for every different assemblage of system components different inputs and outputs exist. At the catchment scale, this would demand that a model must not just take into account the distribution of particular vegetation, but the relationship between that vegetation and its locally identifiable suite of interrelationships. This concept can be continued as the focus identifies relationships even at the micro level.

A conundrum is created; if water quality is considered in the complex systems view, as interrelated at all spatial and temporal scales with the enveloping ecological system. Then models, such as the RUSLE (Lu et al., 2001b) with its satisfying deterministic simplicity, may be too crude to estimate the impact of erosion on a regional scale. However, the complex, process based models that are helping us to explain the detailed connective relationships in small catchments would be too unwieldy to provide models on a regional scale.

It is the acceptance of the complex systems view that also requires that the modelled data be spatially distributed. In this present model, it is recognized that, while the output is distributed and the inputs are distributed, the processes and interrelationships between variables are not distributed.

Grey box models are models in which system-identification is augmented by expert judgement. In a grey box model, the definition of system components and the relationships between variables are constrained by the intervention of heuristic rules. Further, in a grey box model, relationships between system components may be expressed using verbal, or fuzzy, language (Lindskog, 1997).

The reality is that the choice of variables in any system must always involve some element of subjective decision-making. In complex systems, system
identification involves a level of generalization, and that generalization must rely on expert knowledge of major system components.

Black box models are models in which no physical relationships, or preordained system identification is assumed. The reality, again, is that some assumptions must be present from the outset of system identification. Data availability and prior knowledge are inescapable elements in model design.

The model constructed for this project could be described as a black box model. However, the choice of variables has been strongly influenced by data availability and, to some extent, by prior knowledge.

Although, determined, primarily by the lack of process models that might adequately perform at a regional level, the use of a semi-distributed model has been defended for other reasons. Wooldridge (2001) hypothesizes that ‘in the case of regional fluxes (in that instance, stream-flow and evapotranspiration), it is not necessary that all the ‘local’ detail should be known. Spatial co-dependencies exist between terrain, soil, climate, vegetation, geological features and drainage networks’.

The model chosen for this project is then, a grey box model because it augments a lack of process information with prior knowledge. It is also semi-distributed, because the physical distribution of the variables is known, but the relationships between model variables are not known, instead they are statistically modelled.

### 7.11 Model selection method

The model selection method chosen for this project will seek to establish a statistical model of stream turbidity using a type of multiple linear regression called stepwise regression.

A statistical model, according to Hopkins (2000) expresses the relationship between variables and can be used as a way of generalising from a sample to a population using effect statistics such as correlation or the difference between means.

Hopkins (2000) comments that when we need to find the way one numeric parameter is affected by another numeric parameter then a suitable simple
model would use linear regression to estimate model parameters. If any of the datasets within a model are nominal, that is they are in the form of names or levels, then there are other techniques to develop models such as logistic regression.

In the case of the current investigation we wish to know how stream turbidity expressed as a numeric is affected by a number of factors also expressed in numeric form. We are assuming a complexity of influences. That is, we are including a number of terms in our statistical model that reflect important system components. This form of regression operation is known as multiple regression and if the regression equation is fitted to a straight line then it is a multiple linear regression.

There are a number of other tools that are available to investigate relationships between numeric parameters, including multivariate statistics such as principal components analysis (PCA), factor analysis, multidimensional scaling (MDS), cluster analysis and artificial neural networks. These techniques are often used to investigate the dependency between a number of discrete datasets. Univariate statistics such as regression are, in a simpler form, often used to model the relationship between a single dependent variable and a number of independent variables.

In the case of this study, while it would be valuable to know the relationship between parameters in the model, the overall aim is to make a predictive model, not an explanatory model. At the outset we have to acknowledge the limitations of data at the regional scale, where there can be large amounts of uncertainty in individual data sets. The discovery of relationships between variables in a multivariate model would be likely to be erroneous. There may be strong correlations between the data sets, but the likely existence of collinearity between these datasets would mean that discreet effects between data sets would be hard to detect.

In stepwise regression the object is to produce a prediction equation, but the process also, explicitly, uses statistical criteria to select which of a number of predictor variables will be included in the final regression equation (McCuen, 2003). These subsets reflect groupings whose $R^2$ (coefficient of determination)
values indicate that they may explain the greater amount of variation in the dependent variable. The process begins by adding the variable that has the highest level of correlation with the dependent variable and then, subsequently, adding all other variables to the model that result in a strong effect on the residual sums of squares (Rawlings et al. 1998a).

The stepwise procedure includes two processes: forward selection and backward elimination. The fundamental procedure of stepwise regression begins with the calculation of an F-statistic for each variable in the model. The F-statistic tests whether the $R^2$ square proportion of variance in the dependent variable accounted for by the predictors is zero and its corresponding p-value estimates the probability that the values of the F-statistic are equal to or greater in magnitude than could be expected, when compared to the variance in the dependent variable (Rawlings et al. 1998a).

The forward selection adds variables to the model until a termination rule stops the process. The termination rule, or alpha level, uses the p-value as an indication of significance. When subsequent variables introduced to the model do not pass the termination rule, the selection process terminates.

The backward elimination process starts with the full model, that is all the variables included, and then eliminates those variables from the model, one at a time, that have the least effect on the residual sum of squares. The process is repeated until the termination rule is breached.

At the outset, available model variables were screened for their practical, process-based, linkages to turbidity. Data chosen were those that most obviously reflected the biophysical characteristics of catchment surface, ecology and hydrology. However, this process was constrained by the availability of data. Since national data sets require huge sums of money to produce, it was beyond the scope of this project to produce data that specifically related to turbidity.

A distinctive characteristic of this model is that the strength of variables was measured in units of their spatial distribution (area). Rather than the absolute value of their occurrence, each variable had to be divided into classes of
relative strength. For this reason, variables not already in categories or classes had to be classified.

Continuous values were classified using ArcGIS 8.2. This process used equal-area classification in which classes represent equal area under the normal distribution curve. For instance, areas of predicted clay content in the A horizon, a data set obtained from the NLWRA was given 3 classes using the equal area method. While some variables from the NLWRA were already classified into five classes, other variables were classified into three classes for the purpose of this project. These classifications, it is hoped, reflect the major variations in those continuous variables (The names of individual data sets and the classifications used are included as a data dictionary in Appendix 4).

Once the potential variables were classified, the catchments were used as cookie cutters to extract the distribution of each variable within each catchment and express it in terms of square kilometres per catchment

This data was exported into Minitab statistical software and each variable was plotted against turbidity for each of the five years. The resultant regression equations, lines of best fit and plots were examined for significant relationships between turbidity and individual variables. Variables, that appeared to have no significant relationship with turbidity, were removed from the data set. This process removed a number of individual classes and entire variables. At this stage the classes and variables removed were those that appeared to have no relationship with turbidity at all. That is, when the variable was plotted against turbidity for each of the five years a visual inspection of the plot coupled with the analysis of variance showed no relationship then variables were removed. There was no absolute threshold used, as some relationships which showed high explanatory power were omitted because outliers in the data set produced false correlation. If some variables showed a relationship in one year and not another, as was the case with numerous variables, the variable was included.

Variables, which lacked a significant spatial distribution, were also removed. Land use variables, for instance, which only appeared in isolated pockets,
were removed. Of the four land use classifications examined, only the very general land use classifications were retained. An attempt was also made to identify variables that measured the same response with turbidity. Collinearity within variables, while not a large problem with predictive models (Rawlings et al., 1998a), was detected through the strength of the Variance Inflation Factor (VIF) and inspection of the correlation matrix and regression plots. Variables that were highly correlated with other variables were removed based on their likely association with stream turbidity. The object was to leave the smallest subset of variables that had the most logical association with the processes that determine stream turbidity.

The most obvious criticism of the stepwise approach must be that relationships within natural systems are complex and generally non-linear. Any attempt to describe these relationships using linear regression must be prone to difficulties. Any interpretation of a simple statistical model must be aware that a feature of this kind of simple statistical model is an oversimplification of the complexity of natural systems.

The problem of oversimplification is also added to in stepwise regression by the danger of including too many variables in the model selection process. The process of finding variables that displayed the greatest independence and yet still showed a significant relationship to turbidity meant that spurious models were reduced as far as possible.

It is a criticism of stepwise regression that by sifting through a large number of potential models, random variation within the data can cause the model to “overfit” the data (Rawlings et al., 1998a) (Scott Armstrong, 1970). That is, random variation within the model may produce a false fit. A strong relationship may be apparent but when repeated with a number of data sets the random variation is revealed. By repeating the model with other data sets, the influence of this random variation can be limited. In this case, models were repeated with data from each of the five years, 1997 to 2001. While no model produced the same results with each year’s data, models that produced significant results across all five years can be thought of as less affected by random variation within a single data set (Table 7-2). The model may still be
reflecting random variation across all five data sets and, because of this, the model remains valid only for the five data sets used in the model validation.

The problem of non-linearity was, partially, tackled by examining, and transforming, all data sets so that their distributions appeared near normal. These relationships may take a number of forms. In the case of the date sets used in this model log (base 10) and fourth root transformations were found to reveal normal distributions in value distributions. This transformation included the turbidity values, so that the model created would be used to predict log turbidity. A visual inspection of a histogram of data values for all model parameters was used to determine normality. The aim of these transformations was to enable the use of simple linear regression. While this dealt in some way with non-linearity in the dataset, it does not deal with non-linearity in the relationship between variables. The resultant model then refers to the static correspondence between the turbidity recorded and the datasets.

### 7.12 Outputs from model selection

The complete list of potential variables was examined for independence, relevance and significance. The result of this heuristic process was to reduce the set of potential variables from 212 to just 59 (see Appendix 2 Model remaining after initial model selection process using catchment-derived data).

Using Minitab, the remaining 59 variables were examined using forward stepping and backward elimination procedures. The results of the stepwise regression produced strong values for $R^2$ (see Table 7-2) and validation over five years of data showed that the model held strong for other data sets.

The difficult question is, however, which selection of variables to choose as a final model. The stepwise procedure identifies models that fit the particular data set to which they are applied. It will not be enough to apply the 1997 forward selected model just because it has the highest value for $R^2$. When applied to the other data sets it will, naturally, score less because it is not fitted to them. Several other options exist. These other options all involve a reduction in the level of variance explained by the model, because no other model is going to be as good as the one constructed to fit that year’s data.

The results of the stepwise procedure produced strong values for $R^2$ adjusted
$R^2$ is an indication of the amount of variation in the dependent variable (turbidity), which can be explained by the independent variables in the regression equation, assuming that values for the dependent and independent variables are normally distributed. In this case, the assumption was made within 95 percent confidence limits.

$R^2$ adjusted ($R^2_{adj}$) is a value of $R^2$, adjusted for the number of variables in the regression. Because this value is weighted according to the complexity of the model, it allows a comparison to be made between models (Rawlings et al., 1998b). Values for $R^2_{adj}$ were determined for a total of five years of data. The values for $R^2_{adj}$ ranged from 42.83% to 61.27%.

While the values for $R^2_{adj}$ were strong for each of the five years, the models arrived at varied considerably. Within the ten models constructed, through five years of forward and backward selection, only one variable ‘irrigated agriculture’ was present in all ten. Five variables also occurred in eight models; one in seven and two in four (see Table 7-2). It seems logical to assume that in different years different variables may be the controlling variables in the occurrence of stream turbidity. Each model is then, a model that fits the data for that particular year.

The first attempt to fit a model across all five years was to construct a model using variables that have the greatest frequency of occurrence in the stepwise process. This model, M1, consisted of the seven variables that occurred in seven or more stepwise models. Surprisingly, the values of $R^2_{adj}$ are not significantly less than the individual models for each year (see Table 7-2). Mean values for $R^2_{adj}$ reduced from 54.6% to 52.03%. The results were still significant.

A number of variables in the initial model were qualitative measures. That is, they were ranked indices of catchment condition, biota condition or land condition. In M1 Land condition 1 and Catchment condition 2 were included. Model M2 omits these variables for two reasons. Firstly, it would seem counter-intuitive to use variables that equated levels of turbidity with a qualitative ranking. There is no evidence in the data, or in published literature, that would directly relate raw measured levels of turbidity with catchment or
stream health. It is possible, then, that these variables are reflecting other factors indirectly.

Model M3 was constructed by stacking all five years of data into columns. A stepwise regression was, then, applied to those five years as a single time period. The forward selected model of eight variables was then applied to each year of data separately. The best overall model was M1. With a mean $R^2$ of 53.74% compared to the mean $R^2$ of 51.5% for the stacked data.

<table>
<thead>
<tr>
<th>Models tested from catchment derived data</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M3</td>
</tr>
</tbody>
</table>

At this stage in the project it was determined that the spatial data that was gathered on a per catchment basis, did not reflect the true hydrological situation. If all catchments were discrete, the data at any point on a stream would reflect the upstream area of each catchment characteristic. However, many of the catchments were nested within larger catchments. That is, some monitoring sites included other sites in their catchment so that their values only represented the area of catchment characteristics downstream from the next upstream water quality gauge.

The problem was tackled by regenerating all the data for potential variables and accumulating grid values to cells that represent the generalised stream location. A raster was generated for each variable. Values were 1 for presence and 0 for absence. These rasters were used as weight grids and the hydrology accumulation function was used to construct a raster where values represented the number of upstream cells with the value 1 from the weight grid that flow into that cell. In the new data set, values at all sites are equal to the number of upslope cells containing the particular characteristic. The newly constructed data was investigated using the stepwise procedure and a model constructed using the most frequent variables (see Table 7-23).
Two models were constructed with this data, one containing the most frequent variables from the stepwise procedure, and one constructed from stepwise investigation of all five years of data stacked. Overall, the use of accumulated values resulted in a reduction in $R^2$ for most years. Comparison of Table 7-2 and Table 7-3 shows that mean values of $R^2$ adjusted fell from !The Formula Not In Table% to 52.17%.

It is clear that not all catchments are the same size, although the model treats them as if they all have the same weight in the regression. One way to give all catchments equal weight was to calculate the area of each catchment characteristic as a proportion of the catchment. In this way the value in the regression would be the relative proportion of the catchment; that is, the percentage of the catchment taken up by that variable. Forward and backward stepwise procedures were carried out on this proportional data; the result was a mean $R^2$ of 33.3% for all five years.

Considerable predictive power has been lost by reducing the influence of catchment size. Clearly, catchment size is a hidden effect in the data; even though regression between turbidity and catchment size itself shows little or no effect. Regression between the turbidity data and catchment size shows values for $R^2$ of less than 2%.

The answer to this puzzle is most likely that the effect of normalising the spatial data is to reduce the influence of variables with limited spatial distribution in large catchments. It may be that the presence of irrigation in a large catchment will have a substantially larger influence than its distribution would indicate. This probably shows that the effect of spatial distribution for each variable is not linear.

By using the absolute area of each variable, the model assumes a linear relationship between the area of a variable and turbidity. While models could be constructed to find the relationship between the spatial distribution of a variable and its contribution to the response, it would require far more detailed data than is currently available at this scale. Proportional data, however, is not the answer in this case, as it treats a small area in a small catchment as equal to a larger area in a larger catchment.
<table>
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<th>$R^2$ Adjusted</th>
<th>62.7%</th>
<th>72.5%</th>
<th>86.7%</th>
<th>85.8%</th>
<th>87.0%</th>
<th>75.9%</th>
<th>66.8%</th>
<th>86.9%</th>
<th>77.0%</th>
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<tr>
<td></td>
<td>($\alpha$)</td>
<td>0.06</td>
<td>0.07</td>
<td>0.12</td>
<td>0.13</td>
<td>0.13</td>
<td>0.15</td>
<td>0.16</td>
<td>0.15</td>
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<tr>
<td></td>
<td>($\beta$)</td>
<td>0.06</td>
<td>0.07</td>
<td>0.12</td>
<td>0.13</td>
<td>0.13</td>
<td>0.15</td>
<td>0.16</td>
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<tr>
<td></td>
<td>($\gamma$)</td>
<td>0.06</td>
<td>0.07</td>
<td>0.12</td>
<td>0.13</td>
<td>0.13</td>
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<td></td>
<td>($\delta$)</td>
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<td>0.16</td>
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Table 7-2: Results of stepwise regression on catchment derived data.
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<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
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</tbody>
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Table 7-3: Results of Stepwise Regression on Accumulated Data

Chapter 7
7.13 Incorporating the model in a GIS

The next step was to incorporate the model within the GIS. While this process could be applied to any model and could be used to derive any number of models from as many combinations of data, for this particular project the process was initially used to derive the spatial distribution of predicted values by the M1 model applied to the 1997 data. The aim of this process is to map the predicted turbidity values, using the regression equation. That is, to model the relationships between the variables within the GIS and map their influence on turbidity at locations other than sampling points.

7.13.1 Create rasters of each variable

As all data used in the project was in integer format, a selection set could be made to isolate a single class and save it as a new raster. This was performed for each variable in the regression equation. Cells in the new rasters had a value of one if they contain the selected variable and ‘no data’ if they did not (see Figure 7-17 - Figure 7-23).

![Altitude of the Catchment Centroid](image)

Figure 7-17 Altitude of the Catchment Centroid
Figure 7-18 Road Density 3

Figure 7-19 Catchment Condition 2
Figure 7-20 Native Vegetation Extent 2

Figure 7-21 Land Use - Irrigation
Figure 7-22 Land Cover - Pasture

Figure 7-23 Land Condition 1
7.13.2 Accumulate each variable

The flow accumulation function in ArcView 3.2 was used to count the number of cells of the independent variables upstream from each cell in the raster. The flow direction raster was named as the direction grid and the independent variable raster, as a weight grid.

It was very important at this stage to make sure that all input rasters had the same cell size and the same projection information. Because the underlying flow direction raster was produced using the DEM, all rasters that were not already created using the DEM were resampled to a consistent resolution of .0025 decimal degrees.

Cell values in the new rasters represented the number of cells containing the independent variable flowing into each cell. These rasters were then divided by 16 to give an approximation of area in square kilometres.

7.13.3 Multiply by coefficient

Using the grid calculator the values in each of these rasters were then multiplied by their coefficients in the regression equation. The regression model used was in the form:

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_p x_p + e \]

Equation 7-1 The regression model

Where \( y \) = dependent variable, \( \beta_0 \) = y intercept, \( \beta_1 x_1 + \beta_2 x_2 + ... + \beta_p x_p \) = independent variables and \( e \) = is the random error.

The final structure of the regression equation for M1 was:

\[
\log(\text{Turb97}) = 1.22 + 0.1454 \text{ LUI} + 0.09884 \text{ LCP} + 0.07934 \text{ LC1} - 0.1534 \text{ NVE2} - 0.124 \text{ RD3} - 0.1524 \text{ ACC} + 0.04754 \text{ CC2}
\]

Equation 7-2 Regression equation for M1 model applied to 1997 data

Where:

Turb97 = median annual turbidity;
LUI = areas of irrigation identified from a land use theme;
LCP = areas of pasture from a land cover theme;
LC1 = areas of land condition 1, identified from a relative land condition theme;
NVE2 = areas of natural vegetation extent, classification 2;
RD3 = areas of road density, classification 3;
ACC = altitude of the catchment centroid; and
CC2 = areas of catchment condition, classification 2.

7.13.4 Solve the regression equation

The grid calculator in ArcMap 8.3 was used to combine the rasters in the form of the regression equation adding the value of the y intercept, to produce a new raster whose values represented log turbidity. Effectively the regression equation has been determined for every cell in the raster.

7.14 Results of modelling

The values of the log turbidity raster were then inverse log transformed to produce the predicted turbidity levels for each cell. The major output from this process was a raster of Victoria, in which cell values represent predicted stream turbidity from the M1 model (see Figure 7-24 and Figure 7-25). The value range (1 – 281) is consistent with the original data range (0.76 – 140).

These predictions are summarised in Figure 7-26, Figure 7-27 and Figure 7-28. Broadly, it can be seen that catchments with high maximum turbidity also have wide ranges of values. However, some catchments, especially, those in Gippsland and in the Otways are predicted to have high mean turbidity values, but low maxima and narrow ranges.
Predicted turbidity using the M1 model on the 1997 data

Figure 7-24 Modelled turbidity values for Victorian streams, using the M1 model

Figure 7-25 Modelled turbidity values for Victorian streams in the Melbourne region, using the M1 model
Figure 7-26 Maximum predicted annual median turbidity using M1 model on 97 data

Figure 7-27 Range of predicted annual median turbidity using M1 model on 97 data
Figure 7-28 Mean predicted annual median turbidity using M1 model on 97 data

Figure 7-29 Distribution of predicted values using the M1 model on 1997 data: 4th root transformed
A brief check of the distributions of the 1997 data and the predictions (Figure 7-29 and Figure 7-30) shows that the distributions are similar.

In Minitab, the residuals were also calculated and divided by the standard deviation. Residuals are the numerical difference between the model predictions and the measured values used to make the predictions. They are, then, a measure of how well the model predicts the real world. If there is no bias in the residuals they should be normally distributed. Figure 7-31, for instance, shows the distribution of residuals for the M1 model on the 2001 data. In a normal distribution 95% of observations are commonly expected to be within two standard deviations and 99.7% of the observations to lie within three standard deviations. Observations that fall outside three standard deviations clearly indicate effects in the response variable not accounted for in the regression model. In the maps of standardised residuals (see Figure 7-32 - Figure 7-36), catchments under-predicted by the model in each of the five years, are clearly visible in red.
Figure 7-31 Model M1, histogram of standardised residuals 2001

Figure 7-32 Modelled stream turbidity – M1 standardised residuals 1997
Figure 7-33 Modelled stream turbidity – M1 standardised residuals 1998

Figure 7-34 Modelled stream turbidity – M1 standardised residuals 1999
While the residuals represent the difference between the fitted values from the regression and the measured values, Figure 7-37 shows a map of the difference between the measured turbidity and the predicted turbidity from the predictive raster. A number of catchments in the north-central part of the state (yellow) are under-predicted by the model, and some over-predicted by the model (purple to dark blue). Catchments that are under predicted by the
model correlate well with those catchments that have high maxima and wide
ranges of turbidity. The exception being catchments in Gippsland where high
measured levels of turbidity are predicted with reasonable accuracy. One
inference that could be drawn from this is that in north-central catchments that
have high and highly variable levels of turbidity, some agent is at work that is
not accounted for in this model. One explanation that could account for this is
that high levels of mobilised sediments in these catchments relate to past land
uses that cannot be captured by current digital data sets.

![Difference between measured turbidity and predicted turbidity from the M1 model using the 1997 data](image)

Figure 7-37 Difference between measured turbidity and predicted turbidity from the M1 model using the 1997 data

7.15 Conclusion

The purpose of chapter 7 was to discuss the construction of a regional spatial
model of stream turbidity for Victoria. The aim of the model produced by this
work was to establish probable turbidity values based on knowledge of
catchment characteristics. These modelled values can be compared to
measured values to provide catchment managers with an initial assessment of
whether measured values are similar to expected values. They could also be
considered as baseline values, from which further modelling might infer a
trend in water quality associated with catchment land use. Additionally, these values could be compared to reference conditions to infer a level of environmental health that connects water quality with catchment land use.

The method detailed a novel approach to deriving distributed model predictions in a raster based GIS. The method consisted of establishing an initial suite of potential model parameters, selecting a test model using a stepwise regression procedure and using a final regression to establish coefficients for model parameters. The modelling outputs were then spatially distributed using hydrological functions within the GIS. The major output from this procedure was a map of Victoria showing predicted stream turbidity.
CHAPTER 8. EVALUATION OF MODELLING METHODOLOGY

8.1 Introduction

Chapter 8 discusses the results of the model developed in chapter 7, evaluating the way in which errors introduced in the modelling process are manifested as uncertainty within the model predictions.

The need to understand the relationships between environmental phenomena underpins the need to generalise complex systems and simplify their often vast complexity in the form of models. The development of models is also driven by the need to make predictions of unknown temporal and spatial states from selected system indicators.

The success with which the model contributes to an understanding of system function, or the degree to which the model can accurately predict unknown states, must be an indication of the model’s performance. In the view of Thomas et al. (2004), a model’s performance can be evaluated through verification, validation and evaluation. The process of verification and validation is where the model results are compared to measured data, and the model outputs have been assigned a ranking based on performance against an accepted user-defined criterion (Thomas et al., 2004).
Model evaluation, however, can have another meaning. Model evaluation involves the comparison of model results or methodologies with other models or other expected outcomes (Thomas et al., 2004). This chapter will consider the performance of this model, by examining the modelling methodology against the intended purpose of the model. The broad intention of this model is that it will provide indicative values of median annual turbidity for Victoria at a higher resolution than the catchment scale, but regional in scope. It is not intended to provide absolutely accurate predictions. This would be an unreasonable expectation, given the coarse resolution of regional data and the heterogeneity of turbidity and associated topography, vegetation and climate.

8.2 Uncertainty


In the case of the current model, and for the purposes of this evaluation, there are three main sources of error in the modelling procedure and, therefore, three main sources of uncertainty in the modelled predictions: model input errors, errors introduced with the statistical methodology and errors introduced with the GIS methodology.

8.3 Model input error

Model input error includes errors introduced into the model due to uncertainty in the underlying data. In particular, errors are inherent in the turbidity data and the regional digital data sets.

8.3.1 Water quality monitoring

As discussed previously, water quality observations represent a miniscule sample of the class of potential samples. These potential samples have a temporal and spatial distribution. The turbidity data used for this project consists of a median value of monthly samples for one year. Continuous
monitoring of turbidity in a particular stream would find that turbidity is extremely variable over the course of a year, increasing during and after storm events (Sadek, 1998).

The physical location of samples represents a tiny sample of potential samples in the stream channel at any instant. These instantaneous measurements then can be influenced by localised environmental phenomena such as point source pollution, local land use or local topography. For catchment scale studies these localised effects may have important consequences for the study at hand, however, at the more generalised scale, a parametric approach helps to reduce the influence of annual temporal variability. Median values, in particular, help reduce the influence of extremes. An assumption made in this project is that the measured values of turbidity at any location reflect the influence of land use in the upstream catchment. However, these instantaneous measurements may be open to errors due to local factors.

8.3.2 Incomplete monitoring data

A possible source of error may also arise because the accuracy of monitoring data was not tested. It can be assumed that inaccuracies exist in the data due to mechanical failure and human error introduced during the recording of observations, and the manipulation of raw data into parametric form.

8.3.3 Uncertainty of point location data

Other errors were introduced with the turbidity data set. Some locational data was inaccurate, and while all attempts were made to locate the 177 sites correctly, it is possible that some sites were not sited properly. Validation of the position of these sites was beyond the scope of this research.

8.3.4 Poor resolution of regional data sets

In raster digital data, resolution refers to the individual cell size. The value in that cell represents one individual estimate that summarises values for the area of the cell. If the number of observations is less than the number of cells, then an interpolation can be used to estimate values for unknown cells. The reliability of an interpolation is influenced by the distance between
observations and how well the heterogeneity of the phenomenon is modelled. The further apart the observations, with regard to the cell size, the greater the uncertainty.

The cell size of data used in this project was for the most part at 9-second resolution: this represents roughly 250 metres on the ground. Data sets produced for the Catchment Condition project were at 5-kilometre resolution, and the Bureau of Meteorology rainfall data was at 0.25 degrees, approximately 25 kilometres. In each case the distance between observations, and the interpolation logic were different. Errors introduced by interpolation also serve to add to, and conceal, data collection and data entry errors that may be present in the raw data. The interpolated values represent an artificial precision to which no recording of uncertainty is attached.

8.3.5 Data currency

It is a simple observation that data that is expensive to collect cannot regularly be updated. Data collected at the regional scale is often collected as part of particular programs or grants and with the emphasis of the individual interest of those who have their hands on the purse strings at the time.

Land use data, in particular, is a snapshot of observations for a particular time and place. Land use can change from season to season and from year to year. Large data sets that take considerable resources to construct can be out of date the day after they are compiled.

Data sets used in this project that were compiled as part of the National Land and Water Resources Audit represent the funding window for the project. Land use data, for instance, relates to a period from 1996 into 1997. It can be seen then that when turbidity data is compared over the years 1997 to 2001 and land use data from 1997 random errors can be introduced. While broad land use classifications may mask some important changes to land management regime, some changes in land use could be significant and highly correlated with stream turbidity, such as a change from irrigated agriculture to dryland farming.
8.3.6 Data methodology

Data collection errors, data entry errors and methodological errors concealed within pre-processed data sets are very difficult to identify, but it must be assumed that they exist. This pre-processed data can contain layers of error and compounded uncertainty. One example is illustrated in Figure 8-1 where obvious anomalies in the North-West of Victoria show how data collected as inputs from different state authorities into the RUSLE have created starkly different interpretations of areal classifications.

While the current project has concentrated on Victoria as the focus region, it can be seen that to widen the region and look at the whole continent, would open the door for a myriad of errors associated with the multitude of state authorities responsible for the collection of spatial data.

![K factor from RUSLE](image)

Figure 8-1 K factor (Soil erodibility) from RUSLE. Changes in classification on the Victorian - South Australian – New South Wales border show how different data collection methodologies between states can manifest as artefacts.

8.3.7 Data coverage

Figure 8-2 shows the area for which there was only one parameter available in the M1 model. The altitude of the catchment centroid has complete coverage of the region, whereas other parameters have only partial coverage.
Simplistically, it could be said that in areas only covered by this theme, altitude was the main determinant of stream turbidity; however, logic tells us that a multitude of factors must be at work in these catchments to determine available sediment in streams. The predictive nature of this model allows estimates of the response variable even if the coverage of the data would not provide sufficient information to explain the physical processes at work.

Figure 8-2 also reveals the pattern of data missing from the Land Cover – Pasture variable. The geometric shapes of the data distribution show artefacts that may have their origin in data entry errors (see Figure 7-22).

![Cells for which Altitude of the Catchment Centroid was the only data for Model M1](image)

**Figure 8-2 Cells for which Altitude of the Catchment Centroid was the only data for Model M1**

### 8.4 Errors introduced with the statistical methodology

Putting the problems of spatial data aside, the statistical approach must treat the data as having no uncertainty. The problems associated with this method, as has already been mentioned, include cross-correlation between variables and the probability that relationships between data can be the result of random correlation.

Figure 8-3 shows clearly that as variables are added to the modelling process, the effect of correlation increases. The chart shows each step in a forward
stepwise regression. On the x-axis is the step number and on the y-axis is the strength of the partial coefficient for each variable. With the addition of each model variable some power is lost to other variables. In fact, by the time the eleventh variable is added to this forward model, the variable LC_urban (urban residential area), which is, logically, cross-correlated with LU2_resi (residential area), develops a negative coefficient instead of a positive coefficient.

![Coefficients for 1997 forward stepwise regression](image)

Figure 8-3 Chart showing the strength of coefficients of model variables during the stepwise process

### 8.4.1 Validation

While opportunities exist for future model validation by ground truthing the model predictions, a key point to make is that the statistical method, which interrogated five years of contiguous data to construct the model, was, in essence, validated by comparison between the five data sets. The degree to which these data sets are autocorrelated is unknown. When climatic variability may present decadal cycles, a series of five years will only be a sample of a particular cycle. However, as land use can change, and has changed greatly, over the course of a decade or two, historical turbidity data, would have to be compared with historical catchment data; of which there is little.
8.4.2 Sensitivity analysis

According to McCuen (2003) sensitivity is ‘the rate of change in one factor with respect to change in another’. In the context of traditional hydrological modelling, sensitivity can be thought of as the rate of change in model outputs with respect to change in model inputs. McCuen further argues that sensitivity analysis can be used to answer questions such as:

- Which are the most important variables of the model?
- What is the effect of error in inputs on the output predicted with the model?
- What physical hydrologic variables are most likely related to fitted model coefficients?
- In calibrating a model, are all of the model coefficients equally important to the accuracy of the model? (McCuen, 2003)

While thorough sensitivity analysis was not conducted on this model, some general observations can be made about the sensitivity of model outputs to changes in model inputs.

If a model form is purely linear, as it is in the case of the present model, then sensitivity in the model equation can be described by a linear ranking of partial coefficients. Parameters with the greatest power in the model will have the greatest influence on model outputs. However, if the model form is non linear, or there is significant correlation between the model parameters, then individual model parameters may exert more influence on model outputs than others, regardless of their ability to explain variation in the response variable. Table 8-1 shows the individual contributions, in terms of explanatory information added to the M1 model by each variable. Comparison with Table 8-2, which shows a ranking of coefficients in the M1 model, implies that there are complex interrelationships between the model parameters that might be difficult to quantify. For instance, “Distance to Roads 3” adds the most information to the model at 8.4%, but it has the fourth strongest coefficient in the model. This implies that some of the strength in its contribution to the model is lost through cross correlation.
The actual influence that a single cell will have on the model outputs will be a combination of the strength of the coefficient and the spatial distribution of the parameter, and the presence or absence of other parameters at any one location.

Table 8-1 $R^2$ from the regression equation. The regression was run taking out each parameter and the reduction in $R^2$ calculated.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$ (adj) without each parameter in the model (M1 model using the 1997 data)</th>
<th>Reduction in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All parameters</td>
<td>57.10%</td>
<td></td>
</tr>
<tr>
<td>Distance to Roads 3</td>
<td>48.70%</td>
<td>8.40%</td>
</tr>
<tr>
<td>Land Cover – Pasture</td>
<td>49.40%</td>
<td>7.70%</td>
</tr>
<tr>
<td>Natural Vegetation Extent 2</td>
<td>49.80%</td>
<td>7.30%</td>
</tr>
<tr>
<td>Land use – Irrigation</td>
<td>51.40%</td>
<td>5.70%</td>
</tr>
<tr>
<td>Altitude of Catchment Centroid</td>
<td>53.10%</td>
<td>4.00%</td>
</tr>
<tr>
<td>Land Condition 1</td>
<td>55.50%</td>
<td>1.60%</td>
</tr>
<tr>
<td>Catchment Condition 2</td>
<td>56.70%</td>
<td>0.40%</td>
</tr>
</tbody>
</table>

Table 8-2 Coefficients in M1 model

<table>
<thead>
<tr>
<th>Data</th>
<th>Coefficient in Model M1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Vegetation Extent 2</td>
<td>–0.153</td>
</tr>
<tr>
<td>Altitude of Catchment Centroid</td>
<td>– 0.152</td>
</tr>
<tr>
<td>Land use – Irrigation</td>
<td>+0.145</td>
</tr>
<tr>
<td>Distance to Roads 3</td>
<td>–0.12</td>
</tr>
<tr>
<td>Land Cover – Pasture</td>
<td>+0.0988</td>
</tr>
<tr>
<td>Land Condition 1</td>
<td>+0.0793</td>
</tr>
<tr>
<td>Catchment Condition 2</td>
<td>+0.0475</td>
</tr>
</tbody>
</table>

More complete sensitivity analysis might include testing for the effects of perturbation; that is, introducing small changes within the model and detecting the strength of effect to model predictions.
8.5 Error Introduced with the GIS methodology

8.5.1 Other methods of flow determination

While distance from streams did not present as a significant variable in the modelling process, flow routing was used extensively as a spatial logic for distributing model predictions. The D8 (see page 153) method used in this model, however, is not the only method for determining the direction of flow. Tarboton (1997) provides a review of other flow direction routing methods within the raster modelling framework.

These include the D8 method (O'Callaghan and Mark, 1984), the MS (Multiple Flow Direction) method (Freeman, 1991, Quinn et al., 1991), a method developed by Lea (1992) and Costa-Cabral and Burges (1994) referred to as DEMON, and to this list Tarboton adds a new method termed the $D^\infty$ method.

In defence of the $D^\infty$ method, Tarboton identifies a number of weaknesses, particularly grid bias due to the orientation of the numerical grid and poor precision with which flow directions are resolved. Grid bias in the D8 method occurs because flow can only occur in either of eight directions: toward four orthogonal cells or the four diagonal cells. Overall precision is compromised by this effect and compounded because flow can only go in one direction at a time. In the real world, flow might diverge in several different directions at once, especially on a saddle or in very flat terrain. Other methods of flow determination try to respond to these problems. The MS method (Freeman, 1991, Quinn et al., 1991), for instance attempts to apportion flow into more than one cell.

Costa-Cabral and Burges (1994) uses terminology developed by Speight (1974) to describe elements of flow determination. The authors refer to the Specific Contributing Area (SCA), the Specific Dispersal Area (SDA), Total Contributing Area (TCA) and the Total Dispersal Area (TDA). The TCA of a contour segment or cell is the plan area of terrain that contributes flow to that cell. The SCA is the TCA divided by the unit contour, or in the case of rasters, the cell length. The TDA is the plan area that drains flow from a cell or contour segment and the SDA is the TDA divided by the unit contour or cell length.
Costa-Cabral and Burges (1994) complain that commonly used models for representing flow present one-dimensional representations of flow paths. For instance in Figure 8-4 it is clear that the D8 method underestimates the TCA.

![Figure 8-4 Total Contributing Area (TCA) of a pixel on a planar slope with aspect angle 315 degrees (a) predicted by D8 method and (b) true TCA. Method D8 underestimates the TCA of a by a factor of 2 (After Cabral and Burges (1994))](image)

The method of Fairfield and Leymarie (1991) called Rho8 introduces a random component in flow determination. While flow is still directed along
cardinal and diagonal directions, the apportionment of flow is done stochastically using probability. Method Rho8 assigns a probability $p$ to a neighbouring pixel and a probability $(p - 1)$ to other neighbouring cells.

The Rho8 method is criticized by Tarboton (1997) and by Costa-Cabral and Burges (1994) because, while the overall direction of flow is an improvement on the D8 method, the results rely on randomness, and are therefore irreproducible.

According to Costa-Cabral and Burges (1994), Lea (1992) solves the problem of the randomness in Fairfield and Leymarie (1991). Lea (1992) introduced a flow routing algorithm that fits a plane that touches each corner of a cell. The elevation of each cell corner is then calculated by averaging the elevations of adjoining cells. Flow direction is routed as if it were a ball released from the centre of the cell. The result is a value for the direction of flow between 0 and $2\pi$. Tarboton (1997) introduced a method for determining the allocation of flow, termed variously as $D^\infty$, D-inf or D-infinity. The method involves the determination of a single value to each cell that reflects the direction (shown as a value between 0 and $2\pi$) of the steepest downhill slope on eight triangular facets formed in a 3 x 3 pixel window centred on the pixel of interest (see Figure 8-6).

In this method flow is apportioned according to how close the direction of flow is to the centre of two nearest down-slope cells. The benefit of this approach is that only one value needs to be stored in each cell yet flow can be apportioned to more than one cell.

The D-Inf method has been tested in the Richardson River catchment (see Figure 8-7) and compared to the D8 method (see Figure 8-8). It is clear from an examination of these figures that the D-Inf method offers more information about the probable distribution of flow. Geometric artefacts in the D8 flow model are clearly less natural and in areas with a more defined flow pattern little difference is observable.
Figure 8-6 D-Inf Flow direction defined as steepest downward slope on planar triangular facets on a block-centred grid. From Tarboton (1997)

Figure 8-7 D-Inf Flow Direction for the Richardson River catchment determined from the 9-second DEM from AUSLIG
Figure 8-8 D8 Flow Direction determined for the Richardson River catchment from the 9-second DEM from AUSLIG.

Figure 8-9 Slope map of the Richardson River catchment produced with the slope function in ArcGIS 8.3. Slope has been displayed with stretched values using a histogram equalise function. The dark brown to black cells are the highest accumulated cells using the D-inf method of flow determination and the strawberry coloured areas are sinks in the DEM that were filled before flow was determined.
In Figure 8-9 flow modelled with the D-Inf method can be seen to disperse in areas of low slope, even though in reality a stream channel exists. Even though more information is available in areas of low slope, the method does not help to define the exact, or probable, location of a stream channel. Even in TauDEM, Tarboton uses the D8 method to define catchment areas and stream locations.

If, in a case such as the methodology presented here, there is a need to model both flow and channel location, and both of these need to function together, then it would seem that the D8 method is the more appropriate method. The methodology used to define channels must be used to define flow.

The problems associated with the determination of flow can be described ostensibly as a decision problem in areas where the determination of flow is not clear. These problems commonly occur in areas of low relief where relative elevation is indeterminable and on saddles where flow may be in more than one direction at once.

While the D8 method is much criticized, Garbrecht and Martz (1999) support the use of single direction flow algorithms to delineate large catchments with well developed channels. Evidence presented would seem to show that the D8 algorithm in the ArcGIS hydrological tool is not the best method to identify flow in areas of divergent flow but it is a useful method to determine catchment boundaries and channel locations.

In future work, consideration might be given to developing a method that used the improved flow modelling capabilities of the D-Inf method with the ability of the D8 model to delineate catchments and channel locations. Such a model might use a least squares function to locate probable catchment and channel locations. The importance of flow direction modelling is highlighted by the fact that it is at the basis of flow accumulation modelling, stream delineation and catchment delineation.
8.6 How do the values in the predictive raster relate to the distribution of human impact?

As outlined in chapter 2, colonial Victorians could have had no idea that their farming techniques, brought from the green fields of Europe, could irreversibly and detrimentally alter the fabric of their new environment. Not only could they not envisage the natural variability inherent in the climate of their new home, they could not envisage that they would, one day, have the responsibility of managing individual streams and catchments in their regional context.

The broad regional map of water quality produced from this project represents a complete departure from earlier strategies. It represents an attempt to create a picture of regional heterogeneity that enables Victorians to see stream turbidity in its wider context. It is a revolutionary view of water quality, when compared with the views of those of early colonists, or the settlers, squatters and twentieth century resource developers that followed them. It presents a regional perspective, enhanced by, modern, remotely sensed data.

In the modern context, in order to manage natural systems, information is needed that describes the regional breadth of that system. It is clear from this map that a simple regionalisation of expected turbidity values based purely on geographic location would be insufficient to describe the spatial variation. While there are some clear trends (high altitude areas appear to have lower turbidity values, for instance) the factors that lead to high turbidity are not entirely related to simple topographic or biological regions.

Figure 8-10 shows that the current EPA trigger values for turbidity (see Figure 6-7) largely account for mean predicted conditions with Victorian catchments. The catchments shown in brown have predicted median annual turbidity that is between six and ten NTU higher than the trigger values.
Figure 8-10 Difference between mean predicted median annual turbidity and EPA trigger values.

Figure 8-11 Difference between maximum predicted median annual turbidity and EPA trigger values.
The implication for these catchments is that they are more likely to have measured levels of turbidity that are higher than the trigger value. Figure 8-11 shows that these levels do not account so well for expected maximum predicted median annual turbidity values. Based on the mean predicted values, the majority of these catchments should have values higher than the EPA trigger values.

Figure 8-12 shows the difference between median annual turbidity in 2001 and the EPA trigger values. A relatively small number of catchments have breached the trigger values in that year. The stark difference between this figure and Figure 8-11, shows that the model predictions would appear to be too high, across most of the catchments for this year.

It seems clear that at this regional scale considerable uncertainty is to be expected. At this scale, it is unlikely the future of complex natural systems could ever be accurately predicted. Modern tools for understanding the flux of regional environmental phenomena must, then, present their outputs in the context that uncertainty is a fundamental property of environmental understanding.
Future management of water resources will require managers to make clear decisions about what is natural and what is not. Not only must management take into account local and regional heterogeneity but water quality must also be seen in the nexus of social, environmental and economic imperatives.

As outlined in chapter 5, the modelled values provide baseline data that can be used in future measurements of environmental health. However, significant environmental change over the region during the last two hundred years has created change to natural turbidity. In areas in the north and central area of the state, in particular, where measured turbidity levels are high, environmental change has been the greatest. Information about the changing environmental conditions during Victoria’s colonisation tells us that sediment transport in today’s streams is a function of natural conditions, overlaid with the effects of significant land use change.

8.7 Recommendations
This is not the whole story, of course. To use stream turbidity as a measure of stream health, future work would be needed to assess the normative conditions and establish the spatial trend. This could be accomplished through a referencing approach. While the referencing approach is well founded, modelling of water quality variables at the regional scale is novel. It is only in recent times that environmental data has been available at the regional and continental scale in Australia, and it is only in recent times that the advance in Geographic Information Systems have allowed the manipulation of geographic data, including digital elevation models, to create spatially distributed hydrological models.

The results of this project show clearly that modelling regional water quality variables can be accomplished using currently available GIS software and using recently updated national scale data sets. The research also found that the use of a more reliable and accurate DEM would provide the basis of a more accurate, regional scale, hydrological model. However, the resolution of the DEM would need to be matched by an increase in the resolution of all catchment data used in the modelling. It is not enough to have a high resolution DEM if other data in the model is coarse.
While the statistical model in this project has been constructed using median annual conditions, incorporating temporal fluctuations in turbidity and stream flow could extend the model further. More complexity in the model construction must also be accompanied by decreased uncertainty in the model inputs. At this stage the levels of uncertainty in regional data are too high to provide an increased level of model accuracy.

The project also found that no single model would be sufficient to predict regional water quality variables. For this reason there is a need for a number of models; a wet year model, a dry year model for a dry year etc.

8.8 Conclusion

This chapter has outlined the results of the model developed in chapter 7, and evaluated the way in which errors introduced in the modelling process, manifested as uncertainty within the model predictions. In particular three main sources of uncertainty in the modelled predictions were discussed; Model input errors, error introduced with the statistical method and errors introduced with the GIS method.
CHAPTER 9. CONCLUSIONS

9.1 Summary
The purpose of this chapter is to summarise the arguments of this thesis, draw together the major ideas and findings, review the objectives and provide recommendations for future research direction.

The objective of this thesis was to investigate the distribution and significance of stream turbidity in Victoria. Specifically, the thesis explored the factors that may have influenced the pattern of regional variation and factors that give it significance in the social, cultural and environmental context. The thesis then reported on the development of a regional spatial model of stream turbidity for Victoria to be used as a tool to explore the regional variation and provide predictions of stream turbidity at ungauged locations.

Chapter 1 set the scene for this thesis by outlining the process of investigation, beginning with an introduction of the major issues. It argued that there has been widespread and mounting community concern for the quality of water in Victorian rivers and streams and the determination of the relative condition of water bodies was an essential part of stream management. However, the meaning of stream health, itself, had changed in recent times; from a focus on the ability of a number of chemical qualities of water to fulfil human-centred beneficial uses such as consumption and recreation, to its ability to support ecological systems that help to maintain water quality.
Recent changes to the National Water Quality Guidelines mean that the investigation of what constitutes acceptable water quality must take into account environmental values. While the information required to elicit environmental value at the local scale can be achieved through stakeholder engagement, at the regional scale, information and understanding requires a regional view.

Based on this rationale, the investigation of the regional significance of stream turbidity required the analysis of the problem to be separated into several broad questions.

- What factors can explain the distribution of water quality and, specifically, stream turbidity in Victoria?
- What is the social-cultural context in which water quality assessment is made?
- Can stream turbidity be used as a metric for assessing the health of water resources?
- How can spatial models be employed to explore the variation and significance of stream turbidity at the regional scale?

These four questions form the framework of the investigation and broad structure of the following chapters.

Chapter 2 began addressing the first of these questions by providing some background information about the state of Victoria, its geography, its climate and how water is distributed. It then described in outline how the process of European colonisation of Victoria interacted with the prevailing geography to produce a unique pattern of water resource utilisation. Early settlers had little understanding of the complexities of their new surroundings, and little appreciation for its environmental integrity. They cleared the land and created English-style farms among the eucalypts; completely altering the natural ecosystems over much of the region.

Evidence provided shows land degradation, in the form of soil erosion and deposition, soil degradation and ecosystem change are processes that have significantly changed the basic natural infrastructure responsible for
maintaining the physico-chemical equilibrium of water quality over large areas of Victoria.

Later Victorians developed strategies to combat the prolonged temporal pattern of drought and plenty by building large dams to conserve the rainfall from times of abundance, to supply water in times of scarcity. In the twentieth century, with their considerably greater economic resources and improved technology, their descendants built even larger dams and began to pour the waste from the emerging industrialisation into the rivers and streams. In Victoria, a web of earthen channels was built across the northern plains to bring water to the desert. Massive dams were built to bring snowmelt to irrigate vast areas of vineyards and other crops, and the pristine mountains were harvested to provide water for a growing Melbourne.

The chapter concluded by outlining the development of a global context for the assessment of environmental condition. Where early European colonists might have viewed their resources in isolation from the rest of the world, modern Victorians have a newly developed global perspective.

Chapter 3 continued to address the first two research questions and showed that the development of water management in Victoria was the result of a complex chain of decisions taken in their social and political context. The chapter identified several important currents in the history of water resource development in Victoria, including the desire for closer settlement, the political power of early squatters, the driving notion of the yeoman farmer, and, in recent times, the development of a global and regional perspective on resource development.

Where chapter 2 outlined the way in which the physical environment of Victoria influenced the characteristics of water use in Victoria, chapter 3 further developed the background on water in Victoria, by outlining how the management of water resources developed in response to the social context and prevailing politics. This management response produced a unique pattern of resource development at the regional scale. A network of open channels weaves its way through some of the most arid parts of Victoria, huge
reservoirs control the flow on the largest rivers and irrigation channels pour water on land where salt sits ominously below the surface.

The chapter began by outlining the management and use of water by Aborigines prior to European colonisation. Although the impact of Aboriginal water management appears to have been minimal, changes to the fauna and flora of Victoria’s catchments caused by the broad-scale use of fire may have been wide-spread.

Within this fire-formed landscape, the progress of European settlement, agriculture and water resource use was fashioned by the competing objectives of large landholders and those who advocated closer settlement. The politics of early Victoria was clearly divided between the Squatters and the Selectors. The Squatters had illegally gained their properties before the formal granting of land, while, the Selectors, who came after them, were impeded in taking up land by the political influence of Squatters.

A significant force within this early culture was the notion of the yeoman farmer. Allied to the push for closer settlement and the political movement opposed to the Squatters, the concept of the yeoman farmer was an agrarian ideal that is thought to have been a motivating force behind the march of small landholders into the untamed Victorian bush. From the 1850’s the discovery of gold led to the expansion of Victoria’s population and the development of water resources to supply a new regional population. After the Gold Rush, farming expanded rapidly, and so did the development of infrastructure, such as railways and roads.

After some small-scale expansion in the mid 1800’s, the development of significant water resources had to wait until after the Irrigation Act in 1886. This Act effectively nationalised the ownership of the Victoria’s water resources and provided the opportunity for the state to support large-scale irrigation schemes. The early twentieth century saw the establishment of the State Rivers and Water Supply. This organization took control of water management and also the establishment of Soldier Settler schemes after the First and Second World wars.
Again the development of water resources was tied to closer settlement and the alienation of land from large landholders. However, the final decades of the twentieth century were characterised by the quest for reform of water management in Victoria. Significant steps were taken, motivated by global and national trends in water management, to reign in the unlimited use of water, and more closely tie the price of water to its perceived costs.

Chapter 4 addressed the second research question by addressing water resources in Victoria from the perspective of sustainability. It described the development of the concepts that are elemental to sustainability and outlined how the concept applies to water in Victoria.

The concept of sustainable management of water resources has developed a new complexion in the last few decades. Where once sustainable management of water meant having enough water left from winter rains to supplement summer supply, in recent years it has begun to have more complex associations. Sustainable water use is now almost universally considered to include maintenance of the environmental health of waterways, and by implication, the environmental health of the whole catchment.

This broadening of the definition of sustainable supply has ramifications for how water quality and availability are measured. The allocation of water for human use must now take into account the ecological management of water resources. The Australian Federal Government has adopted a policy of ESD: measuring water quality, which in past decades was a test of its fitness for particular human uses, such as irrigation and potable supply, is now entering a new phase where it is expected to reflect the wider concerns of ESD. Within the framework of ESD, water quality and water availability are intrinsically linked. Water availability is constrained by the acceptable biological health of the catchment.

Chapter 5 tackled the third research question and surveyed various methods for defining environmental health relevant to water resources. The objective was to identify those attributes of environmental health that best suit the measurement of sustainable water resources at the regional scale and against
this examine the efficacy of stream turbidity as an indicator of stream and catchment health.

The chapter began with an argument that the limits to water resource use are, increasingly, viewed as the health of the environment rather than the purely physical limitations of rainfall, temperature and evaporation. Several reports were cited that outlined a trend, from colonial times, through to the post war boom in resource development. In colonial times, environmental problems were ignored as an element in water resource management, then in the late 1960’s and 1970’s the notion of environmental value crept into water resource planning: the environment had to be considered. The intactness of an unmodified landscape was seen as having premium environmental value. The environment was still only a competing element in water resource planning, even up until 1992, but after this time, the environment became the major consideration. Environmental health became the major determinant of water availability. When the Australian Water Resource Assessment concluded that a large number of surface water areas were overused, it did not mean that water had stopped flowing, it meant that environmental condition had declined or was declining.

A number of concepts used for measuring relative environmental health were then outlined. Concepts of environmental health are specific to the focus of the study for which they are developed. These concepts have been used in Australia and overseas to establish metrics of relative environmental condition as it relates to water resources. The chapter sketched in several methods including: traditional water quality monitoring, RIVPACS, AUSRIVAS, SIGNAL, the Index of biological integrity, the index of riparian quality, the index of Stream Condition, the Assessment of River Condition, Geomorphic River Styles and HABSCORE.

Chapter 5 concluded with an argument that, while there was merit in all of these approaches, the suspended sediment load of a stream, reflected in the measure of stream turbidity, offered several important attributes. These included, a data record that was extensive, both spatially and temporally, raw data that had not already been interpreted, (enabling all qualitative
interpretations to remain explicit), and a direct physical relationship to catchment processes.

Chapter 6 described the history of the measurement of turbidity and various methods that have been used to measure it, including the Jackson Candle Turbidimeter and the nephelometric turbidimeter. The chapter then described various ways in which stream turbidity has been interpreted. Turbidity is considered by the agricultural community as a sign of soil erosion and a loss of agricultural potential, while from the ecological perspective it is a sign of deteriorating river health. Importantly, absolute levels of turbidity are not an indication of erosion or deteriorating river health. Natural levels of turbidity can be high and highly variable.

A main conclusion of this chapter is that turbidity can be considered as a surrogate for suspended sediment. It is also closely bound with land use practice and, in the Australian context, turbidity can be considered a measure of the consequences of land management practices on soil erosion and runoff. The chapter also outlined how the Victorian Water Quality Monitoring Network monitors stream turbidity. Particular emphasis was placed on the limitations of measuring the whole stream from a point location. No matter how many locations water quality is measured, there will always be a need to extrapolate point measurements to more distant locations.

The chapter concluded by outlining how new biological objectives for streams in Victoria have been set based on a statistical analysis of measured turbidity within a biological regionalisation developed by the EPA.

The purpose of chapter 7 was to investigate the fourth research question. It sought to build a regional spatial model of stream turbidity for Victoria. The aim of the model was to establish probable turbidity values based on a regional knowledge of catchment characteristics. These modelled values can be compared to measured values to provide catchment managers with an initial assessment of whether measured values are similar to expected values. They could also be considered as baseline values, from which further modelling might infer a trend in water quality associated with catchment land use. Additionally, these values could be compared to reference conditions to
infer a level of environmental health that connects water quality with catchment land use.

Chapter 8 discussed the results of the model developed in chapter 7, evaluating the way in which errors introduced in the modelling process were manifested as uncertainty within the model predictions. In particular, uncertainty was seen as entering the predictions through errors in the turbidity data, errors in the regional spatial data, errors in the statistical methodology and errors associated with the GIS modelling.

### 9.2 Conclusions

Ecologically Sustainable Development requires us to consider the complex relationship between the stream and the catchment it drains. While, there is not a history of stream turbidity being used as a measure of environmental health, levels of turbidity are clearly related to the health of the whole catchment. Unlike biological measures of river health, stream turbidity can be mechanistically related to catchment processes. Turbidity is a characteristic of streams that is easily measured, has a history of measurement and is uniquely related to catchment land management.

This work was an exploration of an idea; to show, comprehensively, how new methods of measuring the health of waterways can be clearly located in a paradigm of sustainability. Along the way the thesis found that the common paradigm of water use, the language used, available model forms, are all anchored in the history of the region and are influenced by the politics of the globe.

There were, of course, many limitations with this approach. First among these is the paucity of digital data representing regional scale environmental phenomena. Current understandings of natural systems at the regional scale are only rudimentary; available data is often wildly inaccurate and full of uncertainty. Even if better data was available, there is still significant difficulty involved in trying to apply regional models to environmental phenomena that are highly variable, both temporally and spatially. Complexity itself, however, is not an insurmountable limitation. Of course if uncertainty is dealt with by trying to model every detailed relationship between environmental
phenomena, the sheer immensity of the model would preclude true understanding. Successful modelling of complexity depends on selective model parameterization; choosing the right indicators of system structure and function.

The model developed for this project is regional in scale and accounts for complexity through the paradigm of systems theory, in its ability to show spatially distributed predictions and in its attempt to connect the condition of waterways with the condition of catchments.

A major success of this work has been in the methodological approach. It has effectively linked the needs of ecologically sustainable resource use with a modelling methodology. The modelling approach within the GIS is novel, and provides a spatial logic that could be applied to any water quality analysis that requires the connection of stream water quality with catchment characteristics.

But, the question that still remains is the usefulness of such an approach from a practical point of view. While the statistical model offers a predictive tool that attempts to deal with non-linear relationships between catchment characteristics and water quality variables, it is dependent upon the quality of data inputs and the strength of correlation between variables. The result from this modelling tells us that some catchments can be identified as having substantial local influences on stream turbidity that cannot easily be attributed to current regional data.

The statistical approach is useful. Analysis of the regression outputs can tell us when values are outside the normal distribution. This is a useful tool, but it also restricts the interpretation of model outputs to identifying values that are probably outside expected values. It cannot be used to assess whether values within the normal distribution are also the consequence of local effects that are not included in the model.

Clearly the model developed using this methodology is a new approach to modelling water quality. However, a glance at the map of modelled turbidity predictions developed in chapter 7 shows a completely new way of visualising stream turbidity. Water quality variables are commonly mapped as point data, or displayed in tabular form, but this project has developed a technique for
displaying water quality as a field of values that relates the water quality parameter to the wider catchment.

### 9.3 Future research direction

Despite these limitations, it is increasingly important for us to venture an educated guess of the degree to which current environmental condition represents the condition prior to the European occupation. Even if the determination of that environmental condition seems impossible; just as it seems impossible, within present technology, to produce an accurate prediction of expected water quality at all locations within a region.

However, it is important for us to know how measured water quality sits, with regard to the regional flux. The next step in this research must be to identify the magnitude and direction of change in natural levels of stream turbidity. Sustainable management of Victorian catchments requires the identification of the level of catchment change and the assessment of its implication in the regional context. While stream turbidity is only one of a number of variables that could be used for measuring changes in environmental health, it is easily measured and, as this research has shown, has a high correlation with regional scale catchment data.

Specific refinements have been mentioned in the body of this thesis that would increase the usefulness of this model. These include the construction of a robust distance coefficient, improvements to the flow routing algorithm and a more thorough testing for the spatial sensitivity of individual variables.

Significant needs have also been flagged for improvements outside the control of the modeller, but necessary for further refinements of this approach, including the improvement of data currency, data resolution and data quality at the regional scale.

From a more theoretical viewpoint, if this work has done nothing else, it has brought to light the difficulty in correlating water quality with land use in the catchment at the regional scale – and yet finding this correlation is vital to the long term management of Victorian water resources.

Water use is linked inextricably with catchment health. How much water Victorians can use in the future will depend on what level of environmental
change they will tolerate. But before these decisions can be made, decision
makers need more information that describes the current state of the
environment, not just in individual catchments but over the whole region.

If the relationship between land use and water quality can be found, if a
universally definition of what constitutes good water quality can be agreed
upon, if the likely current direction and strength of change in water quality can
be identified, if a balanced, regional, approach can be employed to equitably
identify the trade-offs that are needed, then Victorian catchments can truly be
managed sustainably.
REFERENCES


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http://dipin.kent.edu/index.htm

References 225


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## APPENDIX 1. MILESTONES 1972 - 2003

**STOCKHOLM TO KYOTO (WORLD WATER ASSESSMENT PROGRAMME, 2003)**

<table>
<thead>
<tr>
<th>Dates</th>
<th>Events</th>
<th>Outcomes</th>
<th>Quotations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>UN Conference on the Human Environment, Stockholm&lt;br&gt;Preservation and enhancement of the human environment</td>
<td>Declaration of the UN Conference on the Human Environment</td>
<td>'A point has been reached in history when we must shape our actions throughout the world with a more prudent care for their environmental consequences.'&lt;br&gt;(6. Declaration of the UN Conference on the Human Environment)</td>
</tr>
<tr>
<td>1977</td>
<td>UN Conference on Water, Mar del Plata&lt;br&gt;Assessment of water resources Water use and efficiency</td>
<td>Mar del Plata Action Plan (MPAP)</td>
<td>'... relatively little importance has been attached to water resources systematic measurement. The processing and compilation of data have also been seriously neglected.'&lt;br&gt;(Recommendation A: Assessment of water resources, Mar del Plata Action Plan)</td>
</tr>
</tbody>
</table>
| 1981 - 1990 | International Drinking Water and Sanitation Decade |  | "Despite the failure to meet the quantitative goals, much was learnt from the experience of the water and sanitation decade... There was further realisation of the importance of comprehensive and balance country-specific approaches to the water and sanitation problem. Most importantly, perhaps, was the realisation that the achievement of this goal that was set at the beginning of the decade would take far more time and cost far more money than was originally thought."
(Choguill C., Franceys R., Cotton A., Planning for water and sanitation, 1993) |
| 1990  | Global Consultation on Safe Water and Sanitation for the 1990's, New Delhi<br>Safe drinking water, environmental sanitation | New Delhi Statement : "Some for all rather than more for some" | 'Safe water and proper means of waste disposal ... must be at the centre of integrated water resources management'

(Environment and health, New Delhi Statement) |
| 1990  | World Summit for Children, New York<br>Health, food supply | Declaration on the Survival, Protection and Development of Children |  |
"We will promote the provision of clean water in all communities for all their children, as well as universal access to sanitation."

*(18. World Declaration on the Survival, Protection and Development of Children)*

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>International Conference on Water and the Environment, Dublin</td>
<td>Economic value of water, women, poverty, resolving conflicts, natural disasters, awareness</td>
</tr>
<tr>
<td>1992</td>
<td>Dublin Statement on Water and Sustainable Development</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>Principle 1: 'Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment'</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>Principle 2: 'Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels'</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>Principle 3: 'Women play a central part in the provision, management and safeguarding of water'</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>Principle 4: 'Water has an economic value in all its competing uses and should be recognized as an economic good'</td>
<td><em>Guiding principles The Dublin Statement on Water and sustainable Development</em></td>
</tr>
<tr>
<td>1992</td>
<td>UN Conference on environment and Development (UNCED Earth Summit), Rio de Janeiro</td>
<td>Cooperation issue, water economics, participation, drinking water and sanitation, human settlements, sustainable development, food production, climate change</td>
</tr>
<tr>
<td>1992</td>
<td>Rio Declaration on Environment and Development</td>
<td>Agenda 21</td>
</tr>
<tr>
<td>1992</td>
<td>'Establishing a new and equitable global partnership through the creation of new levels of cooperation among States, key sector societies and people.' <em>(Rio Declaration)</em></td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>'The holistic management of freshwater ... and the integration of sectoral water plans and programmes within the framework of national economic and social policy, are of paramount importance for action in the 1990s and beyond.' <em>(Agenda 21, Section 2, chapter 18)</em></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Ministerial Conference on Drinking Water Supply and Environmental Sanitation, Noordwijk</td>
<td>Drinking water supply and sanitation</td>
</tr>
<tr>
<td>1994</td>
<td>Action Programme</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>'To assign high priority to programmes designed to provide basic sanitation and excreta disposal systems to urban and rural areas.' <em>(Action Programme)</em></td>
<td></td>
</tr>
</tbody>
</table>
1994  
**UN International Conference on Population and Development**  
Programme of Action

'To ensure that population, environmental and poverty eradication factors are integrated in sustainable development policies, plans and programmes.'  
*(Chapter III - Interrelationships between population, sustained economic growth and sustainable development, C- Population and Environment, Programme of Action)*

1995  
**World Summit for Social Development, Copenhagen**  
Poverty, water supply and sanitation  
Copenhagen Declaration on the Social Development

'To focus our efforts and policies to address the root causes of poverty and to provide for the basic needs of all. These efforts should include the provision of ... safe drinking water and sanitation.'  
*(Chapter I - Resolutions adopted by the Summit, Commitment 2, b. Copenhagen Declaration)*

1995  
**UN Fourth World Conference on Women, Beijing**  
Gender issues, water supply and sanitation  
Beijing Declaration and Platform for Action

'Ensure the availability of and universal access to safe drinking water and sanitation and put in place effective public distribution systems as soon as possible.' *(106 x, Beijing Declaration)*

1996  
**UN Conference on Human Settlements (Habitat II), Istanbul**  
Sustainable human settlements development in an urbanizing world  
The Habitat Agenda

'We shall also promote healthy living environments, especially through the provision of adequate quantities of safe water and effective management of waste.'  
*(10. The Habitat Agenda, Istanbul Declaration on Human Settlements)*

1996  
**World Food Summit, Rome**  
Food, health, water and sanitation  
Rome Declaration on World Food Security

'To combat environmental threats to food security, in particular, drought and desertification ... restore and rehabilitate the natural resource base, including water and watersheds, in depleted and overexploited areas to achieve greater production.'  
*(Plan of Action, Objective 3.2, Rome Declaration)*

1997  
**1st World Water Forum, Marrakech**  
Water and sanitation, management of shared waters, preserving ecosystems, gender equity, efficient use of water  
Marrakech Declaration
"... to recognize the basic human needs to have access to clean water and sanitation, to establish an effective mechanism for management of shared waters, to support and preserve ecosystems, to encourage the efficient use of water..."  
*(Marrakech Declaration)*

<table>
<thead>
<tr>
<th>2000</th>
<th>2nd World Water Forum, the Hague</th>
</tr>
</thead>
<tbody>
<tr>
<td>(March)</td>
<td>Water for people, water for food, water and nature, water in rivers, sovereignty, interbasin water education</td>
</tr>
</tbody>
</table>

- Involve all stakeholders in integrated management;
- Move to full-cost pricing of water services;
- Increase public funding for research and innovation;
- Increase cooperation in international water basins;
- Massively increase investments in water*

*(Vision Statement and Key Messages, World Water Vision)*

<table>
<thead>
<tr>
<th>2000</th>
<th>7 challenges: Meeting basic needs, Securing the food supply, Protecting ecosystems, Sharing water resources, Managing risks, Valuing water, Governing water wisely</th>
<th>Ministerial Conference on Water Security in the 21st Century</th>
</tr>
</thead>
<tbody>
<tr>
<td>(March)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"We will continue to support the UN system to re-assess periodically the state of freshwater resources and related ecosystems, to assist countries, where appropriate, to develop systems to measure progress towards the realisation of targets and to report in the biennial World Water Development Report as part of the overall monitoring of Agenda 21."

*(Ministerial Declaration, 7.B)*

**UN Millennium Declaration**

"We resolve ... to halve, by the year 2015 ... the proportion of people who are unable to reach or to afford safe drinking water."

*(UN Millennium Declaration, 19.)*

<table>
<thead>
<tr>
<th>2001</th>
<th>International Conference on Freshwater, Bonn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water - key to sustainable development Governance, mobilising financial resources, capacity building, sharing knowledge</td>
</tr>
<tr>
<td></td>
<td>Recommendations for action</td>
</tr>
</tbody>
</table>
'Combating poverty is the main challenge for achieving equitable and sustainable development, and water plays a vital role in relation to human health, livelihood, economic growth as well as sustaining ecosystems.'

*(Ministerial Declaration)*

'The conference recommends priority actions under the following three headings:

- Governance
- Mobilising financial resources
- Capacity building and sharing knowledge'

*(Bonn Recommendations for Action)*

<table>
<thead>
<tr>
<th>2002</th>
<th>World Summit on Sustainable development, Rio+10, Johannesburg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poverty eradication, sanitation, energy, financing, integrated water resources management, Africa</td>
</tr>
</tbody>
</table>

Plan of Implementation

'We agree to halve, by the year 2015 (...) the proportion of people who do not have access to basic sanitation, which would include actions at all levels to:

- Develop and implement efficient household sanitation systems;
  - Improve sanitation in public institutions, especially schools;
  - Promote safe hygiene practices;
  - Promote education and outreach focused on children, as agents of behavioural change;
  - Promote affordable and socially and culturally acceptable technologies and practices;
  - Develop innovative financing and partnership mechanisms;
  - Integrate sanitation into water resources management strategies.

*(Plan of Implementation)*

<table>
<thead>
<tr>
<th>2003</th>
<th>3rd World Water Forum, Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ministerial Declaration</td>
</tr>
</tbody>
</table>


Extracts from the general policy:

'We recognize that good governance, capacity building and financing are of the utmost importance to succeed in our efforts.'

*(Ministerial Declaration)*
APPENDIX 2. MODEL REMAINING AFTER INITIAL MODEL SELECTION USING CATCHMENT-DERIVED DATA

Variables remaining in model after initial model selection
See data dictionary (page 251) for explanation of codes

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variables</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow98</td>
<td>NatVegF2</td>
<td>Roads5</td>
</tr>
<tr>
<td>Flow99</td>
<td>NatVegF5</td>
<td>SaltHazard</td>
</tr>
<tr>
<td>Flow00</td>
<td>BioCond2</td>
<td>LC_pasture</td>
</tr>
<tr>
<td>Flow01</td>
<td>BioCond5</td>
<td>LC_urban</td>
</tr>
<tr>
<td>DTime97</td>
<td>CovCrop1</td>
<td>LC_orchard</td>
</tr>
<tr>
<td>DTime98</td>
<td>CovCrop2</td>
<td>LC_othwood</td>
</tr>
<tr>
<td>DTime99</td>
<td>N345Cat</td>
<td>LandCond1</td>
</tr>
<tr>
<td>DTime00</td>
<td>AveRain97</td>
<td>LandCond2</td>
</tr>
<tr>
<td>DTime01</td>
<td>AveRain98</td>
<td>SoilDegred1</td>
</tr>
<tr>
<td>X</td>
<td>AveRain99</td>
<td>SoilDegred2</td>
</tr>
<tr>
<td>Y</td>
<td>AveRain00</td>
<td>SoilDegred5</td>
</tr>
<tr>
<td>X2</td>
<td>AveRain01</td>
<td>WatHold11</td>
</tr>
<tr>
<td>Y2</td>
<td>NatVegE2</td>
<td>WatHold12</td>
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<td>X*Y</td>
<td>NatVegE4</td>
<td>altdiff</td>
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<td>CC1Cat</td>
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<td>CatCond2</td>
<td>ClayB1</td>
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<tr>
<td>CatCond3</td>
<td>LU_built</td>
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<tr>
<td>CatCond4</td>
<td>LU_natcon</td>
<td>AreaSlope2</td>
</tr>
<tr>
<td>Erode1</td>
<td>LU_forest</td>
<td>SlopeF1</td>
</tr>
<tr>
<td>Erode2</td>
<td>LU_irrig</td>
<td>SlopeF3</td>
</tr>
<tr>
<td>Erode3</td>
<td>Roads3</td>
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APPENDIX 3. ENVIRONMENTAL QUALITY OBJECTIVES FOR RIVERS AND STREAMS – WATER QUALITY

<table>
<thead>
<tr>
<th>Region</th>
<th>Turbidity (NTU)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>75th percentile</td>
</tr>
<tr>
<td>Highlands</td>
<td></td>
</tr>
<tr>
<td>All areas</td>
<td>≤5</td>
</tr>
<tr>
<td>Forests – A</td>
<td></td>
</tr>
<tr>
<td>Wilsons Promontory, Strezelecki Ranges &amp; East Gippsland Coast</td>
<td>≤5</td>
</tr>
<tr>
<td>Upper Murray, Kiewa &amp; Mitta Mitta Catchments</td>
<td>≤5</td>
</tr>
<tr>
<td>The Grampians</td>
<td>≤5</td>
</tr>
<tr>
<td>All other areas define this</td>
<td>≤5</td>
</tr>
<tr>
<td>Forests – B</td>
<td></td>
</tr>
<tr>
<td>Otway Ranges</td>
<td>≤5</td>
</tr>
<tr>
<td>All other areas</td>
<td>≤5</td>
</tr>
<tr>
<td>Cleared Hills and Coastal Plains</td>
<td></td>
</tr>
<tr>
<td>Lowlands of Barwon, Moorabool, Werribee &amp; Maribyrnong catchments</td>
<td>≤10</td>
</tr>
<tr>
<td>Lowlands of Yarra, Western Port, Latrobe, Mitchell, Tambo &amp; Snowy catchments</td>
<td>≤10</td>
</tr>
<tr>
<td>Uplands of Moorabool, Werribee, Maribyrnong, Campaspe, Loddon, Avoca, Wimmera and Hopkins catchments</td>
<td>≤10</td>
</tr>
<tr>
<td>Mid-reaches of Ovens &amp; Goulburn Catchments</td>
<td>≤10</td>
</tr>
<tr>
<td>Murray and Western Plains</td>
<td></td>
</tr>
<tr>
<td>Lowlands of Kiewa, Ovens &amp; Goulburn Catchments</td>
<td>≤30</td>
</tr>
<tr>
<td>Lowlands of Campaspe, Loddon &amp; Avoca Catchments</td>
<td>≤30</td>
</tr>
<tr>
<td>Lowlands of Wimmera catchment</td>
<td>≤10</td>
</tr>
<tr>
<td>Lowlands of Glenelg, Hopkins, Portland &amp; Corangamite catchments</td>
<td>≤10</td>
</tr>
</tbody>
</table>

Environmental quality objectives for rivers and streams – water quality (Environment Protection Authority Victoria, 2001)
## APPENDIX 4. DATA DICTIONARY

<table>
<thead>
<tr>
<th>Data set</th>
<th>Classifications</th>
<th>Abbreviation</th>
<th>Transformations for catchment derived data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site id number</td>
<td>Site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Does stream dry up at particular time of year?</td>
<td>Intermittent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name of site</td>
<td>Name</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location of site</td>
<td>Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turbidity annual medians</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median annual turbidity, 1997</td>
<td>Turb97</td>
<td>Log (10)</td>
<td></td>
</tr>
<tr>
<td>Median annual turbidity, 1998</td>
<td>Turb98</td>
<td>Log (10)</td>
<td></td>
</tr>
<tr>
<td>Median annual turbidity, 1999</td>
<td>Turb99</td>
<td>Log (10)</td>
<td></td>
</tr>
<tr>
<td>Median annual turbidity, 2000</td>
<td>Turb00</td>
<td>Log (10)</td>
<td></td>
</tr>
<tr>
<td>Median annual turbidity, 2001</td>
<td>Turb01</td>
<td>Log (10)</td>
<td></td>
</tr>
<tr>
<td><strong>Stream flow annual medians</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median annual streamflow, 1997</td>
<td>Flow97</td>
<td>Log (10)</td>
<td></td>
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<tr>
<td>Median annual streamflow, 1998</td>
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<td>Median annual streamflow, 1999</td>
<td>Flow99</td>
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<tr>
<td>Median annual streamflow, 2000</td>
<td>Flow00</td>
<td>Log (10)</td>
<td></td>
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<td>Land cover - other woody</td>
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<td>Areas of land cover change - (reprojected) tabulated for each catchment</td>
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<td>Land cover change - decrease</td>
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<td>Areas of Land condition index (reprojected), 5 kilometre grid, 5 classes (reprojected) tabulated for each catchment. Classified for the Catchment Condition Project using equal area under the normal distribution.</td>
<td>Land condition index- value 1</td>
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<td>Land condition index- value 3</td>
<td>LandCond3</td>
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<td>Land condition index- value 4</td>
<td>LandCond4</td>
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<td>Land condition index- value 5</td>
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<td>Areas of Soil acid hazard - 5 kilometre grid, 5 classes (reprojected) tabulated for each catchment. Classified for the Catchment Condition Project using equal area under the normal distribution.</td>
<td>Soil acid hazard - value_1</td>
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<td>Soil acid hazard - value_3</td>
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<td>Soil acid hazard - value_4</td>
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<td></td>
<td>Soil acid hazard - value_5</td>
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<td>Areas of Soil degradation, 5 kilometre grid, 5 classes (reprojected) tabulated for each catchment. Classified for the Catchment Condition Project using equal area under the normal distribution.</td>
<td>Soil degradation – value 1</td>
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<td>Soil degradation – value 2</td>
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<td>Soil degradation – value 3</td>
<td>SoilDegred3</td>
<td>4th root</td>
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<td>Soil degradation – value 4</td>
<td>SoilDegred4</td>
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<td>Soil degradation – value 5</td>
<td>SoilDegred5</td>
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<td>Areas of Soil depth, 5 kilometre grid, 5 classes (reprojected) tabulated for each catchment.</td>
<td>Soil depth – value 1 (thinnest)</td>
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<tr>
<td>Areas of predicted Available Soil Water Holding Capacity of layer 1 (A Horizon - Top-soil) Whpk_1 (reprojected) tabulated for each catchment. Classified using natural Breaks (Jenks) in ArcMap 8.3</td>
<td>Soil water holding capacity - layer 1, value 1</td>
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<td>Soil water holding capacity - layer 1, value 2</td>
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<td>Soil water holding capacity - layer 1, value 3</td>
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<td>Areas of predicted Available Soil Water Holding Capacity of layer 2 (B Horizon - Top-soil) Whpk_2 (reprojected) tabulated for each catchment. Classified using natural Breaks (Jenks) in ArcMap 8.3</td>
<td>Soil water holding capacity -layer 2, value 1</td>
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<td>Soil water holding capacity -layer 2, value 2</td>
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<td>Soil water holding capacity -layer 2, value 3</td>
<td>WatHold23</td>
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<td>Areas of Altitude of catchment centroid Centroid calculated using ArcMap 8.3</td>
<td>Altitude of centroid</td>
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<tr>
<td>Areas of altitude of catchment pour point. Altitude calculated using ArcMap 8.3</td>
<td>Altitude of pour point</td>
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<td>Difference in altitude between pour point and centroid in metres calculated using ArcMap 8.3 Distance between each 250m grid cell and the catchment centroid calculated in ArcMap 8.3</td>
<td>Difference in altitude in metres.</td>
<td>altdiff</td>
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<td>Distance to catchment centroid in metres</td>
<td>Distance to centroid in km</td>
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<td>Mean Aspect calculated in ArcMap 8.3.</td>
<td>Mean aspect in degrees</td>
<td>AveAspect</td>
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<tr>
<td><strong>Agriculture on steep slopes - value_1</strong></td>
<td>AgSteep1</td>
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<tr>
<td><strong>Agriculture on steep slopes - value_2</strong></td>
<td>AgSteep2</td>
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<td><strong>Agriculture on steep slopes - value_3</strong></td>
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<td><strong>Agriculture on steep slopes - value_4</strong></td>
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<td><strong>Agriculture on steep slopes – value 5</strong></td>
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</tbody>
</table>

**Areas of Agriculture on steep slopes, 5 kilometre grid, 5 classes (reprojected) tabulated for each catchment.** Classified for the Catchment Condition Project using equal area under the normal distribution.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Classifications</th>
<th>Abbreviation</th>
<th>Transformations for catchment derived data</th>
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<td>Area of catchment calculated in ArcMap 8.3</td>
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<td>Perimeter of each catchment calculated using ArcMap 8.3</td>
<td>Perimeter in kilometres</td>
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<td>Shape factor is 4 pi Area divided by perimeter squared. Circular shapes have a value of one and less than one for elongated shapes. Calculated in ArcMap 8.3</td>
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<td>Mean slope, calculated in ArcMap 8.3.</td>
<td>Mean slope in degrees</td>
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<td>Areas of Slope classified from DEM (reprojected) tabulated for each catchment Classified using natural Breaks (Jenks) in ArcMap 8.3</td>
<td>Slope value 1</td>
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<td>Areas of R factor from the RUSLE (or erosivity) tabulated for each catchment</td>
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<td>S factor – value 3</td>
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APPENDIX 5. MAPS OF DATA USED IN MODEL
Appendix 5-1 Clay content of A horizon

Appendix 5-2 Clay content of B horizon
Appendix 5-3  Interim Biogeographic Regionalisation of Australia

Appendix 5-4  Catchment Condition Index– Catchment Condition Project
Appendix 5-5 Biota Condition Index– Catchment Condition Project

Appendix 5-6 Erosion Ratio– Catchment Condition Project
Appendix 5-7 Industrial Point Sources – Catchment Condition Project

Appendix 5-8 Natural Vegetation Fragmentation – Catchment Condition Project
Appendix 5-9 Natural Vegetation Extent – Catchment Condition Project

Appendix 5-10 Nutrient Point Sources – Catchment Condition Project
Appendix 5-11 Road Density 3 – Catchment Condition Project

Appendix 5-12 Land Condition Index – Catchment Condition Project
Appendix 5-13 Salinity risk 2000 – Catchment Condition Project

Appendix 5-14 Distance to River
Appendix 5-15 C factor from RUSLE

Appendix 5-16 K factor from RUSLE
Appendix 5-17 L factor from RUSLE

Appendix 5-18 R factor from RUSLE
Appendix 5-19 Average rainfall 1997

Appendix 5-20 Average rainfall 1998
Appendix 5-21 Average rainfall 1999

Appendix 5-22 Average rainfall 2000
Appendix 5-23 Average rainfall 2001

Appendix 5-25 Simplified land use ALUMC Version 4

Appendix 5-26 Secondary land use ALUMC Version 4
Appendix 5-27 Tertiary land use ALUMC Version 4

Appendix 5-28 Farms with significant degradation problems