

FLUVIAL GEOMORPHOLOGY  
RIVER REHABILITATION  
ENVIRONMENTAL FLOWS  
CATCHMENT HYDROLOGY

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## Geomorphology of the Maribyrnong River, Victoria



A report prepared for

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Melbourne Water

By

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Fluvial Systems Pty Ltd

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ABN 71 085 579 095

July 2000

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Arundel Street Weir with recently installed fishway (C. Gippel, 1999).

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July 2000

## Executive summary

### Introduction

Fluvial Systems Pty Ltd was commissioned by Melbourne Water to undertake a study of the fluvial geomorphology of the Maribyrnong River and to report on options for future management. This study is part of Melbourne Water's approach to strategic planning for the management of streams in Port Phillip and Western Port catchments.

In 1989 Melbourne Water commissioned Camp Scott Furphy Pty Ltd to undertake an assessment of the erosion occurring along the floodplain reach near Keilor. This study identified high priority sites between Arundel Weir and the Calder Freeway, which were subsequently stabilised. The purpose of the current study is to review this work in the context of current geomorphic processes, and make appropriate recommendations regarding management of the river, principally in the area from the Trestle Bridge to the junction of Jacksons and Deep Creeks.

### Hydraulics and stream power

The mean stream power of the river varied spatially, and as a function of discharge. The channel mean stream power exceeded  $50 \text{ Wm}^{-2}$  over about half of the reach length for the 1:2 yr ARI flood event. The stream power did not increase very much beyond that experienced for the 1:5 yr ARI event, because higher discharges spilled onto the floodplain. However, these floods produced high stream powers exceeding  $100 \text{ Wm}^{-2}$  at a few locations.

The Maribyrnong River varies considerably in cross-section size and shape, and slope, over the study area, and this gives rise to considerable spatial variation in stream power.

### Channel geomorphic processes

The Maribyrnong River is an actively eroding stream, and the most severe erosion would be expected on the outside bends of relatively tight meanders in alluvial bank material. Thus it is not surprising that the survey of Camp Scott and Furphy (1990) reported the most severe erosion in these locations. Despite rating many sites as having "severe" erosion, this cannot be interpreted as relating to a particular erosion *rate*. The survey of Camp Scott Furphy (1990) was based entirely on subjective visual inspection, and no erosion rate data were presented. Comparison of 1931 and 1993 aerial photographs revealed bend migration of 10-20 m at three locations only, but photographic distortion made the comparison difficult. There was no strong evidence available to suggest that erosion rates have increased in recent times.

The morphology of the channel was found to be variable throughout the study area, with some sections being more susceptible to erosion because of high stream power, high and steep banks, low width/depth ratio, confinement of floods, and poor riparian vegetation cover. Rock beaching conducted in response to the survey of Camp Scott Furphy (1990) was done at sites showing "severe" erosion, and these sites also had hydraulic and geomorphic characteristics that rendered them more susceptible to erosion. The visual assessment of the channel conducted in mid-1999 as part of this study did not attempt to rate erosion sites. However, the channel had a relatively stable appearance, with even vertical banks showing signs of recent vegetative colonisation, no doubt associated with the recent long period of drought.

The bed of the Maribyrnong River is stable, being controlled by a series of artificial weirs, rock grade control structures and natural rock bars.

The sediment supply, catchment hydrology and channel hydraulics may have altered slightly in historical times. Such subtle changes usually have no significance for channel erosion rates. However, if a small change caused the channel to cross a geomorphic threshold, then rejuvenation (incision, widening, or accelerated rate of bend migration) could occur. This process cannot be modelled with any level of certainty. In high-energy systems like the Maribyrnong River, it is known that poor riparian vegetation cover is conducive to ongoing bank erosion. Removal of the native riparian vegetation cover was probably the biggest single disruption to the geomorphology of the stream system during historical times. The vegetation of the riparian zone is currently more intact than it was in 1931, but much of it is composed of alien or weed species.



There is evidence of a massive slump failure on the left side-slope at chainage 14.8–15.0 km. This failure pre-dates the 1931 aerial photograph. Such failures probably occur during large rainfall and flood events, when high velocity overbank flows erode the saturated soils of the toe of the side-slope or terrace. Although infrequent and difficult to predict, these failures are catastrophic, and likely to occur again in the future.

### Review of 1990 erosion study

The erosion survey conducted in 1990 by Camp Scott Furphy (1990) used a subjective visual assessment technique that incorporated non-geomorphic variables such as the perceived cost of stabilisation, or potential loss of assets if the site was not stabilised. However, there is no way of knowing how these factors were incorporated into the operators' judgements, nor how influential they were in determining the final rating. Camp Scott Furphy (1990) did not measure variables that might act as surrogates for erosion, such as channel morphology, or stream power. It is important to note that the erosion severity ratings were in no way connected to actual erosion rates, as such data were unavailable.

Analysis of a sample of 62 cross-sections, from the Trestle Bridge to the junction of Deep and Jacksons Creeks (21.7 km of river, and 43.3 km of bank), revealed that 13% of the banks were rated as having severe erosion. This equates to 5.6 km of severely eroded bank, an estimate that includes left and right banks. Of this total, 2.6 km was located in the Keilor reach from Calder Freeway to Browns Road (4.8 km of river, and 9.7 km of bank).

Not unexpectedly, the majority of sampled sites (64%) that were rated as having severe or moderate erosion were located on concave (outside) bends in alluvial material. Sites that were rated as having severe or moderate erosion that occurred within this type of channel morphology were associated with high bankfull stream power and steep bank angle. Steep bank angle is commonly thought (sometimes incorrectly) to be a good indicator of active bank erosion, and it is one of the indicators used in the Index of Stream Condition. Steep bank angle is a dramatic feature that is likely to make a strong visual impression when undertaking erosion assessments. Stream power at bankfull discharge is known to be a predictor of bank erosion potential, but it cannot be directly visually assessed during a low flow channel survey. It appears that the surveyors were responding to a combination of some artefact of high stream power, and steep bank angle. Bank angle was not this artefact, as bank angle and stream power were not correlated.

The distribution of erosion sites identified by Camp Scott Furphy (1990) was as expected, with most sites located on the outside (erosional) bend of meanders, and the more severely eroded sites being associated with steep bank angles and high stream power. This distribution would be found on any alluvial river, because it is natural for alluvial rivers to erode their banks as part of the meander migration process.

Camp Scott Furphy (1990) recommended stabilisation of the sites rated as severely eroded, even though they produced no data on actual erosion rates. Thus, it is possible that sites that were rated "severely eroded", were stable at the time of the survey. Similarly, it is possible that sites rated as having no erosion could have become unstable since the time of the survey. Camp Scott Furphy (1990) did not do a cost-benefit analysis of conducting the proposed bank stabilisation works.

It is difficult to identify active erosion using rapid visual assessment. This technique can identify sites of past erosion, which is probably a reasonable guide to sites of likely future erosion. The biggest problem is that the technique does not provide data on erosion rates, so it is difficult to predict the consequences of future erosion.

The Maribyrnong River is an actively eroding river. However, the rates of bend migration are relatively low by world standards, with only three bends showing measurable migration from a comparison of 1931 and 1993 aerial photographs. Distortion of the images, and poor quality of the earlier images compromised measurement of erosion rates from available photographs, so changes in the order of  $\pm 10$  m could not be detected by this method. The Camp Scott Furphy (1990) study recommended channel stability works at several high priority sites. Melbourne Water at a cost of about \$1 million subsequently undertook a programme of works. Decisions regarding erosion control works are driven partly by geomorphic considerations, but also by concerns about asset protection, and social factors (some of these were subjectively incorporated into the erosion severity rating scheme used in the survey). Thus, while the



Maribyrnong River is not a highly active river by world standards, the decision to conduct the post-survey stability works was justified at the time in terms of local social, economic and physical factors, and was consistent with the dominant Australian stream management paradigm that values absolute (in management time-scales) stability. This conventional paradigm is now falling out of favour in some circles, where it is recognised that a level of channel instability is desirable from an ecological perspective, and that channel stability is difficult and expensive to attain. The stability works done on the Maribyrnong River during the 1990s addressed sites where assets were threatened, and/or where there was an apparent risk of catastrophic channel change.

### **Ecological considerations**

Based on macroinvertebrate community composition, the lowland Maribyrnong River is in relatively good condition for an urban lowland river, certainly relative to the Yarra River, which is severely degraded by the time it reaches its estuary. Relatively undisturbed lowland river communities in urban settings are quite rare. The Maribyrnong River is also one of the few large basaltic plain streams in Victoria. Thus the Maribyrnong is a valuable scientific resource, in addition to its obvious values as a community resource.

The Maribyrnong River is not pristine, but in terms of hydrological modification and water quality impacts, the river is less disturbed than most other large lowland rivers in the Melbourne Water area. The condition of the riparian vegetation appears to be better now than it was in the 1930s. Because the biotic communities of the Maribyrnong River are not severely disturbed, local-scale improvements to habitat and water quality are more likely to have measurable results in community recovery than in severely degraded systems. In severely degraded streams, multiple disturbances acting synergistically are likely to confound the potential success of local-scale restoration efforts.

Three major groups of disturbance have been identified as potential degrading processes to the Maribyrnong River ecosystem: 1) Land uses leading to bank and channel instability, and poor quality runoff in the Keilor floodplain area, 2) High nutrient loads, 3) Freeway runoff and general urban stormwater pollution.

### **Suggested management priorities**

Bank erosion is a problem in two respects: landowners are concerned about loss of productive land, and the entrained sediment enters the fluvial system causing degraded water quality and deposition of sediment on habitats. The impact of bank erosion on substrate habitat quality is probably minor, as the macroinvertebrate community is in a fairly healthy condition despite bank erosion being a characteristic of this river for many years.

Water quality records suggest that the Maribyrnong River does not export an exceptionally high load of suspended sediment compared with some other rivers in the Melbourne Water area. Continued bank stabilisation works may be justifiable in terms of protection of private land or assets, but this can only be established through a cost-benefit analysis.

The weight of evidence gathered during the course of this study points to the conclusion that a large investment in further bank stabilisation works would represent poor value for money in terms of expected waterway health benefits.

The small weirs located on the river were constructed to create pools that were once used for pumping irrigation water in dry periods. It is recommended that Melbourne Water negotiate with landholders to repair or remove these weirs where necessary. This process will ensure that fish passage is maintained. Disused weirs do not require any treatment. The weirs help to stabilise the bed, but Milburns, Koroneos and McNabs Weirs may interfere with fish passage. Reconstruction of these weirs is recommended. The grade control structures appeared to be in good condition and do not require attention at this time.

The riparian vegetation is in poor to very poor condition in the areas that are used for intensive agriculture. Landholders have historically shown a reluctance to support re-establishment of the riparian zone. It is recommended that Melbourne Water continue to work with landholders to improve riparian vegetation, as this will bring environmental benefits, and should improve bank stability. The margins of the side-slopes and terraces (sometimes distant from the



channel) are subject to potentially erosive flows during very large events (in the order of 1:50 year ARI), and the stability of these areas would be enhanced by re-vegetation.

Ecologically, the Maribyrnong River is in a relatively good condition, which is rare for a lowland river close to Melbourne. It is also one of the few large basaltic plain streams in Victoria. Thus, the river represents a valuable ecological resource and should be managed as such. The major threat to the river's ecology appears to be poor quality runoff from urban stormwater drains, and turbid runoff from quarries located close to the river. Arundel Creek drains Melbourne Airport and is a possible source of contamination, but lack of data prevents assessment of this issue.

Stormwater runoff from future urban development in the catchment must be managed with tight controls on water quality. Urban stormwater probably represents the biggest threat to the integrity of the river.

The Maribyrnong River channel is incised, with localised overtopping occurring during the 1:2.5 year ARI event. More extensive inundation of the Keilor floodplain occurs for floods greater than the 1:10 year ARI event (e.g. Nov 1971 and Oct 1983 flood level). Widespread flooding occurs for floods greater than the 1:50 year ARI event (e.g. May 1974 flood level). The floodplain is cleared and has a low roughness coefficient, so that 1:50 year ARI flood flows overtopping the channel near Arundel Road, crossing south-east and re-entering near the Calder Freeway, could reach velocities sufficient to strip the floodplain soil, and threaten an avulsion. The same risk applies to the meander bend upstream of Flora Street, where a soil quarry is currently operating, and the grassed right bank floodplain on the bend downstream of Flora Street, but for smaller floods of around 1:2.5-1:10 year ARI.

### Recommendations

1. Having relatively undisturbed hydrology and water quality, and being one of the few large basaltic plain streams in Victoria, the Maribyrnong River represents a valuable ecological resource and should be managed as such.
2. Eleven established cross-sections should be surveyed following events exceeding the 1:2 yr ARI flood event ( $225 \text{ m}^3\text{s}^{-1}$ ). The survey data should be plotted and compared with previous surveys to monitor the bank migration rate.
3. The most effective way to reduce nutrient loads would be improvements to the quality of effluent from the Sunbury STP. Pollution control measures for urban stormwater and freeway runoff would likely be the next most effective approach to nutrient reduction in the lower Maribyrnong River.
4. Source control of urban nutrient and sediment pollution is a high priority action. There may be opportunities for construction of wetlands for the purpose of stormwater treatment. New developments must be planned using water sensitive urban design principles.
5. Control of runoff from soil quarries and market gardens would reduce localised concentrated sediment inputs to the river. This is regarded as a matter of high priority.
6. The impact of Arundel Creek (which drains part of Melbourne Airport) on the water quality of the Maribyrnong River requires assessment before recommendations on the most appropriate management approaches for this tributary can be made.
7. It is recommended that Melbourne Water negotiate with landholders to repair or remove low level weirs where necessary. This process will ensure that fish passage is maintained. Disused and heavily degraded weirs do not require any treatment.
8. Melbourne Water should continue to work with landholders to improve riparian vegetation, as this will bring environmental benefits, and may improve bank stability. However, the history of landholder indifference or opposition to this strategy means that it may be a low priority due to the high level of effort that would be required to achieve success. Re-vegetation of the margins of the side-slopes and terraces would enhance the stability of these areas under infrequent, but potentially catastrophic, large flood conditions.



9. The weight of evidence gathered during the course of this study suggests that a large investment in further bank stabilisation works would currently represent poor value for money in terms of expected river health benefits. Channel works should be directed towards the long-term management time frame.
10. There is a risk of localised floodplain soil stripping for floods >1:5 year ARI, with much of the Keilor floodplain under threat for floods of around 1:50 year ARI. There is a risk of avulsion during these large floods. Current land use practices (market gardening and soil quarrying) increase the risk because they maintain low floodplain surface roughness and vegetative cover. Any floodplain development proposals must consider this serious risk.
11. Re-vegetation of the margins of the side-slopes and terraces would enhance the stability of these areas under infrequent, but potentially catastrophic, large flood conditions. This type of revegetation may be considered by landholders to be incompatible with the current land use. This recommendation relates to long-term planning; any major change in land use on the floodplain should involve seeking opportunities to increase floodplain stability and roughness, and the best method is re-vegetation.
12. Future geomorphic investigations should attempt to establish erosion rates, or model erosion potential. It is risky to base large investments on subjective visual assessment of erosion severity.

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## 1 Introduction

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### 1.1 Purpose of Study

Fluvial Systems Pty Ltd was commissioned by Melbourne Water to undertake a study of the fluvial geomorphology of the Maribyrnong River and to report on options for future management. This study is part of Melbourne Water's approach to strategic planning for the management of streams in Port Phillip and Western Port catchments.

In 1989 Melbourne Water commissioned Camp Scott Furphy Pty Ltd to undertake an assessment of the erosion occurring along the floodplain reach near Keilor. This study identified high priority sites between Arundel Weir and the Calder Freeway, which were subsequently stabilised. The purpose of the current study is to review this work in the context of current geomorphic processes.

### 1.2 Objectives of study

The objectives of the study, as defined in the terms of reference, were to:

- broadly describe the historical nature and extent of the geomorphic changes to the catchment, the River and its floodplains, over the period of European settlement, including recent management phases utilising historic records and reference materials;
- assess and provide a detailed description of the current stream conditions relating to the hydrogeomorphic processes operating on the Maribyrnong River and identify broad sections of the River where particular processes are dominant;
- undertake a critical review of geomorphic processes in the waterways in relation to stream power and flood frequency;
- identify areas that are prone to major change in an episodic event;
- document the causes of the present management problems, including human impacts such as channel modification, weir construction and alteration to drainage patterns;
- review the erosion study undertaken in 1990 by Camp Scott Furphy Pty Ltd in the context of the geomorphic processes identified above;
- assess erosion sites including those that have been stabilised, to provide an assessment of erosion and the degree of risk associated with each site; (are these sites still undergoing significant erosion? Have they stabilised over the past 9 years? What implications would a major flood event have on the rate of erosion and movement of sediment?)
- identify any further management actions required; and
- define the best options for management activities and programs, in relation to the geomorphology and waterway dynamics to meet waterway sustainability, ecological requirements and optimum flood passage. Document works required in options and provide costing estimates and priorities.

### 1.3 Structure of this Report

The initial sections of this report cover the background to the study (Section 1). The physical characteristics of the River and its catchment are reviewed in Section 2. Section 3 describes the hydrology and hydraulics of the River, as they pertain to the geomorphology of the river and its sustainable management. Section 4 details the current river geomorphological processes.

The study of Camp Scott Furphy (1990) is reviewed in Section 5. Section 6 covers the ecological aspects of the river as they pertain to the geomorphology of the river and its sustainable management.

Section 7 deals with the management of the river in the medium to long term. Recommendations arising from the study are presented in Section 8.



## 2 Physical Setting of the Maribyrnong River and Catchment

The physical characteristics of the Maribyrnong River and catchment have been previously well described in Metropolitan Board of Works (MMBW) (1975a), Water Resources Council (WRC) (1981) and Melbourne Metropolitan Board of Works (MMBW) (1986) and Camp Scott Furphy (1990), and in less detail in Melbourne Metropolitan Board of Works (MMBW) (1976) and Fisher (1999). The description below is drawn from these sources.

### 2.1 Geology

The oldest Cambrian (approx.  $550 \times 10^6$  yr BP) rocks (greenstones) can be found in the upper parts of the catchment near Mt William. Cambrian shales, overlain by Lower Ordovician (approx.  $500 \times 10^6$  yr BP) marine sediments lie to the west of this. To the east is the Melbourne Trough, in which a 5 000 m thick sequence of Silurian (approx.  $420 \times 10^6$  yr BP) sediments (sandstones, greywackes and siltstones) was deposited over the Ordovician rocks. Deep Creek flows through these Silurian sediments for most of its course, and there are many outcrops along the lower Maribyrnong River.

Tectonic activity in the middle Devonian resulted in uplift, faulting and folding of sediments along north-south axes. During the Upper Devonian (approx.  $350 \times 10^6$  yr BP) period, granitic magmas were intruded through the sediments, and volcanics were extruded. The Macedon and Cobaw Ranges are composed of these granitic rocks. Faulting and folding occurred during the Upper Palaeozoic and the Mesozoic (approx.  $300\text{--}100 \times 10^6$  yr BP).

Basalts were extruded during the Tertiary (peaking  $20\text{--}40 \times 10^6$  yr BP), and these are known as the Older Volcanics. They are exposed in the banks and beds of the Maribyrnong River near Tullamarine and Keilor. The Brighton Group is a sequence of Tertiary clays, silts, sands and gravels deposited under fluvial conditions, located in the lower eastern corner of the catchment.

At the beginning of the Quaternary ( $6\text{--}7 \times 10^6$  yr BP) the Newer Volcanics were extruded over the area, with activity peaking at approximately  $2 \times 10^6$  yr BP. These rocks now outcrop from Lancefield to Essendon, forming an undulating plain. The basalt is generally 50–100 m thick. It is this volcanic material that is largely responsible for the topographic character of the mid-lower Maribyrnong catchment. Following regional uplift, rivers and creeks incised steep-sided valleys and gorges into this basalt, depositing intermittent and narrow bands of alluvial material along their courses. In places the underlying Palaeozoic bedrock was exposed.

### 2.2 Development of the drainage system

Prior to extrusion of the Newer Basalts, the ancestral Deep Creek, which flowed south towards Sunbury, was the major stream in the area. The course of the river was forced east by the lava flows. Konagaderra Creek, Emu Creek and Jacksons Creek developed on the basaltic terrain. These streams all flow into Deep Creek to form the Maribyrnong River at Bulla.

After cessation of the volcanic activity, in response to regional uplifting, the drainage system incised into the basalt to produce deep valleys and gorges. There is a constriction at Keilor formed by more resistant basaltic rocks, upstream of which lateral river erosion has excavated a wider valley. In the middle and lower reaches of the catchment, stream gradient is controlled by lithology, with steeper gradients associated with basalt.

Thick alluvial deposits of gravel, sand and silt were formed on the Maribyrnong River's floodplain during the Pleistocene. However, the stream subsequently rejuvenated several times, causing further entrenchment. During the Holocene, the sea level fell by about 3 m to form the current coastline (Camp Scott Furphy 1990, p. 13). There has been speculation that erosion and deposition rates have been influenced to some extent by alternating low and high rainfall regimes during the past 30 000 years (Camp Scott Furphy 1990, p. 14–15).

The remnants of the rejuvenation process are well-defined high-level alluvial terraces. Following the discovery of the Keilor cranium in 1940, there was interest in dating these terraces (Jenkin 1988, p. 385–386). There are three terraces near Keilor:

- Arundel Terrace (approx. 31 000 years old)
- Keilor Terrace (25 000 – 6000 years old)
- Maribyrnong Terrace (2000 – 4000 years old)

The highest and oldest is the Arundel Terrace, or the Arundel Formation which consists of clay with thin sandy and gravelly lenses, and near the base it contains pebbles and boulders of basalt and Silurian bedrock. Doutta Galla Silt of the Keilor Terrace overlies the Arundel Formation, and consists of uniform silt. The Maribyrnong Terrace is the youngest terrace. The Maribyrnong Alluvium consists of grey to black sandy and clayey silt. Both craniums (Keilor and Green Gully) were found in Doutta Galla Silt (Jenkin 1988, p. 386).

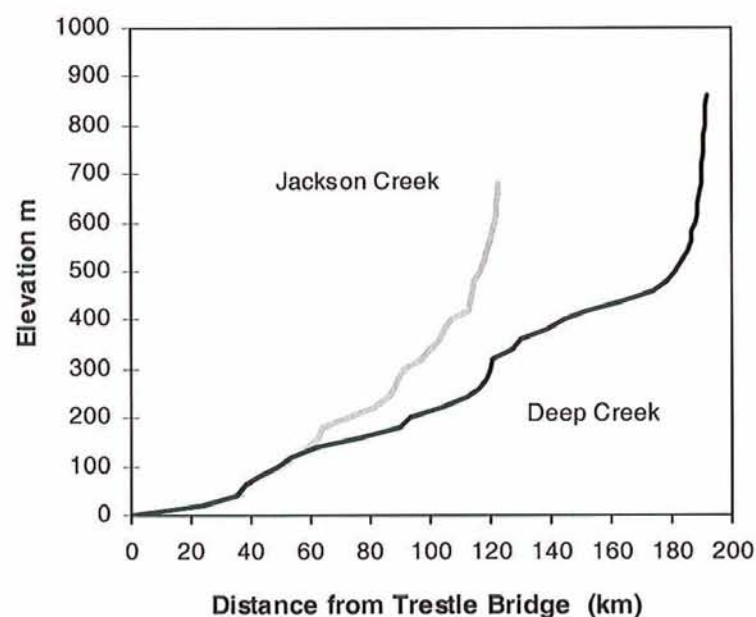
Yellow and red duplex soils have developed on the terrace material in the Upper Deep Creek catchment, along Jacksons Creek near Sunbury, and along the Maribyrnong River. The soils are of medium depth with moderate to low permeability. They have moderate to high susceptibility to erosion when they form the banks of streams (WRC 1981, p. 16).

## 2.3 Catchment Physiography

The Maribyrnong River has a catchment area of 1450 km<sup>2</sup>. The Maribyrnong River joins the Yarra River about 4 km from Port Phillip Bay. The basin can be divided into three sections (Figure 1):

- The hills
- The upper plains
- The lower plain

The hills lie above 450 m in elevation. Several peaks reach 600 m, with Mt Macedon rising to 1000 m. The upper plains lie between 150 m and 450 m. It is an extensive plain of flat to undulating country, principally formed on basalt. Jacksons Creek is noticeably steeper than Deep Creek in the upper plains section (Figure 1). The lower plain lies below 150 m. This area takes in the lower reaches of Jacksons and Deep Creeks, and the Maribyrnong River (Figure 1). The main focus of this study is the lower 22 km of the river system (i.e. the Maribyrnong River proper, which forms below the junction of Jacksons and Deep Creeks).



**Figure 1. Long profile of Jacksons and Deep Creeks (confluence at approx. 20 km chainage).**



## 2.4 Rainfall

Rainfall is spatially variable over the catchment, ranging from 1200-1500 mm/annum in the Mt Towrong area to 500 mm/annum at Sydenham. The rain shadow area from Bulla and Sunbury to Darraweit Guim has the lowest rainfall in Victoria south of the Great Dividing Range. In the upper plains, most rainfall occurs in the winter months. In the middle part of the catchment, this seasonality is less pronounced and is spread over winter and spring. In the lower catchment, rainfall is fairly evenly distributed, with a slight spring dominance.

## 2.5 Hydrology

Mean annual natural discharge is 120 600 ML (WRC 1981). In 1981, only about 5% of the total discharge was harvested for town water (2 400 ML), irrigation (2 300 ML) and other rural uses (1200 ML) (WRC 1981). The estimated mean annual discharge in 1981 with diversions was 115 300 ML. The amount of water required for urban use increased over the next two decades as Sunbury and Gisborne developed.

Jacksons Creek and Deep Creek contribute about 30% and 70% respectively of the annual flow in the Maribyrnong River. In the hills region the runoff coefficient is about 0.2, while the lower parts of the catchments have runoff coefficients of 0.01 to 0.14 (WRC 1981, p. 26-27). Diversions do not make a major impact on annual flows in the Maribyrnong River or its tributaries. Unlike some other catchments close to Melbourne, the Maribyrnong catchment is not used to supply water to metropolitan Melbourne. Also, the limited area of alluvial flats restricts opportunities for intensive irrigated agriculture. The total population of the catchment that depends on the rivers for town water supply is quite small (17 500 people in 1976) (WRC 1981, p. 14).

The coefficient of variation ( $C_v$ ) of annual flows for streams gauging stations in the Maribyrnong catchment (0.67 to 0.76) (WRC 1981, p. 29) are high by world standards, and similar to other Australian catchments of this size and climate (McMahon et al. 1992). The flows in the Maribyrnong River catchment are more variable than most streams south of the Great Dividing Range and east of Melbourne (WRC 1981, p. 28). Annual flows vary from about 10 000 ML to 430 000 ML (WRC 1981).

Flows are relatively evenly distributed throughout the year, with a slight spring maximum, on Willimigongon Creek at Upper Macedon, and Barringo Creek at Gisborne. In contrast, Jacksons Creek, Riddells Creek, Emu Creek and the Maribyrnong River have strongly seasonal flows, with a winter/spring dominance (WRC 1981, p. 28).

While diversions do not have a large impact on annual flows, they do affect low flows. For example, Willimigongon Creek has a large number of licenced diversions, which has a significant impact on flow during dry periods (WRC 1981).

There were five notable drought periods in the flow record on the Maribyrnong River, 1914-15, 1944-45, 1967-68, 1982-83 and the current dry period (1997-current).

According to WRC (1981) the river breaks its banks at Maribyrnong when flow reaches  $200 \text{ m}^3 \text{ s}^{-1}$  [note that MMBW (1975b) gives bankfull discharge at  $270\text{--}320 \text{ m}^3 \text{ s}^{-1}$  depending on tidal influence]. Houses, roads and private gardens begin to flood at a flow of  $400 \text{ m}^3 \text{ s}^{-1}$ , while serious damage occurs at flows above  $500 \text{ m}^3 \text{ s}^{-1}$ . These floods have an estimated return period of 4, 10 and 18 years respectively (WRC 1981, p. 32). Between 1871 and 1986 there were 25 recorded occasions when the river overtopped its banks at Maribyrnong township. The actual number of times that the river overtopped would be greater than this because of under-reporting and because of missing records. Flows were gauged from 1908, but there is a gap in the record from 1934 to 1955.

## 2.6 Water quality (suspended solids)

Water quality is of interest with respect to geomorphology because high suspended solids concentrations during storm events can indicate active bank erosion. The Victorian Water Quality Network samples turbidity much more frequently than it does suspended solids. The data for current sites (Table 1) suggest that storm event turbidity is higher in Jacksons Creek than Deep Creek. The lower Maribyrnong River (Keilor) has higher turbidities than at Bulla,



which is located upstream of the junction of Jacksons Creek. The higher turbidities can only be partly explained by contributions from Jacksons Creek, because flow from Jacksons Creek is only about 30% of the total Maribyrnong River flow. Thus, it would appear that turbidity does increase in the reach from the confluence to Keilor. The source could be bank erosion or runoff from agriculture and urban areas.

**Table 1. Turbidity data (NTU) for sites in the Maribyrnong catchment (Hunter and Zampatti 1994).**

Site	Median	p90	Max.
Barringo Ck, Barringo	2.5	6.2	29
Jacksons Ck, Sunbury	10	77	470
Emu Ck, Clarkfield	5.9	27	77
Deep Ck, Darraweit Guim	3.4	34	330
Maribyrnong R, Bulla	3.4	48	260
Maribyrnong, Keilor	5.8	73.5	370

The highest suspended solids concentration reported by Hunter and Zampatti (1994) for the Maribyrnong River was  $350 \text{ mgL}^{-1}$  at Keilor ( $N = 90$ ). At Bulla, the maximum reported was  $94 \text{ mgL}^{-1}$  ( $N = 41$ ). Using EPA and MMBW data, Bray (1989) reported a maximum value of  $440 \text{ mgL}^{-1}$  at Brimbank over the period 1984–1988. The high values were always associated with storm events. However, these monitoring programmes made no effort to sample the entire hydrograph, so these maximum values do not necessarily represent the peak concentrations. The same can be said for the maximum turbidities (Table 1), while the 90<sup>th</sup> percentile turbidities probably represent typical values for minor events.

Camp Scott Furphy (1990) attempted to develop a linear regression relationship between EPA suspended solids concentration data and discharge at the time of sampling. Such “rating curves” can sometimes be used to estimate sediment loads, which can indicate the rate of bank erosion or surface erosion. However, without knowledge of the relative importance of these processes, or knowledge of the background (undisturbed) rates of sediment transport, the results of sediment load modelling can be difficult to interpret. Regardless, Camp Scott Furphy (1990) found no significant correlation between discharge and suspended solids concentration at any of the sampling stations located in the catchment. This is not unusual, because the processes of sediment entrainment and transport are not linearly related to river discharge.

Although Camp Scott Furphy (1990) found that discharge and suspended solids concentration data were not correlated, an earlier study by MMBW (1975b) did generate a sediment rating curve using data from Calder Highway Bridge sampled during the period 1972–1975. The rating curve was used to estimate sediment loads for the river during the May 1974 flood (1 in 50 year ARI event). The estimated load of sediment was  $300\,000 \text{ t day}^{-1}$ . In this analysis, the correlation coefficient ( $r = 0.43$ ) was statistically significant (at  $P \leq 0.05$ ), but the considerable scatter in the relationship meant that the load estimates had very wide confidence intervals. Also, the rating curve was extrapolated well beyond the range of discharge for which it was derived. Interestingly, the maximum concentration of suspended solids of  $422 \text{ mgL}^{-1}$  sampled in this period was similar to that of the later data sets (see above).

Even given the shortcomings of the sampling, the observed peak suspended solids concentrations and turbidities in the Maribyrnong River are not alarmingly high. These values would be expected in a river with average rates of erosion.



## 3 River Hydrology and Hydraulics

### 3.1 Introduction

The hydrology and hydraulics of the Maribyrnong River have been thoroughly investigated in previous reports (MMBW 1975a and 1975b, MMBW 1986, Camp Scott Furphy 1990). These reports were initiated by concerns over flooding in the lower catchment areas, and erosion of the lower channel.

This section of the report reviews previous studies and presents a revised HEC-RAS model for the lower Maribyrnong River. The hydraulic model was used to estimate stream power along the course of the river for a range of flood events. Stream power is a useful indicator of the energy available to transport and deposit sediment, and erode or build-up the banks.

This report is not specifically concerned with the particular hydrological conditions that cause floods, the extent of flooding, flood mitigation, or flood warning. These are important issues for flooding *per se*, but are of little geomorphological interest. Flood studies tend to focus on extreme events, while it is lower magnitude, but more frequent events (in the range 1:0.5 to 1:10 year ARI) that do most of the geomorphic work. However, given the variability of flows in the Maribyrnong River (and Australian rivers in general) it is unlikely that its channel form is adjusted to a particular event. More likely, large floods cause catastrophic change, and during the intervening years, medium-sized floods redistribute bank and bed material. In this way, the channel can be seen as quite dynamic, strongly reflecting the history of flows over the preceding 10 years. This natural cycle of change is superimposed on subtle changes in hydrology due to climate change, or changes in the discharge regime, sediment regime and level of channel stability, brought about by land use change, flow regulation, riparian vegetation change, channel management actions, and continued adjustment on a geological time-scale.

### 3.2 Flood frequency

The calculated return period of floods depends on the method of calculation, and the data used (Table 2). The estimates of WRC (1981) differ only slightly from those of the later instantaneous maximum, lumped, partial series estimate for Keilor by MMBW (1986, section 7.2). Camp Scott Furphy (1990b) split the flow record into two phases (based on data availability) and produced different estimates, particularly for <10 year ARI events (Table 2). The partial duration series showed higher flood peaks (2%-12%) for all return periods in the period 1956-1988, compared with the period 1908-1933. This is not surprising, as rainfall in the catchment (as with many other catchments in south-eastern Australia) was below average from the late 1800s until the late 1940s, but above average from the 1950s until the late 1970s (Camp Scott Furphy 1990b, Pittock 1983). Note that all estimates of the 2 year ARI floods were extrapolated because this flood was lower in magnitude than the selected threshold discharge for the partial series analysis (Table 2).

In this study we elected to use the Camp Scott Furphy (1990) analysis for the period 1956-1988. The rationale for this was that it represented the most recent period of flow record. However, it is not known whether the future regime will more closely resemble the earlier period of record (1908-1933) or the later period of record (1956-1988). In some respects the 1871-1986 (MMBW 1986) analysis is superior; it covers a much longer period of record, and it includes the 1871 flood that occurred before establishment of the gauge.

### 3.3 Channel Hydraulics

#### 3.3.1 Stream power

Channel hydraulics describe the physical characteristics of the flow for a given discharge. For flood studies, the water surface profile is important, because this determines the location, depth and extent of overbank flooding. For geomorphological investigations, stream power is an important variable because it indicates the capacity of the stream to do work (i.e. sediment transport, erosion and deposition).

**Table 2. Peak discharge in  $\text{m}^3\text{s}^{-1}$  (partial series) at Keilor for a range of average recurrence interval (ARI) floods estimated for various flow records (ne is not estimated).**

ARI	1871-1981 <sup>1</sup>	1871-1986 <sup>2</sup>	1908-1933 <sup>3</sup>	1956-1988 <sup>3</sup>
100	ne	840	725	810
50	710	710	635	710
20	520	530	518 <sup>5</sup>	571 <sup>4</sup>
10	402	400	430	465
5	ne	270	340	365
2	ne	125	220	225

1. WRC (1981) threshold discharge  $400 \text{ m}^3\text{s}^{-1}$ .
2. MMBW (1986) threshold discharge  $250 \text{ m}^3\text{s}^{-1}$ .
3. Camp Scott Furphy (1990) threshold discharge  $250 \text{ m}^3\text{s}^{-1}$ .
4. Estimated from Camp Scott Furphy (1990) data using regression.
5. Estimated from Camp Scott Furphy (1990) data using regression.

Of relevance to this study is the power available to erode the channel bed and banks, and to destroy in-channel rehabilitation (stabilisation) works. For channelised sand and gravel bedded rivers in England, Wales and Denmark, Brookes (1988), Brookes (1990) and Brookes and Sear (1996) highlighted a threshold bankfull stream power of  $35 \text{ Wm}^{-2}$  above which erosional adjustments dominate, and below which the dominant process is deposition. Straightened channels with bankfull stream power above  $35 \text{ Wm}^{-2}$  actively restored their sinuosity, while those with stream power below  $35 \text{ Wm}^{-2}$  did not adjust.

Channels with bankfull stream power between approximately  $15 \text{ Wm}^{-2}$  and  $35 \text{ Wm}^{-2}$  are stable, channels with stream power between  $35 \text{ Wm}^{-2}$  and  $100 \text{ Wm}^{-2}$  are actively meandering, and channels with stream power above  $100 \text{ Wm}^{-2}$  are usually braided (or eroding). Below  $15 \text{ Wm}^{-2}$  stream rehabilitation (habitat enhancement) works (such as revegetation, installation of roughness elements and flow deflectors) are likely to fail through excessive deposition of sediment. When bankfull stream power is above  $100 \text{ Wm}^{-2}$  stream rehabilitation works are likely to fail through excessive erosion (Sear, 1996). The data of Brookes (1990) suggest that channel rehabilitation works will generally be successful when bankfull stream power is in the approximate range  $10\text{-}50 \text{ Wm}^{-2}$ . Brookes (1990) also noted that stream rehabilitation works are generally unsuccessful where the channel confines floods greater than the 1:5 year event.

Measured in  $\text{Wm}^{-2}$ , stream power is expressed as:

$$\omega = \rho g R S V$$

where

$\rho$  = water density ( $1000 \text{ kg m}^{-3}$ )

$g$  = acceleration due to gravity ( $9.8 \text{ m s}^{-2}$ )

$R$  = hydraulic radius (m)

$S$  = energy slope

$V$  = mean cross-sectional velocity ( $\text{m s}^{-1}$ )

### 3.3.2 Existing hydraulic model

Water surface profiles, and the variables required to determine stream power, are calculated using a hydraulic model. HEC-RAS is a one-dimensional hydraulic backwater analysis model developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers



(1997). The HEC-RAS model has been used extensively (as an earlier version called HEC-2) in river hydraulic studies worldwide, and is regarded as the industry standard.

Hydraulic models require cross-section data, roughness coefficients, downstream water levels and calibration against known water surface profiles. The flood study by MMBW (1986) calibrated a hydraulic model for the lower Maribyrnong River (below Maribyrnong) on the basis of the 1974 ( $710 \text{ m}^3\text{s}^{-1}$ ) and 1983 ( $450 \text{ m}^3\text{s}^{-1}$ ) floods.

Camp Scott Furphy (1990) established a HEC-2 model for Jacksons Creek from the Organ Pipes national park to the confluence of Deep Creek and from this confluence along the Maribyrnong River to the railway trestle bridge at East Keilor. The total length of river modelled was 6.7 km for Jacksons Creek, and 21.7 km for the Maribyrnong River. The model was used to estimate overbank threshold flows and velocity profiles for various discharges.

The HEC-2 model was based on 95 cross-sections with an average spacing of approximately 500 m. These cross-sections were taken from 1:2500 maps with a 1 m contour interval. These maps allowed identification of the base of the banks, top of the banks and the floodplain. However, these maps did not permit accurate characterisation of the shape of the channel bed or banks. Typically, only four points defined a channel cross-section. This limit of detail prohibited the modelling of low flows.

The Camp Scott Furphy (1990) model was calibrated to the 1974 and 1971 ( $407 \text{ m}^3\text{s}^{-1}$  at Keilor) floods. An arbitrary centreline chainage was adopted, with the zero chainage located at the railway trestle bridge crossing, and distance increasing upstream. A Manning's  $n$  value of 0.06 was used for the Maribyrnong River channel, and 0.08 for overbank areas. The model was run for discharges of 100, 200, 400 and  $715 \text{ m}^3\text{s}^{-1}$ .

Although water surface profiles were modelled at approximately 500 m intervals for nearly 30 km of Jacksons Creek and the Maribyrnong River, discharge-velocity relationships were prepared for only a 10 km section of the Maribyrnong River. The main output of this modelling exercise was a table of mean channel velocities for four discharges at 18 cross-sections between Brimbank Park Ranger Depot (chainage 4.75 km) to McNabs Weir, Keilor (chainage 15.94 km). The selected cross-sections were those that corresponded to sites of the most severe erosion (as classified in the report). The modelling also estimated the bankfull discharge along this reach to range from  $80 \text{ m}^3\text{s}^{-1}$  near Koroneos Weir to  $450 \text{ m}^3\text{s}^{-1}$  near the hard rock quarry on the left bank near Milburn Rd. Over most of the reach, the bankfull discharge was between  $200 \text{ m}^3\text{s}^{-1}$  and  $300 \text{ m}^3\text{s}^{-1}$  (2-5 year ARI event).

### 3.3.3 Development of improved hydraulic model

The Camp Scott Furphy (1990) hydraulic model has two main limitations for the purpose of geomorphic analysis. First, the channel was not well defined in the cross-sections, and second, stream power was not calculated. The poor cross-sectional definition meant that the calculations for in-channel flows were inaccurate. While Camp Scott Furphy (1990) calculated mean velocity, stream power is a better index of the ability of the stream to do work.

A HEC-RAS model was developed for the Maribyrnong River from the Trestle Bridge (chainage 0.00 km) to the junction of Jacksons and Deep Creeks (chainage 21.67 km). A section of river between the Calder Freeway Bridge (chainage 8.86 km) to Browns Road (chainage 13.70 km) was selected for more detailed hydraulic modelling. Over this section, supplementary cross-sections were surveyed (limited by available resources to 11 new cross-sections). This section of river is where the floodplain is at its maximum width, and historically, where the channel has been most active in the lateral direction. Also, the floodplain in this area is used for intensive market gardening, and the landholders have expressed concern about the stability of the channel. This part of the river lies within the section defined by Camp Scott Furphy (1990) as most affected by severe erosion. In addition, this area has recently been targeted for bank stabilisation works (Fisher 1999).

Two sets of cross-section data were used in the HEC-RAS model (Table 3). Eleven cross-sections were surveyed in the field in 1999, with special attention paid to detailed characterisation of the channel. The average distance between cross-sections used in the model was 270 m.

**Table 3. Source of cross-sections used in HEC-RAS model**

Chainage (km)	From 1:2 500 map	Field survey (1999)
21.67-13.70	✓	
13.43		✓
13.00		✓
12.76		✓
12.60		✓
12.52		✓
12.29		✓
12.05	✓	
11.90	✓	
11.50	✓	
11.27		✓
11.01		✓
10.75		✓
10.52	✓	
10.00	✓	
9.85	✓	
9.62		✓
8.99		✓
8.86-0.00	✓	

Manning's  $n = 0.07$  was used for discharges  $\geq 500 \text{ m}^3\text{s}^{-1}$ . A value of  $n = 0.08$  was used for lower values of discharge where the form roughness of the channel exerts more influence. The model was calibrated to fit the water surface profiles in Camp Scott Furphy (1990).

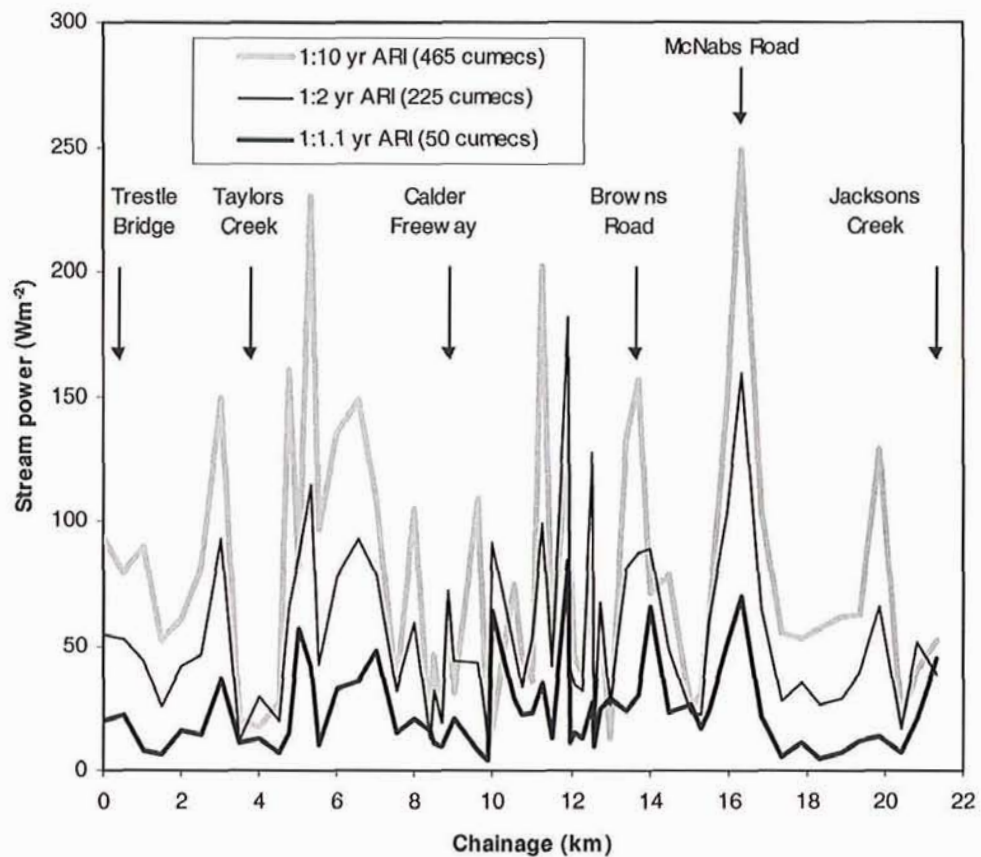
The hydraulic model was run for a range of discharges from  $100 \text{ m}^3\text{s}^{-1}$  to  $710 \text{ m}^3\text{s}^{-1}$ . This discharge range included the 1:50, 1:10, 1:5, 1:2 yr ARI floods, as calculated by Camp Scott Furphy (1990) for the period 1956-1988 (Table 2).

### 3.3.4 Hydraulic model results

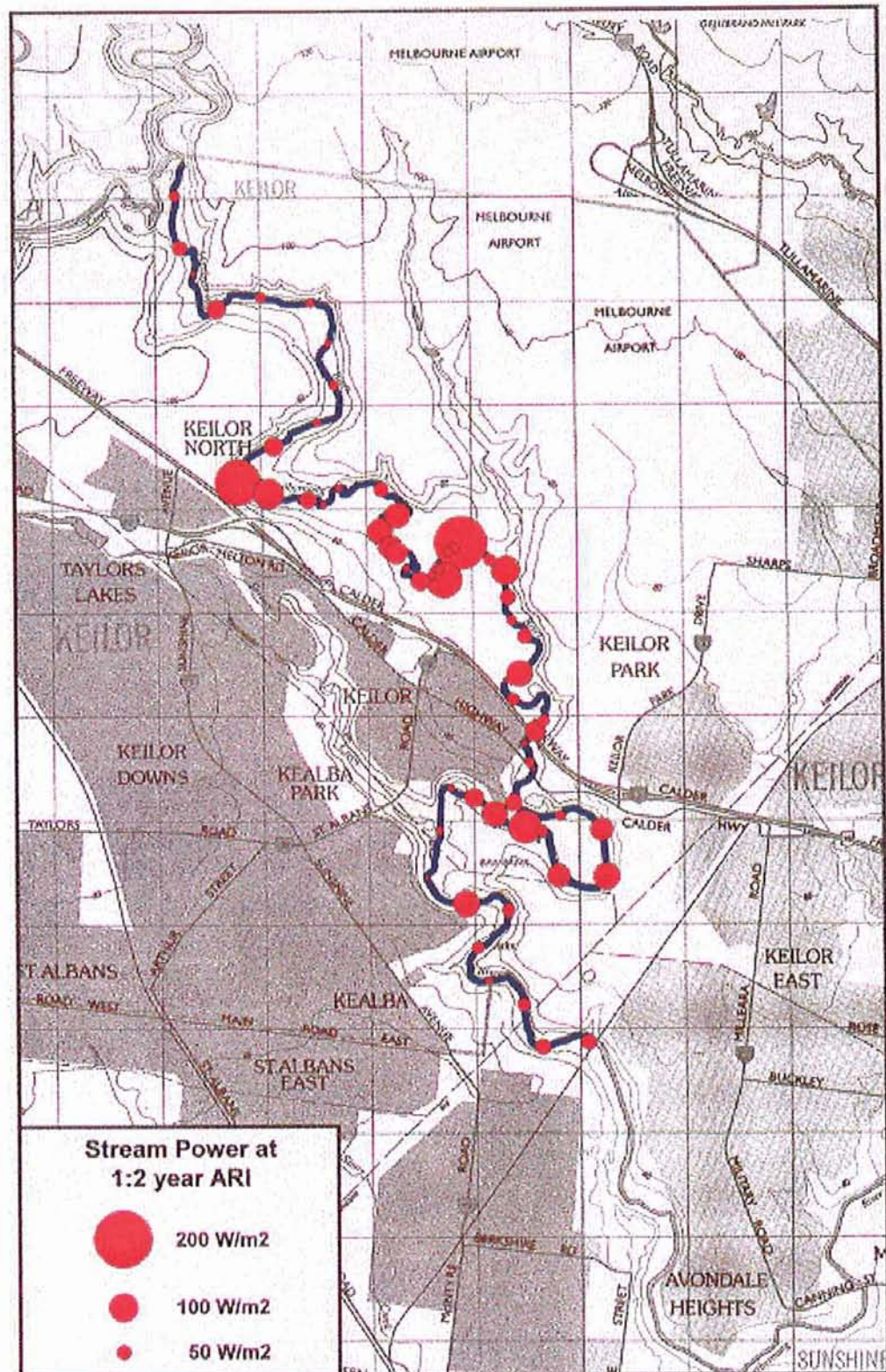
The mean stream power varied spatially, and as a function of discharge (Figure 2). The channel mean stream power exceeded  $50 \text{ Wm}^{-2}$  over about half of the reach length for the 1:2 yr ARI flood event. The stream power did not increase very much beyond that experienced for the 1:5 yr ARI event, because higher discharges spilled onto the floodplain. However, these floods produced high stream powers exceeding  $100 \text{ Wm}^{-2}$  at a few locations.

The Maribyrnong River varies considerably in cross-section size and shape, and slope over this section, and this gives rise to considerable spatial variation in stream power (Figure 3).





**Figure 2. Variation in mean stream power for a range of discharges on the Maribyrnong River between the Trestle Bridge and the junction of Jacksons and Deep Creeks.**



**Figure 3. Modelled mean stream power at the 1:2 yr ARI event ( $225 \text{ m}^3 \text{ s}^{-1}$ ) at 62 cross-sections on the Maribyrnong River.**



## 4 Current Stream Processes

### 4.1 Introduction

The river systems of the Maribyrnong River catchment have been developing in their current position for the past two million years or so. The streams now flow through deeply incised valleys (sometimes exceeding 100 m deep). Alluvial flats occur only in the lower reaches, and they are quite limited in extent. These alluvial sections have been quite active during the past 30 000 years in particular, as the stream rejuvenated in response to changing rainfall regime and lowered sea levels. Camp Scott Furphy (1990, p. 13) noted that the stream was described as actively eroding in 1920.

The question of whether the Maribyrnong River has now adjusted to the rejuvenation caused by the Holocene fall in sea level cannot be answered. Rivers can adjust very quickly to changes in external controlling factors. For example, over the past 150 years many rivers in Victoria have dramatically incised in response to European disturbances and then stabilised as land management improved. In the case of the Maribyrnong River, the geological time-scale adjustments are subtle and difficult to quantify. However, it is likely that rejuvenation initiated by the Holocene fall in sea level has slowed. The River has cut to bedrock in many places, and the terraces of the previous depositional and erosional phases have been extensively re-worked. The major channel changes through the European historical period can be attributed to the particular hydrological regime that prevailed, superimposed on the impacts of land and river management practices.

After European settlement, the alluvial flats became the focus of intensive agriculture, which altered their character. A major change was the loss or severe reduction in riparian vegetation. Originally, the banks would have been wooded with River redgum (*Eucalyptus camaldulensis*) and a thick understorey (including river bottlebrush *Callistemon sieberi*). Of the 233 plant species recorded in the Keilor reach, 52% are exotic (Fisher, 1999). The original vegetation would have added considerable strength to the bank material. The channel would have had a high loading of large woody debris, which would have added stability to the bed. Although the Maribyrnong River would always have been fairly active in its alluvial sections (due to high stream power and active geological downcutting), disturbance of the riparian vegetation would have accelerated the rate of channel change. At the time of the first aerial photograph taken on 13<sup>th</sup> April 1931, the floodplain and riparian zone had been almost completely denuded of trees (Figure 4).

### 4.2 Previous studies of channel instability

Camp Scott Furphy (1990) reported concern that erosion of the channel of the Maribyrnong River had increased in recent years. The erosion study by Camp Scott Furphy (1990) was preceded by three other studies in 1979 (see MMBW 1983), 1988 (Sutherland and Rumble 1988) and 1989 (Jenkin 1989).

Camp Scott Furphy (1990) found that the river was eroding (mostly on the outside of meander bends, where it would be expected). Sites of erosion were classified as severe, moderate or slight. However it was not possible to determine the rate of erosion, as there were no previous surveys available for comparison. The report examined the available evidence for changes in the factors that might promote channel erosion. Climatic variation was ruled out as insignificant.

Land use has changed considerably in the catchment since European settlement. Most of the original vegetation has been eliminated for agriculture and urban development (including Melbourne Airport). Such change can lead to increases in runoff, but this is not noticeable in the flow records. Camp Scott Furphy (1990) speculated that catchment runoff and sediment supply both increased, but the major changes took place in the early 1900s.



**Figure 4. 1931 aerial photograph of Keilor reach of Maribyrnong River (MMBW Aero 2,13/4/1931, Runs 15, 16 & 17. 12:00 hrs No. 03452).**

The indigenous riparian vegetation has been largely eliminated and replaced with weed species. In the market garden area near Keilor cultivation right to the edge of the bank has resulted in removal of much of the riparian vegetation, although photographic evidence suggests that riparian tree density is currently greater than it was in the 1930s (compare Figure 4 and Figure 5). Tree roots greatly enhance the strength of bank material, so bank stability is probably lower than it was prior to European occupation. This area is heavily irrigated, so seepage through the banks would be expected here.

Rosslynne Reservoir was constructed in 1974. It has minimal impact on flood frequency and magnitude in the Keilor area (Camp Scott Furphy 1990). The reservoir stores all incoming bed material, but it is unlikely that this significantly impacts channel erosion processes near Keilor.

A number of small weirs have been constructed across the Maribyrnong River to provide water for irrigation (Scott 1993). Arundel Weir was constructed prior to 1945 and raised in



1947 and again in 1952 and 1967. In 1940, sites were selected for the construction of ten smaller weirs. Only eight of these weirs were constructed, with the last one (McNabs Weir) finished in 1969. Only two of these small weirs and Arundel Weir remain in sound condition. Camp Scott Furphy (1990) noticed significant local erosion around the weirs, and the remnants of breached weirs. Also, the weirs act as local sediment storages.

The Maribyrnong River was surveyed in 1852. Since that time the course of the river has been altered along three sections, all of which involved shortening of the river by meander cutoff. The oldest of these cutoffs are located at chainages 9.87 to 10.1 km and 10.75 to 11.15 km (Figure 5). The cutoffs apparently occurred sometime between 1890 and 1926. The most likely initiation date is the record flood of 1906, as the cutoff channels were heavily silted up by 1926 (Camp Scott Furphy 1990). The upper cutoff reduced river length by 260 m, and the lower cutoff reduced it by a further 300 m. This represents 20% of the river length between the site of the lower cutoff to Arundel Weir (which ultimately controls headwards bed erosion). The rock bars present in this reach probably limited downcutting, so some bank erosion probably followed the meander cutoffs.



**Figure 5. 1993 aerial photograph of Keilor reach of Maribyrnong River.** Chainage is zero from Railway Trestle Bridge. Framed reaches are magnified in Figs 25 and 26.



An artificial cutoff was created in 1984 at chainage 8.54 to 8.70 km during the construction of the Calder Freeway Bridge. The original meander near Keilor can be seen on the original 1931 aerial photograph (Figure 4). This realignment shortened the river by 100 m. In 1984, upstream of this cutoff to Arundel Weir, a concrete ford, three weirs, and several rock bars controlled the bed. It is unlikely that headward retreat of the bed occurred in response to this realignment, but some accelerated bank erosion could have occurred.

### 4.3 Management response to perceived channel instability

Desnagging, trimming of bank vegetation and willow clearing have been practiced in Brimbank Park. Most of the channel works have involved bank protection in the form of rock beaching. Some desnagging has been conducted below Arundel Weir (Scott Seymour pers. comm. 1999). Camp Scott Furphy (1990) reported six locations where extensive rock beaching had been undertaken during the 1980s:

- Brimbank Park downstream of the ford (chainage 4.13 km)
- Brimbank Park up- and downstream of the gauging weir (chainage 5.03 km)
- Immediately downstream of Flora St bridge on both banks (chainage 9.40 km)
- Along the right bank of Koroneos market garden (chainage 10.50 km)
- Along the right bank of Koroneos market garden, downstream of Arundel Rd Bridge (chainage 11.65 km)
- Beneath the Arundel Rd bridge (chainage 12.00 km)

Following the report of Camp Scott Furphy (1990), approximately 1000 m of river bank (representing 5 sites) were treated at a cost of \$1M (Fisher 1999). Camp Scott Furphy (1990) recommended soft engineering solutions such as timber groynes, but site difficulties deemed this approach impractical. After some initial failures using single sized rocks placed over geotextiles, the favoured technology was to first batter the banks, lay down a 300 mm thick filter layer of crushed rock, then key in larger rocks of mixed sizes. Topsoil was placed across the upper rock work. The crushed rock filter allowed riparian plants to recolonise. The five sites treated to date are (see Figure 5):

- Site 59, near meander cutoff (chainage 9.9 km) (Figure 6 and Figure 7)
- Site 63, near meander cutoff (chainage 11.0 km)
- Site 67, right bank below Arundel Weir (chainage 11.6 km)
- Site 69, left bank below Arundel Weir (chainage 11.9 km)
- Site 75, meander above Arundel Weir (chainage 12.4 km)

In addition, the neck of low land near chainage 12.30 km above Arundel Weir was stabilised with rock. Fishways have recently been constructed on Arundel Weir (Figure 8) and two weirs in Brimbank Park.

Revegetation of the banks has been an integral part of the stabilisation strategy. However, this requires excision of a riparian strip from cultivation. Such agreements have proved elusive above Arundel Rd, and this area of the river remains largely unprotected. Extension of the stabilisation scheme to this area will require a change in landuse or a change in attitudes (Fisher 1999).

It has been suggested that vertical banks in areas above Arundel Rd have remained stable for the past decade (Fisher 1999). However, there is considerable uncertainty about whether this stability will persist. Also, Fisher (1999) questioned the assessment of Camp Scott Furphy (1990) that break out and re-entry flows during floods were of relatively minor importance as a cause of erosion.





**Figure 6. Site 59 (9.9 km) looking upstream in 1990 (Camp Scott Furphy 1990).**



**Figure 7. Site 59 (chainage 9.9 km) looking upstream in 1999 (after works).**



**Figure 8. Arundel Street weir looking upstream (chainage 12 km), with recently installed fishway on left bank.**



## 4.4 Current channel morphology

### 4.4.1 Channel stability concepts

Geomorphologists agree that the stability of a channel is dependent on many interrelated factors. Stable channel geometries have been empirically described for channels in some parts of the world (especially in the USA), but there is no database available for Australian rivers. The options are to rely on overseas data, or to adopt a more theoretical approach, such as calculation of the threshold tractive force required to move bed material. A complicating factor in the case of the Maribyrnong River is the presence of artificially stabilised banks, grade control structures, weirs and rock bars.

It is clear from the erosion severity maps in Camp Scott Furphy (1990) that the most severe erosion was associated with the outside of meander bends. Nanson and Hicken (1986) developed an empirical relationship between the ratio of meander bend radius ( $r$ ) to channel width ( $B$ ), and meander migration rate ( $M$ ). The highest migration rates occurred on bends with  $r/B$  ratios of 2.5–3.5. Migration (erosion) rates rapidly decline for  $r/B$  values greater or less than 3. This relationship can be used to help identify sites along a river reach that have the highest potential for erosion.

Width/depth ratio,  $F$ , (measured at bankfull level) is an indicator of bank stability. Schumm et al. (1984, p. 166) reported that incised streams draining catchments between 600–1 000 km<sup>2</sup> located in northern Mississippi were approaching stability when their  $F$ -value reached approximately 12. Schumm (1960) also related  $F$  to percentage silt-clay. The alluvium present in the Maribyrnong terraces is classed as silts, so the percentage silt-clay would be quite high. Camp Scott Furphy (1990, p. 18) reported a mean silt-clay content of 62%. Silty bank material is unstable (incising) for  $F$ -values less than approximately 3–5. Richards (1982, p. 171) plotted a relationship between  $F$  and silt-clay percentage as a function of mean annual flood. For the Maribyrnong River, with a mean annual flood of approximately 140 m<sup>3</sup>s<sup>-1</sup>, silty bank material is unstable for  $F$ -values less than approximately 12.

Bank stability is also a function of height and slope angle. Empirical relationships can be derived, depending upon the strength of the bank material, which is a function of vegetation and bank silt-clay composition. TFISRWG (1998, p. 7-61) produced some indicative graphs which suggest that steep sided banks (>45°) are at risk of being unstable when saturated at bank heights of <3 m. Steep banks when dry are potentially unstable at heights of 4–10 m.

The channel long profile will indicate the existence of knickpoints that are possible sites of headward bed incision.

### 4.4.2 Stability characteristics of the Maribyrnong River channel

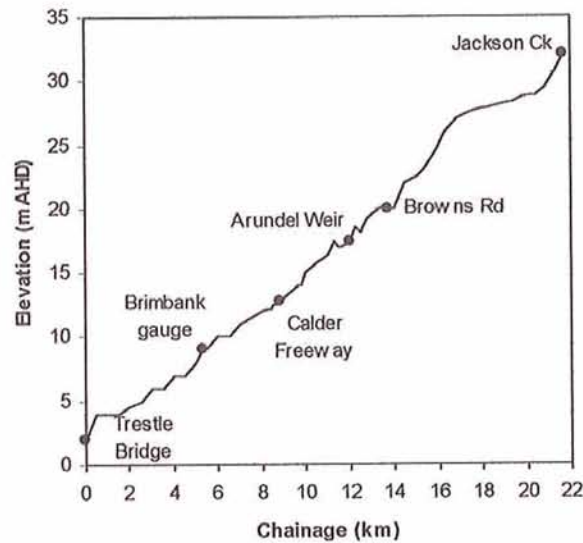
#### 4.4.2.1 Long Profile

The detailed long profile of the Maribyrnong River channel bed from the confluence of Jacksons and Deep Creeks to the Trestle Bridge does not reveal the existence of a headward eroding nickpoint (Figure 9). A steeper section of channel exists upstream of Browns Rd where the channel bed is controlled by Silurian sedimentary outcrops (Figure 9). From Browns Rd to the Trestle Bridge the channel has a relatively uniform slope of 0.0013.

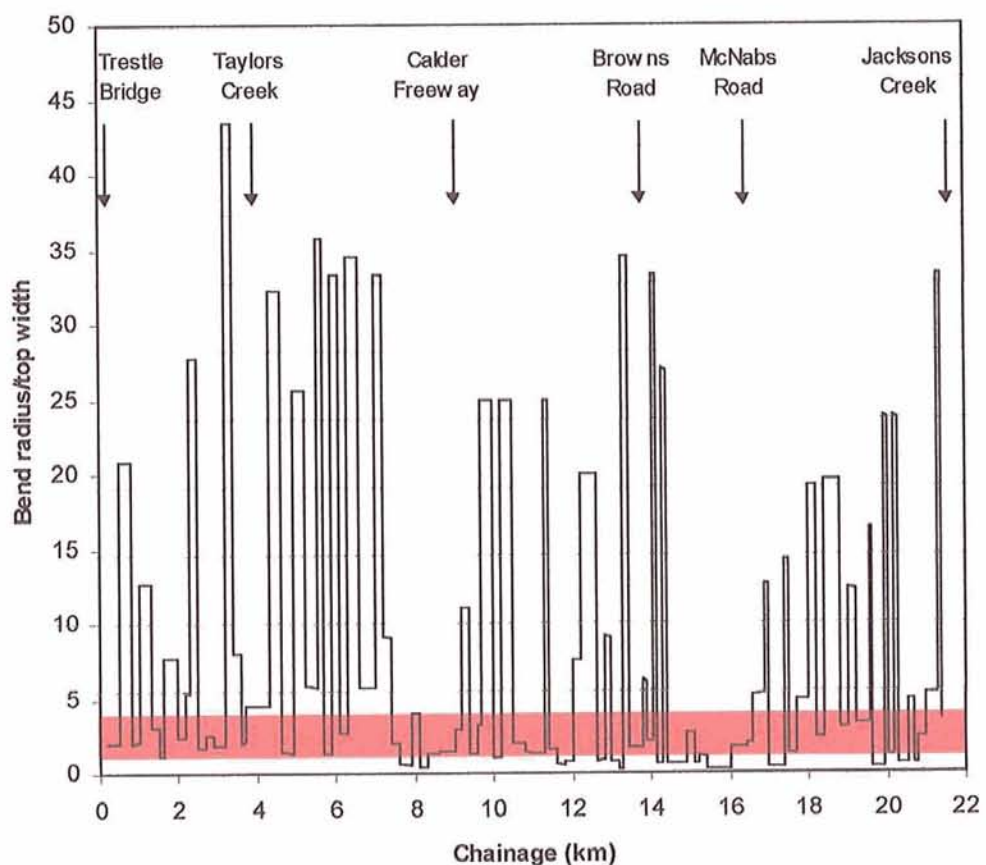
#### 4.4.2.2 Meander bend/width ratio

The tightest meander bends on the Maribyrnong River tend to occur in the reach 7.5 km to 16 km (Figure 10). Several of these bends have  $r/B$  ratios within the range 2–4, where the potential for meander migration is highest. Brimbank Park had some bends with high potential for migration, but this area also had many bends with large bend radius (Figure 11). Some of the bends with radius/width ratios that suggest high erosion potential are in fact very stable, due to other factors, such as bedrock confinement.

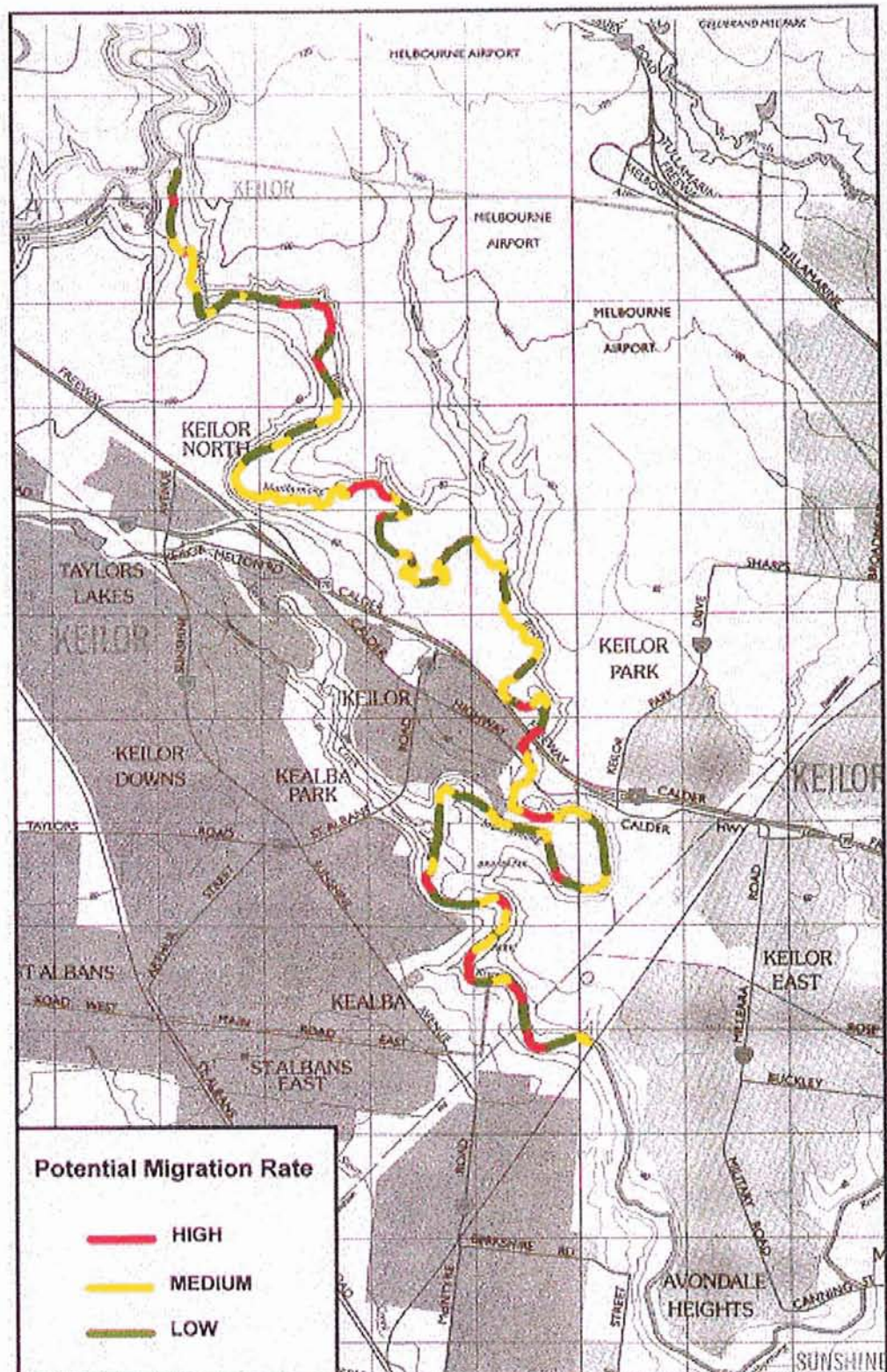




**Figure 9. Detailed long profile of the bed of the Maribyrnong River from Jacksons Creek to the Trestle Bridge (source: MMBW 1:2 500 Yarra and Darley Series).**



**Figure 10. Bend radius/channel width ratios along the Maribyrnong River, from Trestle Bridge to the junction of Jacksons and Deep Creeks (source: MMBW 1:2 500 Yarra and Darley Series). Shaded area indicates potential for relatively high bank migration rate (2-4).**



**Figure 11. Bend radius/width ratio expressed as potential bend migration rate (low:  $r/B > 6$ ; medium:  $r/B$  0-2 and 4.1-6.0; high:  $r/B$  2.1-4.0), Maribyrnong River.**



#### 4.4.2.3 Channel width and width/depth ratio

The width of the bed of the Maribyrnong River varied between 10-20 m in most locations, but the top width was much more variable (Figure 12). The river had a low ratio of width to depth (<10) over much of its course from Brimbank Park to Browns Road (Figure 12 and Figure 13).

For its catchment area, the Maribyrnong River is narrow and deep compared to most other rivers. However, channel shape is also strongly dependent on bank material composition and vegetation. Given that much of the native riparian vegetation has been removed, the channel would appear to be susceptible to widening. Although WRC (1981, p. 16) classed the silty terrace soils as having moderate to high susceptibility to erosion when they form the banks of streams, Camp Scott Furphy (1990, p. 18) correctly labeled this material as cohesive due to its high silt and clay content. This explains the vertical nature of the banks on the erosional side (outside or concave bend) of the channel.

Schumm's width/depth ratio data from USA rivers suggest that the Maribyrnong River has not yet reached quasi-equilibrium, but this may simply reflect differences in the cohesivity of bank material.

#### 4.4.2.4 Bank height and angle

The active alluvial banks of the Maribyrnong River were quite high in many places (Figure 14). The angle of the banks was generally less than 60°, but a few cross-sections had banks that were near to vertical (Figure 15). On the basis of height and angle, these banks would be classified as susceptible to instability when saturated.

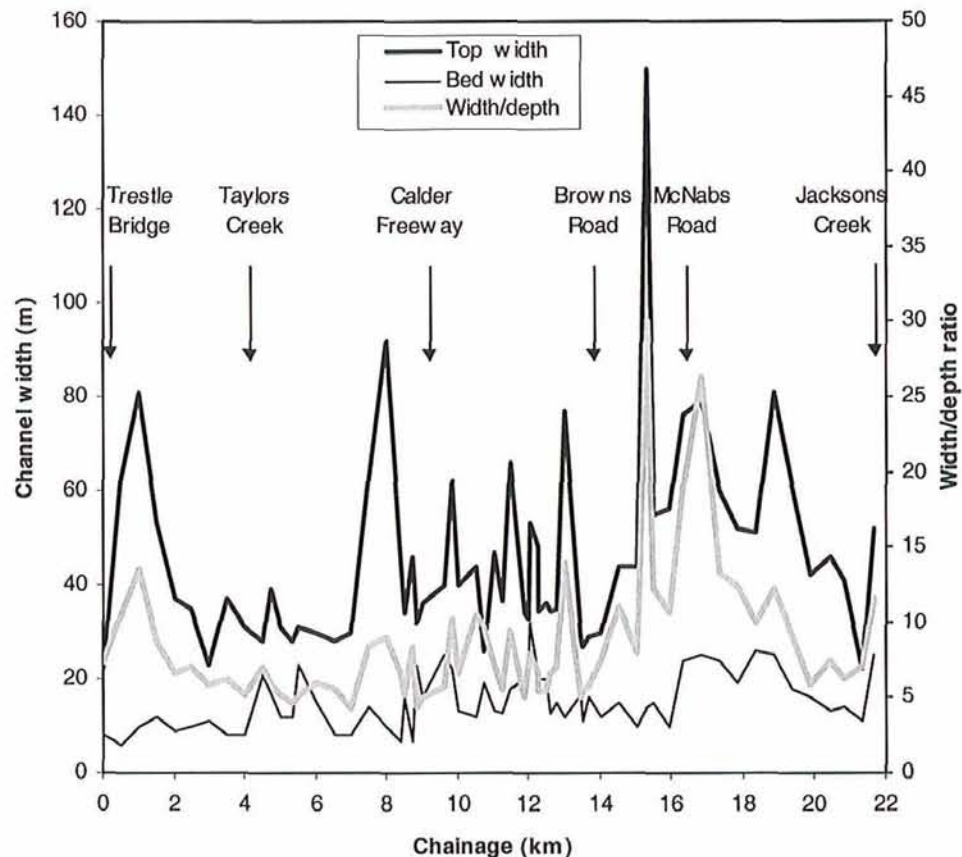
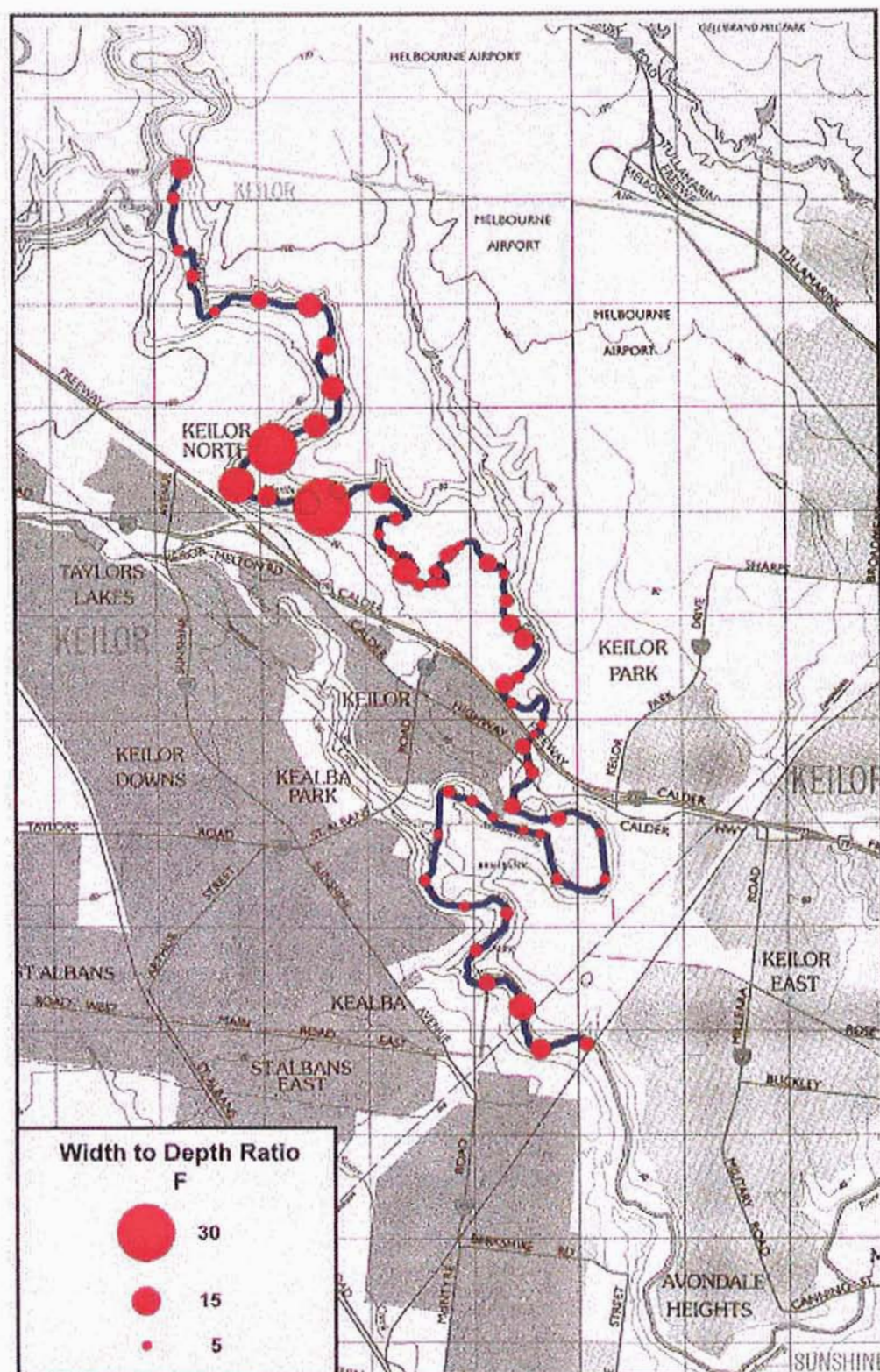


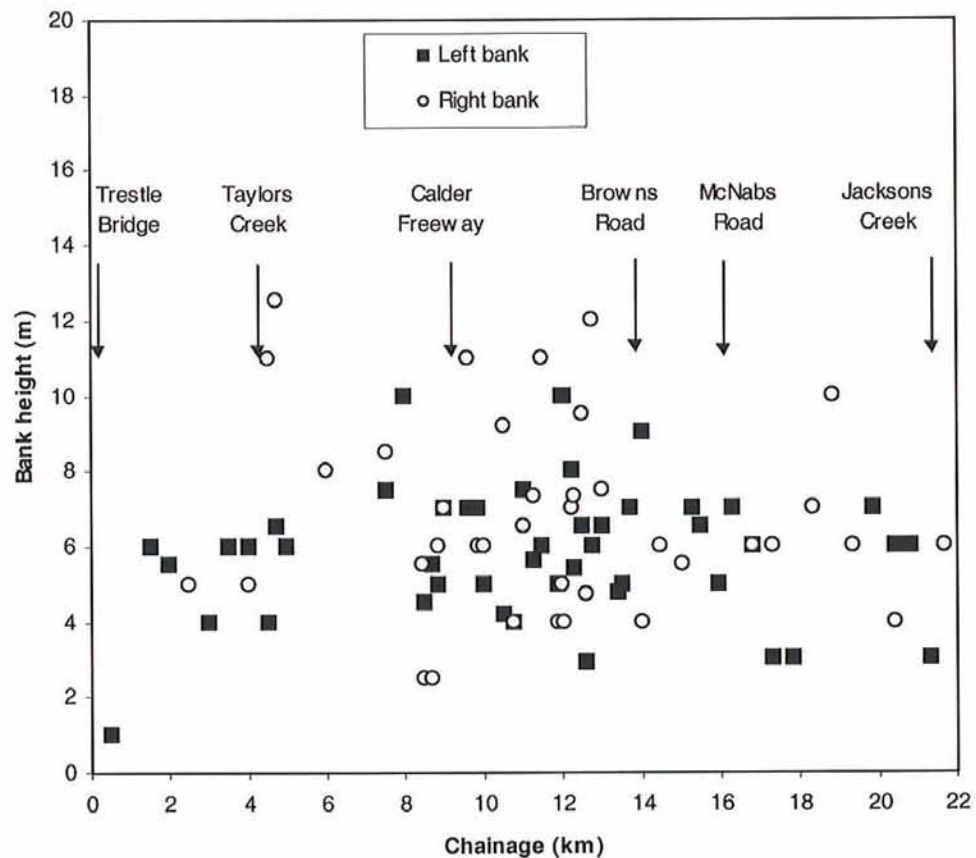
Figure 12. Maribyrnong River width and width/depth ratio (source: cross-sections, see Table 3).





**Figure 13. Width/depth ratio measured at 62 cross-sections on the Maribyrnong River.**





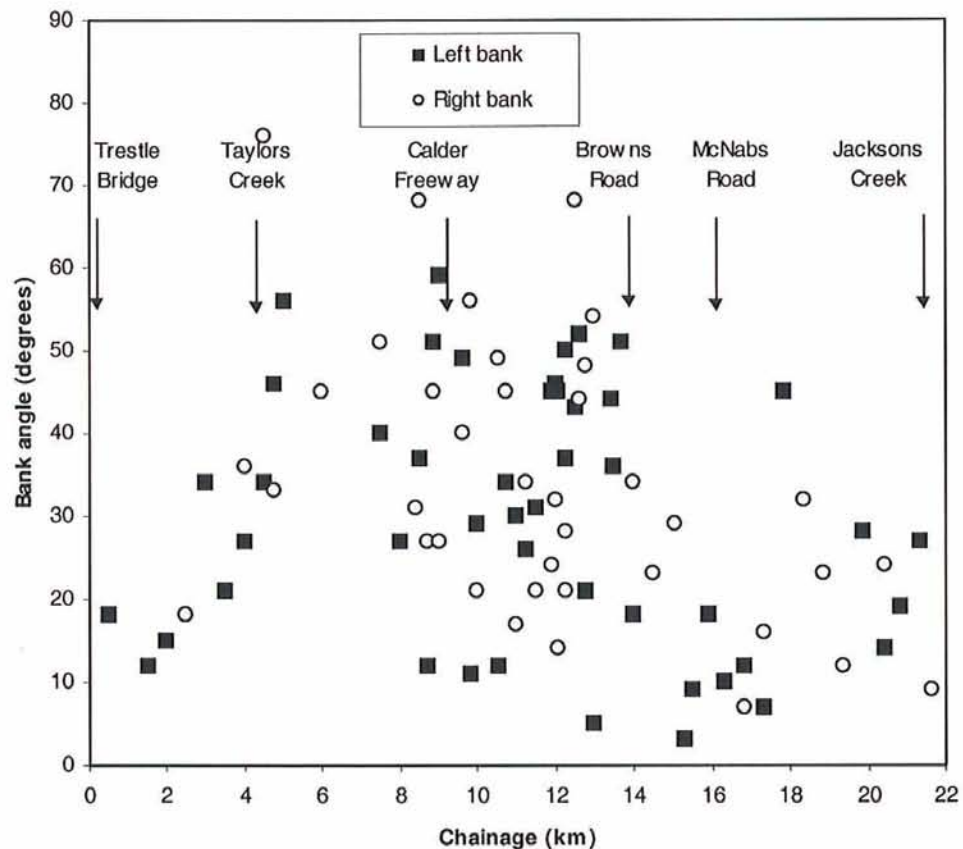
**Figure 14. Maribyrnong River bank height (alluvial banks only) (source: cross-sections, see Table 3).**

#### 4.4.2.5 Channel confinement

Confinement of the channel refers to the degree of confinement of flood discharge to the channel, as opposed to the floodplain. In this study we used the 1:2.5 yr ARI flood ( $250 \text{ m}^3 \text{ s}^{-1}$ ) as a measure of confinement, as this was the approximate bankfull discharge defined by Camp Scott Furphy (1990) for the alluvial reach near Keilor (Figure 16). Most of the alluvial reach between the upper part of Brimbank Park and Browns Road was sufficiently incised to contain the bankfull discharge, although there were some sections where the flow would spill onto the floodplain (Figure 17). The bankfull discharge has a fairly low frequency of recurrence compared to most rivers, and this discharge ( $250 \text{ m}^3 \text{ s}^{-1}$ ) has fairly high stream power in some parts of the river (Figure 2). This degree of confinement deems this channel susceptible to instability.

#### 4.4.2.6 Riparian vegetation intactness

The Index of Stream Condition is an integrated measure of the state of a stream and is intended as a practical assessment tool to assist managers to make strategic decisions about management activities (Ladson and White 1999; White and Ladson 1999). The Streamside Zone sub-index includes a measure of structural intactness, relative to natural or pre-disturbance condition. A rating of 0 (large divergence from natural), 1 or 2 (same as natural) is given to the tree layer, the shrub layer and the ground layer. These ratings are then summed and multiplied by 0.667 to give an overall rating that ranges from 0 to 4.



**Figure 15. Maribyrnong River bank angle (alluvial banks only) (source: cross-sections, see Table 3).**

In this study we adapted the ISC structural intactness rating to assess the riparian vegetation of the Maribyrnong River. Whereas the ISC makes a single assessment for the whole riparian zone, we assessed vegetation intactness for the bank, and for the top of the bank separately. The ISC method uses visual field assessment to measure vegetation intactness for both banks over a 30 m wide transect. In this study we required data for 62 cross-sections. The channel is deeply incised, so it could be accessed from the channel or the floodplain, but it was difficult to move between these environments. The method of direct field assessment of riparian vegetation intactness was deemed impractical. Rather we assessed vegetation intactness (as existed at the time of the 1990 erosion study) from the library of photographs associated with the report of Camp Scott Furphy (1990), and 1993 aerial photography. We assumed that for each structural layer, the natural (undisturbed) cover was  $\geq 80\%$ . This may be a false assumption, particularly with respect to bank vegetation. The steep banks in this river are probably a natural feature that existed prior to European occupation, and these banks may not have supported dense vegetation. We were able to qualitatively assess changes in the riparian vegetation intactness over the past 10 years by comparing the photographs of Camp Scott Furphy (1990) with those taken from the channel and the floodplain during field surveys conducted in 1999.

The vegetation intactness rating was highly variable, both between the left and right banks at each cross-section, and between bank and bank-top vegetation. However, the bank values and the bank-top values were closely correlated, so for each cross-section they were averaged to give a combined vegetation intactness rating. Vegetation intactness also varied spatially, with higher values recorded in the area of Brimbank Park, and lower values in the agricultural areas upstream of the Calder Freeway (Figure 18 and Figure 19). It is notable that the majority of combined vegetation intactness values ranged between 0.7 and 2.0 (on a scale of 0-4, where 4 is undisturbed from natural). The ISC manual (Ladson and White 1999) does not attach a



value description to this range of numerical ratings of intactness, but it can be assumed to represent a condition that diverges considerably from the natural undisturbed condition.

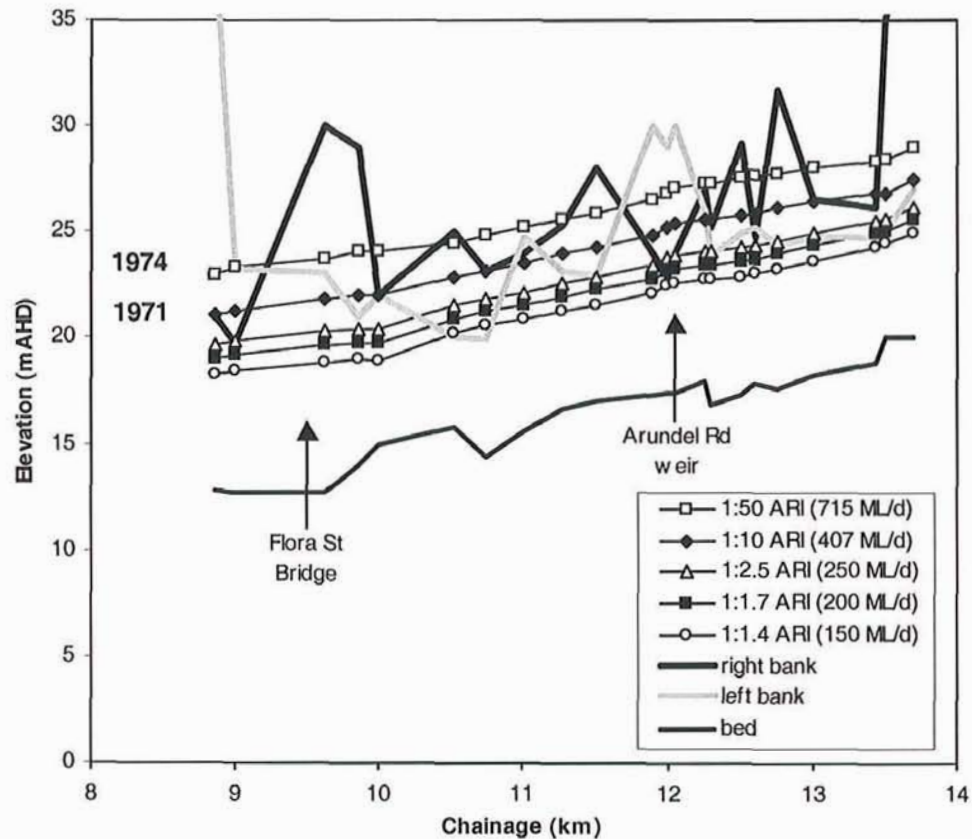


Figure 16. Degree of confinement of channel in the Keilor alluvial section from Calder Freeway to Browns Road. Flood peak magnitudes (mean daily flow) given in parentheses (ML/d) (source: HEC-RAS model output).

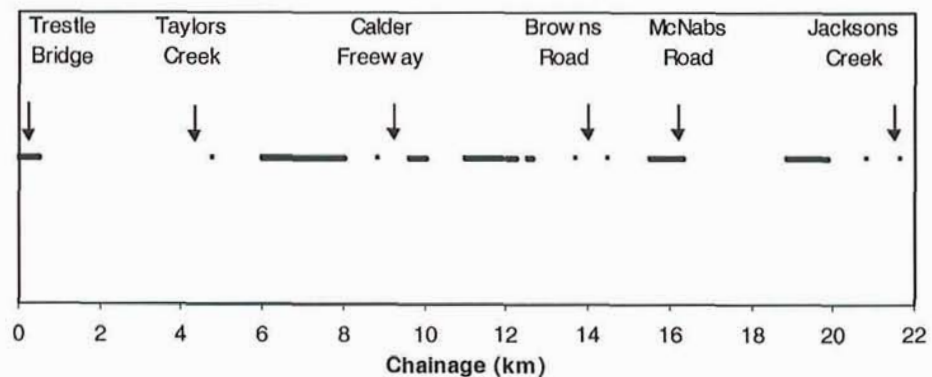
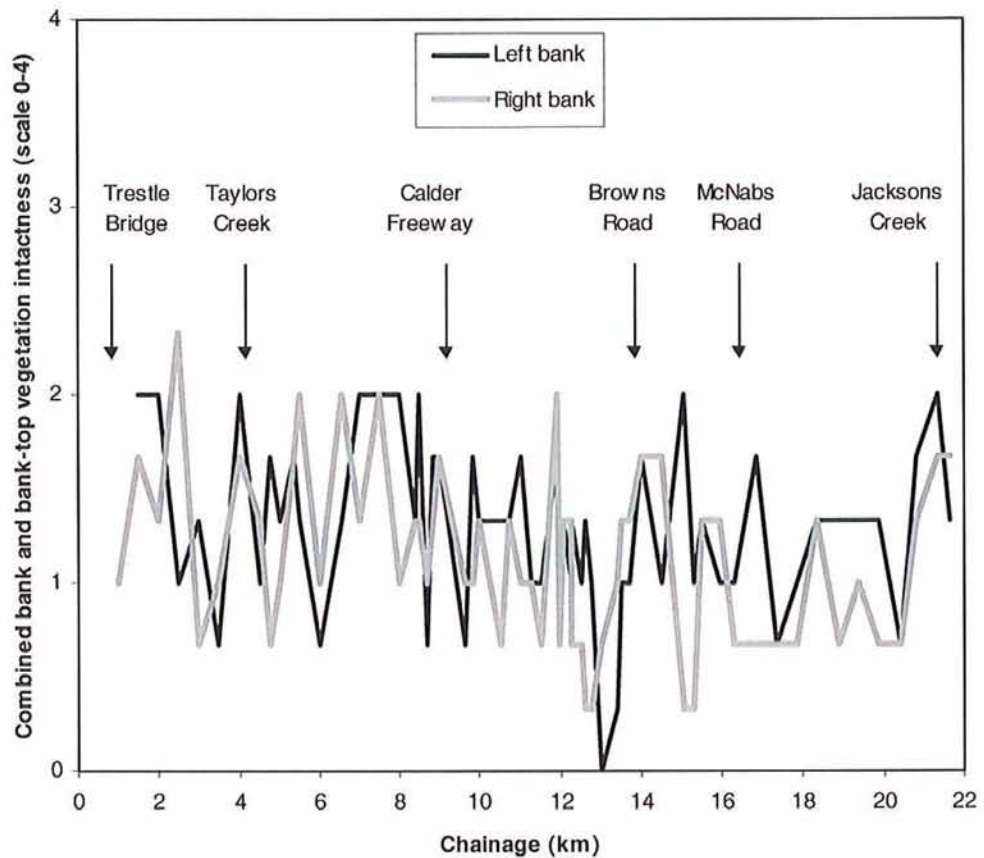


Figure 17. Solid line indicates that channel contains the bankfull discharge ( $250 \text{ m}^3 \text{ s}^{-1}$ ), while space indicates that flow spills onto floodplain.

The morphological data and the stream power data were combined to indicate those cross-sections (for the alluvial reach from Calder Freeway to Browns Road) that have the highest potential for erosion. The criteria used to indicate erosion potential were based on values in the literature, with the vegetation intactness values averaged for right and left banks (Table 4). The site at 12.5 km featured as having a high potential for erosion on the basis of all criteria

(Table 5), and not surprisingly, the left bank in this area was identified by Camp Scott Furphy (1990) as having severe erosion, and it was subsequently stabilised by rock beaching.

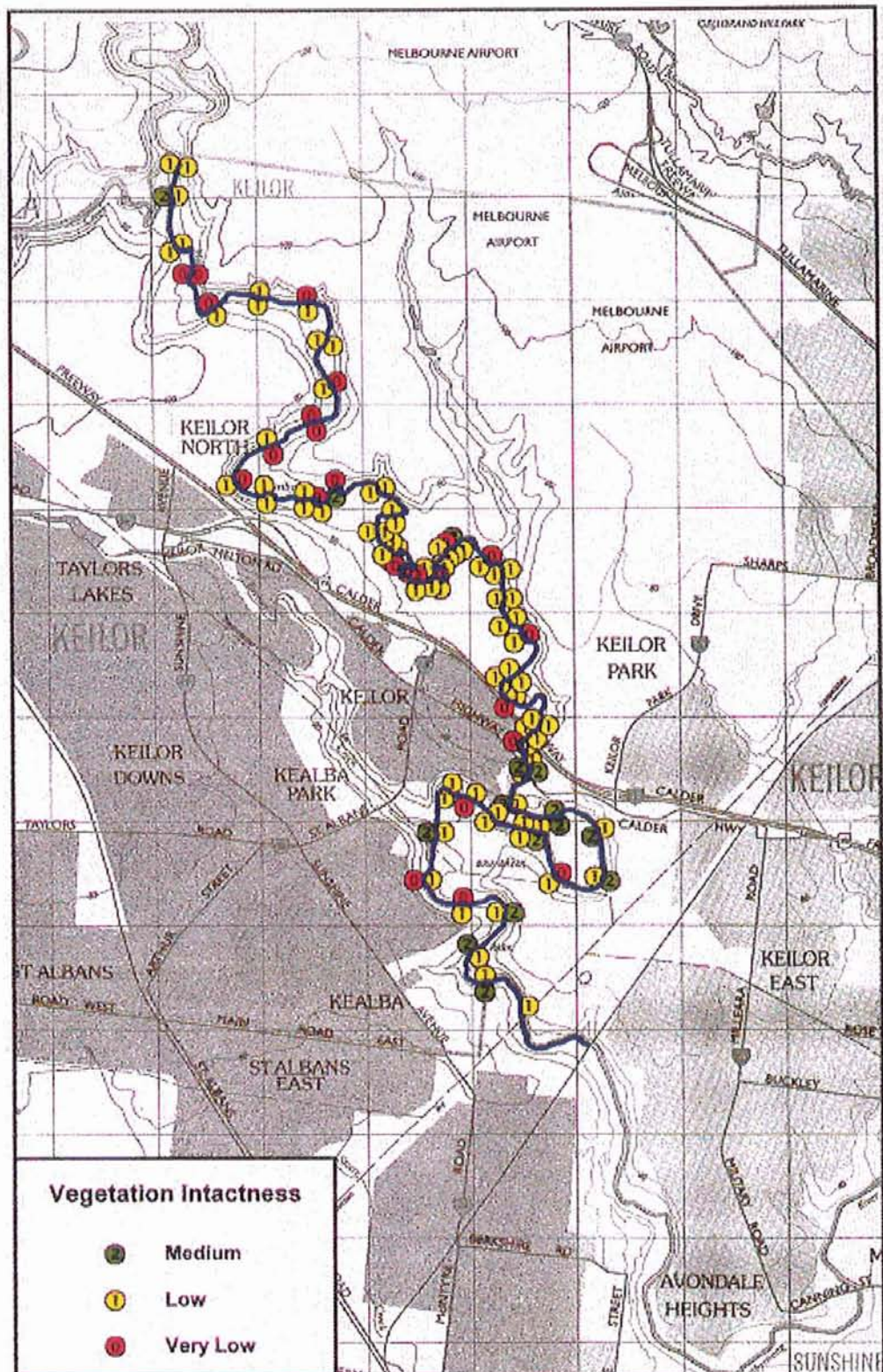


**Figure 18.** Variation in ISC combined bed and bank vegetation intactness rating on the Maribyrnong River between the Trestle Bridge and the junction of Jacksons and Deep Creeks.

**Table 4.** Criteria used to classify bank erosion potential

Variable	High	Medium	Low
Stream power (1:2 yr ARI) $\text{Wm}^{-2}$	>50	50-35	<35
r/B	2.5-3.5	1-2.5 or 3.5-4	<1 or >4
F-ratio	<5	5-10	>10
Flood confinement (flood confined)	1:2.5 yr	1:1.7 yr	1:1.3 yr
Bank height (m)	>10	10-4	<4
Vegetation intactness	<1.5	1.5-3.0	>3





**Figure 19. Vegetation intactness measured by ISC sub-index at 62 cross-sections on the Maribyrnong River.**



**Table 5. Summary of erosion potential of cross-section sites between the Calder Freeway (8.9 km) and Browns Road (13.7 km). High potential is shaded. Asterisked and bolded chainages indicate banks stabilised by rock beaching works.**

Chainage (km)	Stream power	r/B	F-ratio	Bank height	Flood confinement	Bank height	Vegetation
13.70	High	Low	High	Medium	High	Medium	High
13.43	High	Low	Medium	Medium	Low	Medium	High
13.00	Low	High	Low	Medium	Medium	Medium	High
12.76	Medium	Low	Medium	Medium	Low	Medium	High
12.60	Low	Low	Medium	Medium	High	Medium	High
<b>12.52*</b>	High	High	High	High	High	High	High
<b>12.29*</b>	Low	Low	Medium	Medium	Medium	Medium	High
<b>12.05*</b>	Low	Low	Medium	Medium	High	Medium	High
<b>11.90*</b>	High	Low	High	Medium	High	Medium	Medium
<b>11.50*</b>	Medium	Low	Medium	High	High	High	High
11.27	High	Low	Medium	Medium	High	Medium	High
<b>11.01*</b>	Low	Low	Medium	Medium	High	Medium	High
10.75	Low	Low	High	Medium	Low	Medium	High
<b>10.52*</b>	Medium	High	Medium	Medium	Low	Medium	High
10.00	Low	Low	Medium	Medium	High	Medium	High
<b>9.85*</b>	Low	High	Medium	High	High	High	High
9.62	Medium	Low	High	High	High	High	High
8.99	Low	Low	Medium	High	Medium	High	Medium
8.86	High	Low	Medium	Medium	High	Medium	Medium

#### 4.4.3 Observed erosion

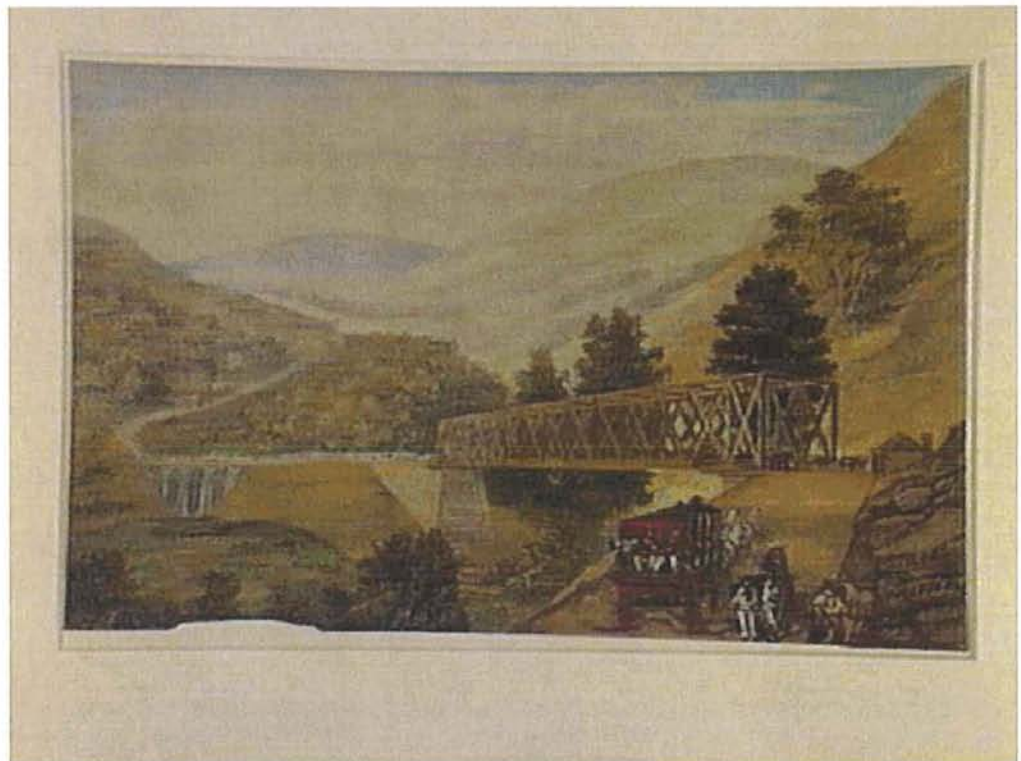
The Maribyrnong River was not surveyed in detail prior to the survey of 11 cross-sections conducted in 1999 as part of this study. The only sources of evidence available to indicate channel migration rates are anecdotal reports provided by landholders, comparison of aerial photographs and comparison of photographs of the channel taken in 1990 (Camp Scott Furphy 1990) and in 1999 (this study).

A search of the State Library of Victoria Multimedia Catalogue (<http://www.slv.vic.gov.au/slv/mmcatalogue/>) using keyword search of Keilor, Maribyrnong River, Jacksons Creek and Deep Creek revealed some drawings of the area dating back to the mid-1800s. All show that the slopes, floodplain and river banks had been almost entirely cleared of native vegetation (Figure 20 and Figure 21). Early photographs of the area also show cleared riparian vegetation (Figure 22).

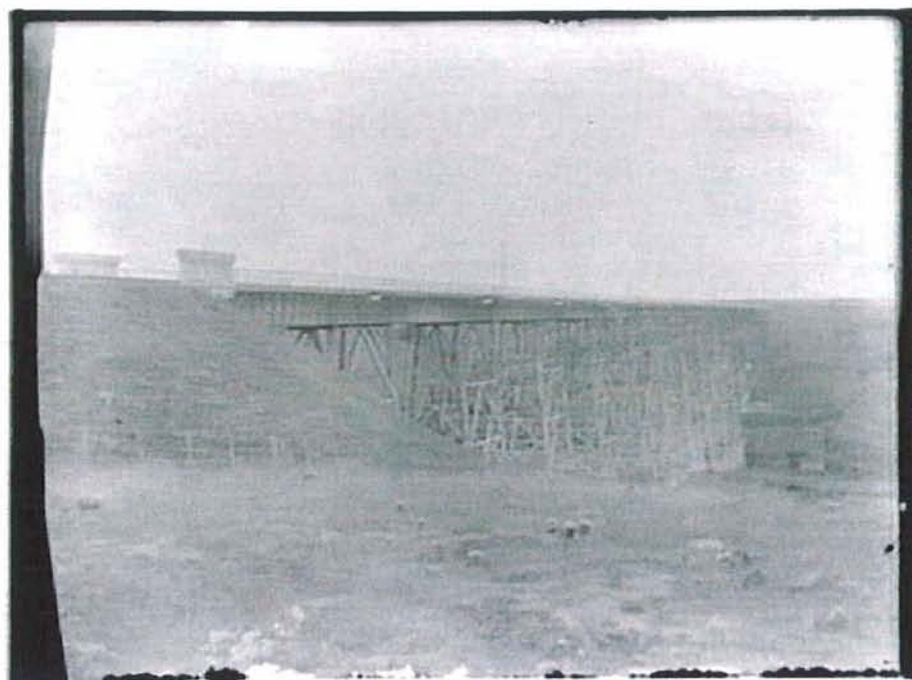




**Figure 20. Township of Keilor from South side of Bridge, Gill, S. T. 1818-1880. Published 1855. Pencil, wash, ink, body colour and gum arabic on green bristol board (source: State Library of Victoria Multimedia Catalogue).**



**Figure 21. Keilor Melbourne, Brees, Samuel Charles 1810-1865. Published 1856. Watercolour with gum arabic and gouache board (source: State Library of Victoria Multimedia Catalogue).**



**Figure 22. Bridge at Keilor [Trestle bridge]. Published 1920 (source: State Library of Victoria Multimedia Catalogue).**

#### 4.4.3.1 Anecdotal reports

Camp Scott Furphy (1990) reported landholder claims that erosion had been worsening over the past 15 years, although no further detail was provided. The property of Denis Brown (Brown's Road, Keilor) was visited on 13<sup>th</sup> May 1999. Denis and neighbour Anthony Senserrick reported general bank erosion problems in the area of chainage 13.0-14.2 km. Denis provided a hand drawn map on 26<sup>th</sup> May 1999 which illustrated areas of erosion similar to those shown in the maps of Camp Scott Furphy (1990). Denis also reported loss of about 0.5 m of topsoil from the floodplain near the river over the past 30 years. At chainage 14.1 km irrigation pipes were observed very close to the edge of the bank. It was argued by Denis that erosion must have occurred after the pipes were laid, as they would be of little value so close to the bank.

Scott Seymour (Melbourne Water, pers. comm., May 1999) reported that erosion occurred on the bend upstream of Arundel Road during a large flood in 1993. Also, a soil quarry at Flora Street (chainage 9.5 – 10.0 km) has been lowering the level of the floodplain, and working close to the channel (Figure 23). At this location the left channel bank contains the 1:2.5-1:5 yr ARI event. The floodplain is also being worked on the right bank just upstream of the Trestle Bridge (Figure 24). This area is also subject to inundation from the 1:5 yr ARI event. Surface runoff from this area is directed into the Maribyrnong River. A few hay bales have been placed on the drainage line in an attempt to trap suspended solids.

#### 4.4.3.2 Aerial photographs

The earliest aerial photograph series is the 1:18 000 B&W taken in 1931 (Figure 4). These photographs were compared with the 1:15 000 colour photographs taken in 1993 (Figure 5). This comparison clearly showed that there has been no major natural alteration of the alignment of the channel over this 60 year time period. It was not possible to accurately measure erosion rates from the photographs; the 1931 photograph has too much distortion to allow detailed comparison with the later photograph, the resolution of the 1931 photographs is poor in places, and vegetation obscures the channel edge, especially in the 1993 photograph.



Although detailed comparison of the 1931 and 1993 photographs was not possible, two reaches of the river between the Calder Freeway and Browns Road did show visible evidence of bank migration. In the area around the Calder Freeway the channel migrated 10-20 m over the period 1931-1993 (Figure 25). Not long after the 1993 photograph was taken, the affected section of bank was moved back closer to its original position and then rock beached and replanted.

The section of channel between 12.8 km and 13.5 km near Brown's property also appears to have migrated between 1931 and 1993, but it is difficult to quantify the migration distance due to excessive distortion in the 1931 photograph (Figure 26). However, the channel appears to have migrated in the order of 10-20 m at two locations. The bend located at chainage 14.1 km (reported to have eroded according to anecdotal reports) was distorted in the 1931 photograph, but there was no major channel migration apparent at this site in the 1993 photograph.



**Figure 23. Soil quarry near Flora Street (chainage 9.5 – 10.0 km). Also, note rock bars in channel.**

#### 4.4.3.3 1990 and 1999 channel photographs

Camp Scott Furphy (1990) produced a photographic record of the erosion sites that they identified. The survey was done by boat, and most of the photographs were taken from within the channel from the boat. The 1999 survey undertaken as part of this study was also done by



boat, although the channel was also inspected and photographed from the floodplain and top of the channel bank. The 1999 photography was not undertaken with the objective of re-photographing the erosion sites identified in 1990. For this reason, most of the photographs are not directly comparable. However, some of the photographs were taken from similar positions.



**Figure 24. Drainage line directed to Maribyrnong River from disturbed soil area on right floodplain about 1 km upstream of Trestle Bridge.**

The comparison of channel photographs did not reveal evidence of any large-scale erosion of the River between 1990 and 1999. The only site to show noticeable erosion was the right bank at Milburns Weir (chainage 13.8 km). This was evident because part of a large drainage pipe had fallen into the channel (Figure 27 and Figure 28); the erosion is local, of the order 1-2 m, and probably related to the existence of the weir structure. The other photographs taken at common locations revealed either no change or an increase in vegetative growth. Other comparisons show the channel before and after rock beaching that was conducted after the 1990 survey (Figure 6 and Figure 7).

There is evidence of a massive slump failure on the left side-slope at chainage 14.8-15.0 km. This failure pre-dates the 1931 aerial photograph. Such failures probably occur during large rainfall and flood events, when high velocity overbank flows erode the saturated soils of the toe of the side-slope or terrace. Although infrequent and difficult to predict, these failures are catastrophic, and likely to occur again in the future.

#### 4.4.4 Conclusion

The Maribyrnong River is an actively eroding stream, and the most severe erosion would be expected on the outside bends of relatively tight meanders in alluvial bank material. Thus it is not surprising that the survey of Camp Scott and Furphy (1990) reported the most severe erosion in these locations. Despite rating many sites as having "severe" erosion, this cannot be interpreted as relating to a particular erosion *rate*. The survey of Camp Scott Furphy (1990) was based entirely on subjective visual inspection, and no erosion rate data were presented. Comparison of 1931 and 1993 aerial photographs revealed bend migration of 10-20 m at three locations only, but photographic distortion made the comparison difficult. There was no strong evidence available to suggest that erosion rates have increased in recent times.

The morphology of the channel was found to be variable throughout the study area with some sections being more susceptible to erosion, because of high stream power, high and steep



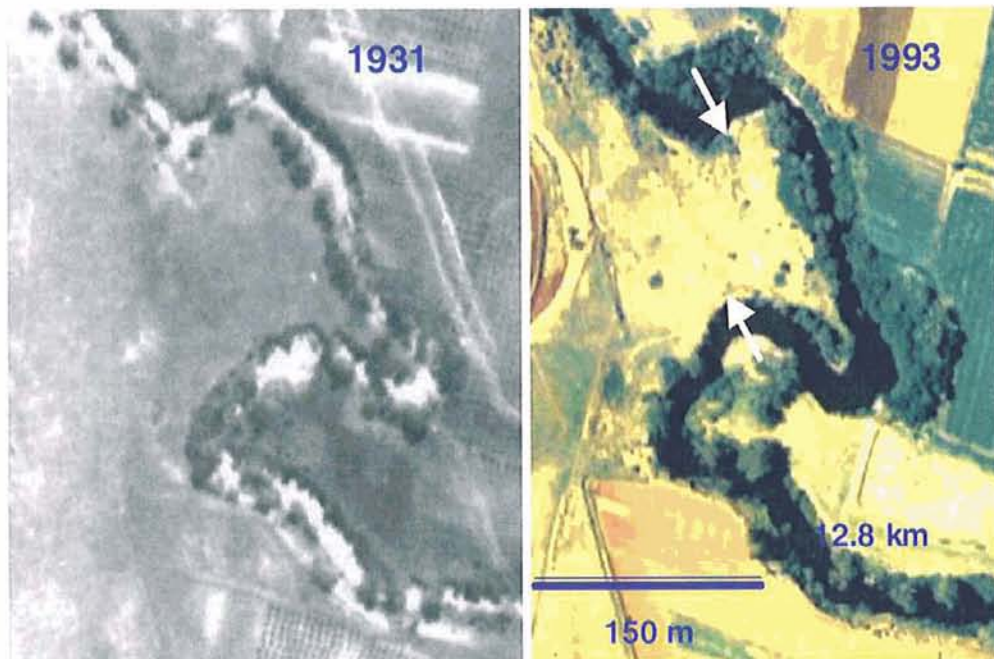
banks, low width/depth ratio, confinement of floods, and poor riparian vegetation cover. Rock beaching conducted in response to the survey of Camp Scott Furphy (1990) was conducted at sites showing "severe" erosion, and these sites also had hydraulic and geomorphic characteristics that rendered them more susceptible to erosion. The visual assessment of the channel conducted in mid-1999 as part of this study did not attempt to rate erosion sites. However, the channel had a relatively stable appearance, with even vertical banks showing signs of recent vegetative colonisation, no doubt associated with the recent long period of drought.

The bed of the Maribyrnong River is stable, being controlled by a series of artificial weirs, rock grade control structures and natural rock bars.

The sediment supply, catchment hydrology and channel hydraulics may have altered slightly in historical times. Such subtle changes usually have no significance for channel erosion rates. However, if a small change caused the channel to cross a geomorphic threshold, then rejuvenation is a possible response consequence. This process cannot be modelled with any level of certainty. In high-energy systems like the Maribyrnong River, it is known that poor riparian vegetation cover is conducive to ongoing bank erosion. Removal of the native riparian vegetation cover is probably the biggest single disruption to the geomorphology of the stream system during historical times. The vegetation of the riparian zone is currently more intact than it was in 1931, but much of it is composed of alien species.



**Figure 25.** Comparison of Maribyrnong River channel in vicinity of Calder Freeway (9.5 – 10.0 km) in 1931 and 1993, showing area of channel migration.



**Figure 26.** Comparison of Maribyrnong River channel in vicinity of Brown's property (12.8 – 13.5 km) in 1931 and 1993, showing areas of channel migration.



**Figure 27.** Milburns Weir (chainage 13.8 km) looking towards right bank in 1990.





**Figure 28. Milburns Weir (chainage 13.8 km) looking towards right bank in 1999.**

## 5 Review of 1990 Erosion Study

### 5.1 Introduction

The erosion study conducted by Camp Scott Furphy (1990) is comprehensive. The background information, history of the catchment, and hydrological analysis are not challenged here.

The analysis of valley and stream sinuosity is unusual (p. 15-17). The conclusion that the section of stream from Calder Freeway to the large bend above Arundel Rd is the only part of the river competent to re-work the sediments is misleading. This section of the river is the only part that has any appreciable width of floodplain, so it follows that this will be the zone of alluvial sediment reworking. Similarly, the analysis of meander wavelength is not useful.

The slopes through the market garden section were claimed to be higher than elsewhere in the river (p. 16). Values of 0.002-0.003 were quoted, but in fact the slope in this reach is relatively uniform at 0.0015. Steeper slopes may occur very locally.

The field classification system for erosion severity was highly subjective. It was influenced by factors such as the parent material, size of the feature, the potential for enlargement and the economic effect of not controlling the erosion. These factors are not geomorphologically based. Rather, they are management based, with the surveyor incorporating judgements about the likely cost of carrying out stabilisation works, and the possible economic consequence of not doing so. For example, high vertical banks adjacent to valuable agricultural land would rate as severe erosion, while another remote site with lower banks (but possibly having a more active erosion rate) would score a less severe rating.

The erosion classification scheme used by Camp Scott Furphy (1990) was a management oriented scheme, rather than a strictly geomorphologically based scheme. The geomorphological analysis done by Camp Scott Furphy (1990) was somewhat naïve and incomplete, but the understanding of long-term processes was essentially correct. The management based classification scheme was appropriate, because there was a requirement to recommend channel works that would arrest erosion that appeared to be threatening valuable assets.

It is important to note that Camp Scott Furphy (1990, p. iii) concluded that *"the overall erosion status is not severe"*. Of 161 identified erosion sites, 34 were rated severe and 66 slight. All of the severe erosion was observed *"...within the flood plain reaches of the river, and are mainly at the outside of river bends where conditions conducive to erosion of the alluvial material occur."* Apart from this process, which could be viewed as entirely natural, the only other serious concern related to erosion that was associated with three meander cutoffs. There was no suggestion made that the two major cutoffs (which occurred at the beginning of the 20<sup>th</sup> century) were promoted by human disturbance.

The erosion survey used a snapshot methodology, so the results only describe the level of erosion viewed on the day of the survey. It is not possible to assess rates of erosion by this method, although the report makes many references to erosion processes. Rates of erosion were also inferred through landholder claims that erosion had been worsening over the past 15 years. Apart from the evidence of meander cutoffs, no previously surveyed cross-sections or bed profiles exist that can be used to compare with current channel surveys. Thus, the rate of erosion is unknown.

Given the difficulty of obtaining knowledge of erosion rates, it was appropriate to use expert opinion to determine the priority sites for erosion control works. It was also appropriate to incorporate the likely economic consequences of not carrying out works. However, one problem with the approach taken is that the economic evaluation was done intuitively, rather than analytically. The assets under threat were not properly valued in economic terms, so it is not possible to determine the benefit-cost ratio of the works that were proposed.

Camp Scott Furphy (1990) demonstrated an enlightened philosophy towards the style of works recommended to control erosion. Many of the recommendations were concerned with



carrying out stream management works so that habitat value would be maximised. Soft engineering (using wood and re-vegetation) was promoted where possible, with hard-lining recommended only where valuable assets were under immediate threat. Many of these recommendations were subsequently adopted by Melbourne Water, but some of the options (e.g. timber groynes) were impractical due to the nature of the site.

## 5.2 Statistical analysis of erosion survey methodology

The visual assessment methodology of Camp Scott Furphy (1990) was evaluated against other objective methods of assessing erosion potential using multivariate analysis. It was not possible to evaluate the visual assessment technique against actual erosion, because reliable and objective data on erosion rates do not exist for the Maribyrnong River.

### 5.2.1 Data

In this study several variables indicative of erosion potential were measured at the 62 cross-sections used for the HEC-RAS modelling (Table 6). Some of these variables could be measured for left and right banks (e.g. vegetation intactness) while others applied to the whole section (e.g. mean stream power), or the concave (outside) bank (e.g. bend radius/width ratio). These variables were used in a multivariate analysis (principal components analysis) with the Camp Scott Furphy (1990) erosion rating as the dependent variable. Erosion rating was recorded for each sampled cross-section (left and right banks) as severe, moderate, slight or none, as indicated on the maps of Camp Scott Furphy (1990). Note that this analysis included only a sample of the erosion sites identified by Camp Scott Furphy (1990). Sites were selected only if they occurred at a cross-section (where the morphologic and hydraulic variables were measured). This procedure ensured that erosion site sample selection was unbiased, as the cross-section locations were determined independently from the erosion site mapping exercise. The cross-sections were located approximately every 500 m, and their position was not influenced by any morphological factor (Figure 29).

**Table 6. Variables used in multivariate analysis of erosion potential.**

Code	Variable	Application	Index used
SP	Mean stream power	mean for x-section	$\text{Wm}^{-2}$ at 1:2 yr ARI ( $225 \text{ m}^3\text{s}^{-1}$ )
CON	Confinement	cross-section	Is 1:2.5 yr ARI event ( $250 \text{ m}^3\text{s}^{-1}$ ) confined? (YES/NO)
WD	Width/depth	cross-section	top width/mean depth
BRWR	Bend radius/width	concave bank	conventional method (linearised)
VR	Vegetation intactness	left and right banks	ISC index mean of bank and bank top (0-4)
BA	Bank angle	left and right banks	top of bank to bed
BF	Bend form	left and right banks	concave/convex/straight
BM	Bank material	left and right banks	alluvial or bedrock confined
ER	Erosion Rating	left and right banks	Camp Scott Furphy (1990) data (1 = severe, 2, = moderate, 3 = slight, 4 = none)

Principal components analysis (PCA) requires that the variables are linearly related. This assumption is uncertain for most variables used here. For example, erosion rating and vegetation intactness were both measured using a four point index, but the data are classified subjectively, and it is not known whether the scales are truly linear, e.g. whether vegetation intactness rated 2 is twice as intact as intactness rated 1.



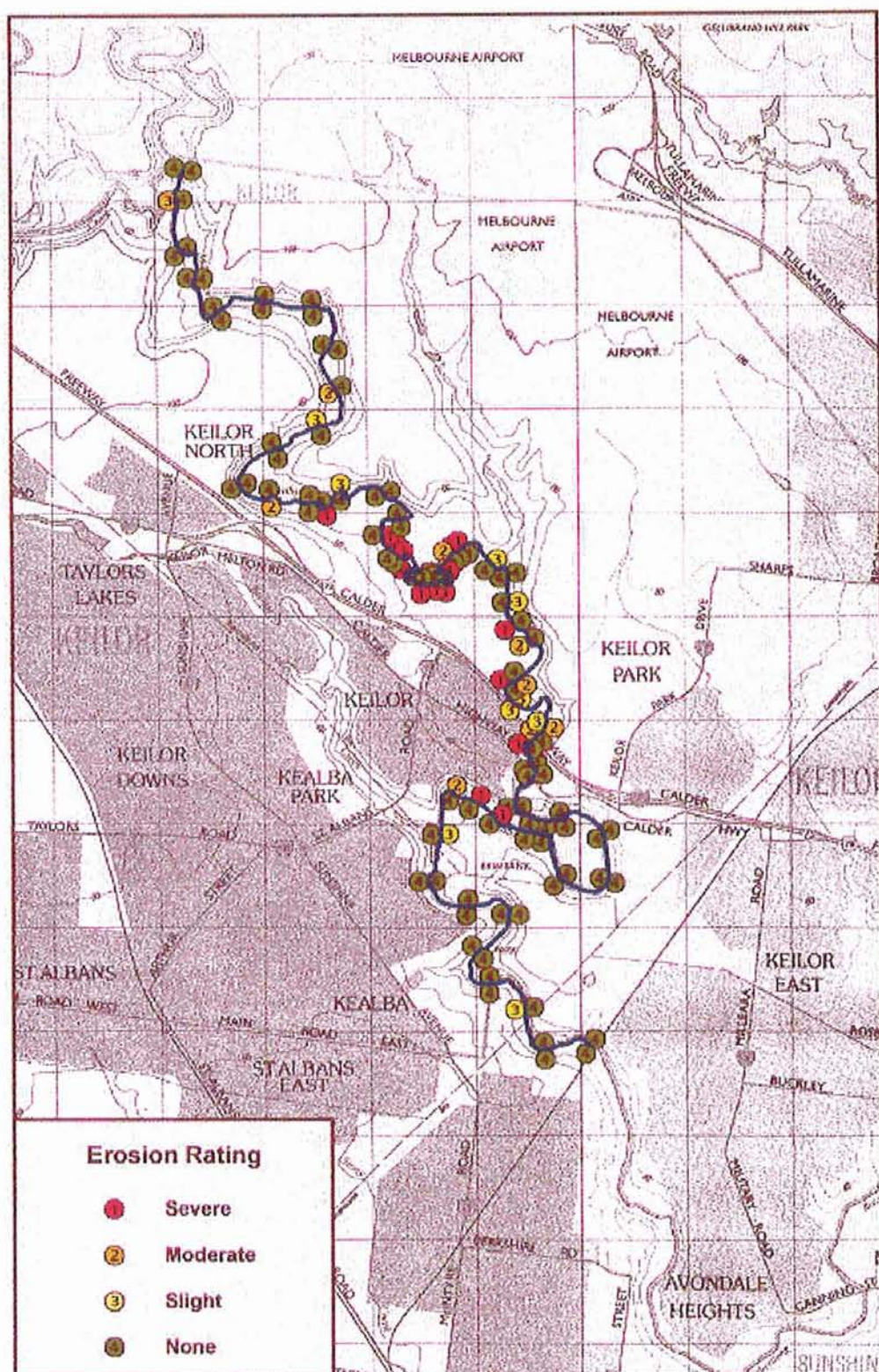
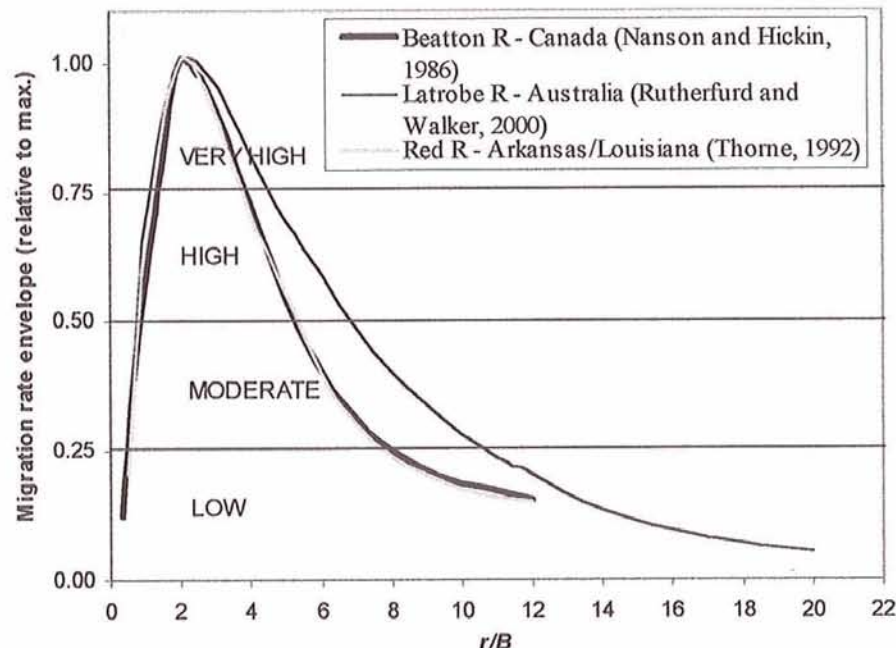


Figure 29. Erosion rating at 62 cross-sections on the Maribyrnong River [source: Camp Scott Furphy (1990)].



It was known that bend radius/width ratio is *not* linearly related to bend migration (erosion) rate. However, the envelopes of bend migration data from three rivers located in three different countries were found to have remarkably similar distributions (Figure 30). The Latrobe River distribution was used to linearise the Maribyrnong data, i.e. bend radius/width ratio was converted to a dimensionless index of potential migration rate.



**Figure 30. Distribution of bend radius/width ratio as a function of dimensionless bend migration rate (migration rate relative to maximum observed rate) for three rivers. Labels indicate relative potential for bend migration.**

### 5.2.2 Preliminary data analysis

The objective of principal components analysis (PCA) is to find the combinations of variables that best explains the dependent variable (erosion rating). Prior to PCA, the raw data were examined to determine if any simple relationships existed.

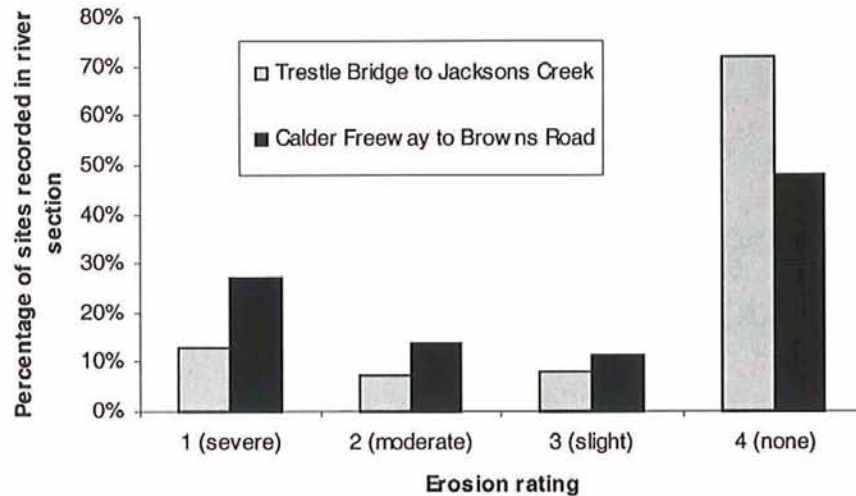
Of 124 observations (left and right bank of 62 cross-sections), 69% were in alluvial material and 31% were bedrock controlled. Most sampled sites were rated as having no erosion, with 67% of the alluvial sites having no erosion and 85% of the bedrock controlled sites having no erosion. Most of the erosion sites were associated with alluvial bank material, with 88% of "severe" (rating 1) sites, 78% of "moderate" (rating 2) sites, and 70% of "slight" (rating 3) sites occurring on alluvial material.

It was not surprising that the alluvial Keilor reach between Calder Freeway and Browns Road contained a higher density of erosion sites, with 27% of sites in this area rated as severe, compared with 13% rated severe for the entire study area from the Trestle Bridge to the junction of Deep and Jacksons Creeks (Figure 31).

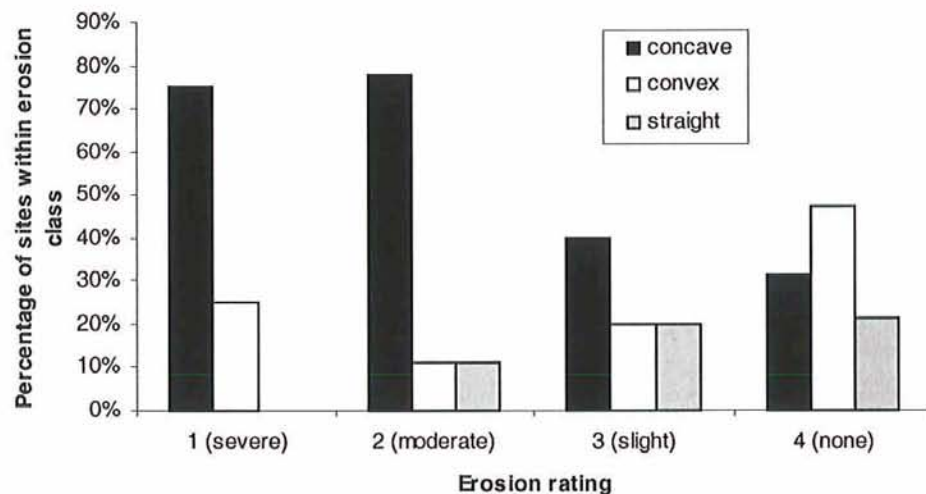
Erosion sites were overwhelmingly associated with concave bends, especially those sites rated as having severe and moderate erosion (Figure 32). Concave bends accounted for 66% of all erosion sites. Convex bends and bedrock confined bank material were clearly associated with stable banks, so these sites were removed from the data set prior to performing the principal components analysis. There were 26 sites on concave bends in alluvial bank material.

While the literature suggests that steep and high banks are more prone to erosion than low gently sloping banks, this relationship was not clearly apparent from the Maribyrnong River data (Figure 33). However, severe erosion was not recorded on banks with a slope lower than

27°, or a bank height less than 2.5 m. In contrast, sites without erosion were evenly distributed across the full range of bank angles and bank heights. Erosion severity was not related in an obvious way to bend radius/width ratio, width/depth ratio, or degree of confinement.



**Figure 31.** Distribution of sampled erosion sites for the study area, compared with that of the largely alluvial Keilor reach from Calder Freeway to Browns Road.



**Figure 32.** Distribution of erosion ratings according to channel shape.

### 5.2.3 Principal components analysis (PCA)

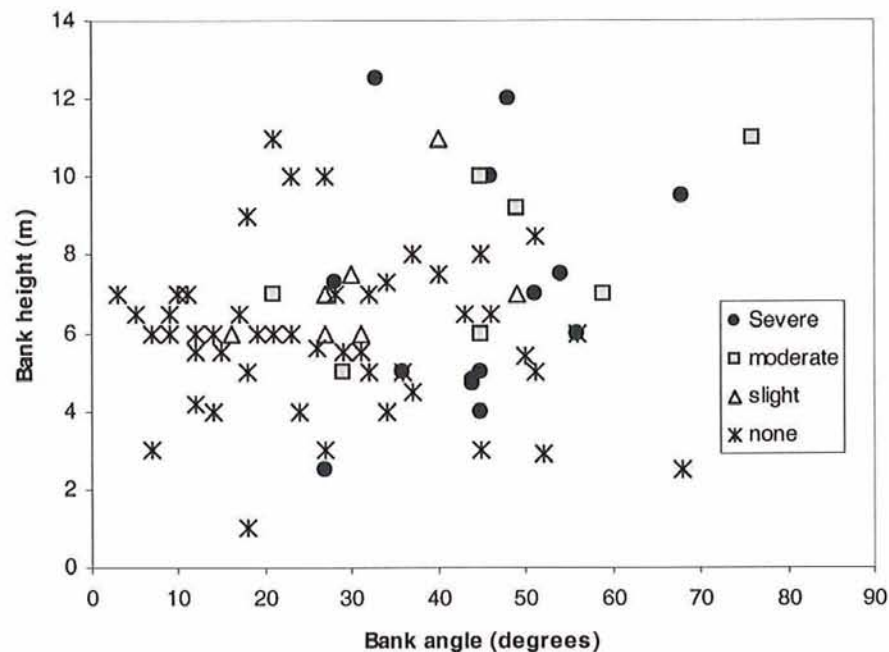
Reduction of the data set to the 26 sites on concave bends in alluvial bank material produced 10 rated severe, 6 rated moderate, 2 rated slight, and 8 rated no erosion. These class sizes are too small for PCA, so the severe and moderate rated sites were merged, and the slight and no erosion sites were merged, to form two new erosion severity classes.

PCA is a means of simplifying data by reducing the number of variables to a small number of indices called the principal components. PCs are the linear combinations of the original



variables. PCA provides an objective way of finding some indices so that the variation in the data can be accounted for as concisely as possible. The objective of the analysis was to take 5 variables – VR, BA, BRWR, WDR, and SP, and find combinations of these to produce Principal Components (PCs) that were uncorrelated. The lack of correlation is a useful property because it means that the PCs are measuring different dimensions in the data. The PCs are so ordered that the first displays the largest amount of variation, the second displays the second largest amount of variation and so on. Using uncentred and unstandardised data, PC1 and PC2 accounted for 99% of variation in the data, with PC1 accounting for 88% of variation. Stream power (explaining 68% of variation) and bank angle (explaining 30% of variation) were the main explanatory variables in PC1.

PCA differentiated the alluvial concave banks with medium to severe erosion from those with slight to no erosion. Stream power and bank angle were the main explanatory variables.



**Figure 33. Relationship between bank angle and bank height according to erosion severity rating, for alluvial sites only.**

### 5.3 Conclusion

The erosion survey conducted in 1990 by Camp Scott Furphy (1990) used a subjective visual assessment technique that incorporated non-geomorphic variables such as the perceived cost of stabilisation, or potential loss of assets if the site was not stabilised. However, there is no way of knowing how these factors were incorporated into the operators' judgements, nor how influential they were in determining the final rating. Camp Scott Furphy (1990) did not measure variables that might act as surrogates for erosion, such as channel morphology, or stream power. It is important to note that the erosion severity ratings were in no way connected to actual erosion rates, as such data were unavailable.

Analysis of a sample of 62 cross-sections, from the Trestle Bridge to the junction of Deep and Jacksons Creeks (21.7 km of river, and 43.3 km of bank), revealed that 13% of the banks were rated as having severe erosion. This equates to 5.6 km of severely eroded bank, an estimate that includes left and right banks. Of this total, 2.6 km was located in the Keilor reach from Calder Freeway to Browns Road (4.8 km of river, and 9.7 km of bank).

Not unexpectedly, the majority of sampled sites (64%) that were rated as having severe or moderate erosion were located on concave (outside) bends in alluvial material. Sites that were rated as having severe or moderate erosion that occurred within this type of channel morphology were associated with high bankfull stream power and steep bank angle. Steep

bank angle is commonly thought (sometimes incorrectly) to be a good indicator of active bank erosion, and it is one of the indicators used in the ISC. Steep bank angle is a dramatic feature that is likely to make a strong visual impression when undertaking erosion assessments. Stream power at bankfull discharge is known to be a predictor of bank erosion potential, but it cannot be directly visually assessed during a low flow channel survey. It appears that the surveyors were responding to a combination of some artefact of high stream power, and steep bank angle. Bank angle was not this artefact, as bank angle and stream power were not correlated.

The distribution of erosion sites identified by Camp Scott Furphy (1990) was as expected, with most sites located on the outside (erosional) bend of meanders, and the more severely eroded sites being associated with steep bank angles and high stream power. This distribution would be found on any alluvial river, because it is natural for alluvial rivers to erode their banks as part of the meander migration process.

Camp Scott Furphy (1990) recommended stabilisation of the sites rated as severely eroded, even though they produced no data on actual erosion rates. Thus, it is possible that sites that were rated "severely eroded", were stable at the time of the survey. Similarly, it is possible that sites rated as having no erosion could have become unstable since the time of the survey. Camp Scott Furphy (1990) did not do a cost-benefit analysis of conducting the proposed bank stabilisation works.

It is difficult to identify active erosion using rapid visual assessment. This technique can identify sites of past erosion, which is probably a reasonable guide to sites of likely future erosion. The biggest problem is that the technique does not provide data on erosion rates, so it is difficult to predict the consequences of future erosion.

The Maribyrnong River is an actively eroding river. However, the rates of bend migration are relatively low by world standards, with only three bends showing measurable migration from a comparison of 1931 and 1993 aerial photographs. Measurement of erosion rates from available photographs was compromised by distortion of the images, and poor quality of the earlier images, so changes in the order of  $\pm 10$  m could not be detected by this method. The Camp Scott Furphy (1990) study recommended channel stability works at several high priority sites. A programme of works was subsequently undertaken by Melbourne Water at a cost of about \$1million. Decisions regarding erosion control works are driven partly by geomorphic considerations, but also by concerns about asset protection, and social factors (some of these were subjectively incorporated into the erosion severity rating scheme used in the survey). Thus, while the Maribyrnong River is not a highly active river by world standards, the decision to conduct the post-survey stability works was justified at the time in terms of local social, economic and physical factors, and was consistent with the dominant Australian stream management paradigm that values absolute (in management time-scales) stability. This conventional paradigm is now falling out of favour in some circles, where it is recognised that a level of channel instability is desirable from an ecological perspective, and that channel stability is difficult and expensive to attain. The stability works done on the Maribyrnong River during the 1990s addressed sites where assets were threatened, and/or where there was an apparent risk of catastrophic channel change.



## 6 Ecological Considerations

### 6.1 Introduction

This section aims to make a preliminary assessment of the geomorphic and hydraulic processes that are likely to be driving ecological processes in the river, and those that are likely to be limiting ecosystem function and community development. From this assessment, management programs may be prioritized to meet ecological requirements for waterway sustainability.

Degradation of the riparian zone and in-stream habitat has been identified as a problem for the Maribyrnong, and has been the subject of recent management works in the Keilor valley (Fisher, 1999). The physical success of such works is relatively easy to assess. However, their benefit to instream biotic communities is less easily determined. The potential for (ecological) success is dependent on matching the scale of works to the scale at which degrading processes act. Restoration of physical habitat may not address the main degrading causes if those causes result from unrecognized larger-scale processes (Lewis *et al.*, 1996).

Nutrient enrichment has also been identified as a problem in the Maribyrnong River (Metzeling, 1990; Bray, 1989), leading to excessive macrophyte growth in periods of low flow (Brown and Davies, 1989). Nutrient enrichment is likely to lead to changes in the ecological function of the river, by shifting the base of the food web from allochthonous detritus to autochthonous production of carbon by primary producers. The type of primary producers (macrophytes, attached algae or phytoplankton) that dominate will in part be dependent on fluvial geomorphological processes. The problem of nutrient loads must therefore be considered in association with a review of fluvial geomorphology.

High nutrient loads in the lower Maribyrnong have been speculatively attributed to agricultural practices (particularly the market gardens of the Keilor valley: Metzeling, 1990), urbanization (Brown and Davies, 1989; Metzeling, 1990; Carvalho *et al.*, 1997), and the Keilor sewerage treatment plant (STP), which ceased operation in November 1998. The influence of the Sunbury STP on the lower Maribyrnong has been considered to be small (Metzeling, 1990). In assessing the macroinvertebrate and plant communities of the lower Maribyrnong, Brown and Davies (1989) were unable to separate the influence of urbanization from that of the Keilor STP.

Two methodological approaches were taken here. Firstly, existing nutrient, suspended solids and macroinvertebrate data were collated and analysed to assess catchment-scale influences on in-stream biota. Secondly, site inspections were conducted on the Maribyrnong River from the head of the estuary to near the confluence with Jacksons and Deep Creeks, to assess local conditions at sites that have been subject to differing levels of stabilisation and instream enhancement works.

### 6.2 Methods

#### 6.2.1 Site locations

Water quality and macroinvertebrate data were collected at various sites on the Maribyrnong River and its two main tributaries: Jacksons Creek and Deep Creek (Table 7, Figure 34). All of the tributary sites have rural catchments, with largely agricultural land use. The Jacksons Creek site at Sunbury lies within the town of Sunbury, and is subject to some urban stormwater runoff. It is, however, upstream of the Sunbury Sewerage Treatment Plant, which discharges into Jacksons Ck upstream of the sites at Bulla and Organ Pipes National Park.

**Table 7. Sites for which data were obtained for this section of the report. Number of sampling occasions for each data source is indicated. MW = Melbourne Water, CRCFE = Urban program of the CRC for Freshwater Ecology, VEPA = Victorian Environment Protection Authority**

Stream	Location	Water quality	Macroinvertebrates	
		MW	CRCFE	MW VEPA
Deep	Gallaghers Ford, Romsey		14	
	Darraweit Guim		14	
	Kinnears Rd, Konagaderra		14	
	Bulla	15	14	4
Jacksons	Settlement Rd, Clarkefield		14	
	Sunbury	15	14	4
	Bulla-Diggers Rest Rd, Bulla		14	
	Organ Pipes National Park		14	
Maribyrnong	Keilor Golf course, Sydenham			4
	Calder Fwy, Keilor			4 1
	Brimbank Park weir, Keilor	60		2
	Canning St ford, Avondale Heights	60		4 1

Data were also collected from four sites on the Maribyrnong River. The Sydenham site is upstream of the Melbourne metropolitan area, while the Calder Hwy site receives some urban run-off from Arundel Creek and the Calder Fwy. This site is also downstream of the intensively farmed Keilor floodplain, and rock and soil quarries. The Brimbank Park site, 3.4 km further downstream receives additional urban runoff from Keilor. The final site, Canning St Ford at the head of the estuary, receives urban runoff from a number of stormwater drains and Taylors Creek.

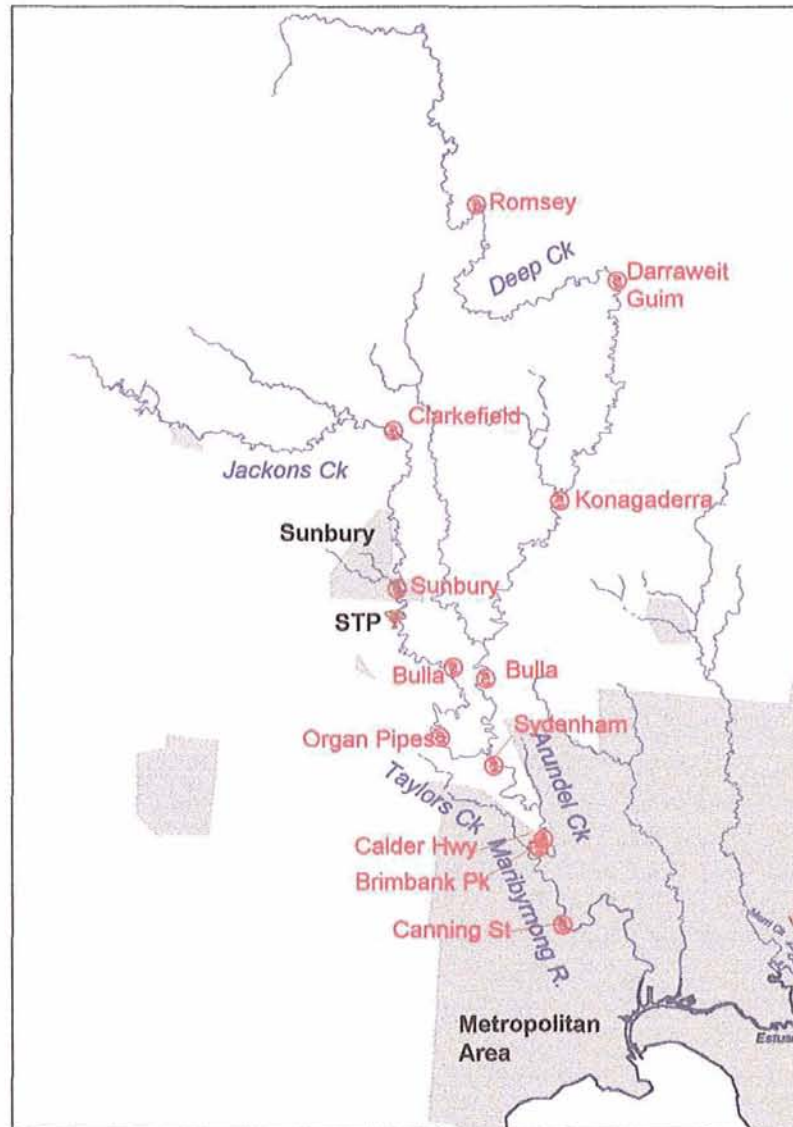
The river was inspected (by CW) on 10-12 June 1999, at Sydenham; Keilor Nth at McNabs Lane; Keilor at Arundel Rd, the confluence of Arundel Creek, and Flora St; and from the bicycle path from Brimbank Park to Canning St Ford.

### 6.2.2 Water quality

Water quality data from Nov 1994 to Dec 1995 were obtained from Melbourne Water's monitoring database, and from the urban program of the CRC for Freshwater Ecology, and was matched to daily discharge data supplied by Melbourne Water. This period of data is likely to be indicative of the current state of the river, except for the influence of the Keilor STP, which has now ceased operation. Insufficient post-operation data are available at this stage to separate the influence of urbanization downstream of Keilor from that of the Keilor STP.

Patterns in nitrate/nitrite concentration ( $\text{NO}_x$ ) and filterable reactive phosphorus concentration (FRP) were assessed, as these are the major biologically available forms of nitrogen and phosphorus. Unfortunately FRP data were only available for the Deep and Jacksons Creeks sites (CRCFE data, Table 7), so total phosphorus (TP) was used for some analysis of catchment-scale patterns. Patterns of total suspended solids concentration (TSS) were also assessed.





**Figure 34. Map of the Maribyrnong River and tributaries indicating macroinvertebrate and water quality sampling sites (in red).**

### 6.2.3 Macroinvertebrate community composition

Macroinvertebrate data were collected for autumn and spring 1994 and 1995 from the Melbourne Water Streamwatch program and from the Victorian EPA monitoring program. Consistency of taxonomic identifications was assured through a collaborative CRC for Freshwater Ecology project (C. J. Walsh and P. F. Breen, unpublished data). All macroinvertebrate samples were collected from riffles using standard rapid bio-assessment methods (Anon., 1994), with sorting of live animals in the field.

Community composition at six sites in the Maribyrnong River and tributaries was compared to that of sites in small tributary streams of the Melbourne region, and to that of sites in the other major lowland river of the Melbourne region, the Yarra River. Previous work has shown that multivariate classification and ordination techniques consistently group macroinvertebrate communities from small streams of the Melbourne region into three groups: two rural groups and a group of sites that fall entirely within the Melbourne metropolitan area (Walsh and Breen, 1999). Communities of the metropolitan group are species-poor compared to the rural groups, and are dominated by pollution-tolerant taxa.

Patterns of community structure across the two groups of rural sites were best explained by differences in electrical conductivity, with sites to the north-west and south of Melbourne

metropolitan streams was best explained by the combined effect of two variables directly related to urbanization: impervious area and BOD (Walsh and Breen, 1999).

In this report, longitudinal series of sites along the two large lowland rivers of Melbourne, the Maribyrnong River and the Yarra River, were combined with the regional set of small stream sites to assess the effect of increasing downstream urbanization on the macroinvertebrate communities of the rivers. For each of the four sampling seasons, macroinvertebrate community presence-absence data from all sites were collated into a taxon-by-site matrix, from which a site-by-site similarity matrix was calculated using the Bray-Curtis similarity measure. The similarity matrix was used to calculate a non-metric multi-dimensional scaling ordination. Longitudinal trends in community similarity for the Yarra River and the Maribyrnong River were assessed within the context of the three small-stream groups in each ordination.

## 6.3 Results and Discussion

### 6.3.1 Nutrients

Ranges of  $\text{NO}_x$  concentrations were relatively consistent along Deep Creek, and in Jacksons Creek upstream of the Sunbury STP (below detection to  $\sim 0.5$  mg/L; Figure 35). Downstream of the Sunbury STP, at Bulla,  $\text{NO}_x$  concentrations were much higher, with some attenuation of concentration further downstream at Organ Pipes (Figure 35). This increased load of  $\text{NO}_x$  downstream of Sunbury is most likely originating from the Sunbury STP. This assertion is strengthened by the relationships between  $\text{NO}_x$  concentration and discharge at the most downstream sites on Deep and Jacksons Creek (Figure 36). In Deep Creek,  $\text{NO}_x$  concentration was positively correlated to discharge. This is the type of relationship that would be expected if nutrient loads were primarily delivered by runoff. In Jacksons Ck, however, peak concentrations were recorded in low to moderate flows, as would be expected if nutrient loads were being delivered by a relatively constant effluent source such as an STP.

Although a similar increase in TP is not evident downstream of the Sunbury STP (Figure 35), FRP did show such an increase, and shows similar relationships to discharge as for  $\text{NO}_x$  (Figure 36). Thus the Sunbury STP is likely to be a large contributor of biologically available nitrogen and phosphorus to the Maribyrnong River.

Attenuation of  $\text{NO}_x$  between Bulla and Organ Pipes is likely to be through uptake by primary producers (macrophytes or algae) and bacteria. Given the preponderance of macrophytes and algae in the lower Maribyrnong (Figure 37; Brown and Davies, 1989), primary production in the river is likely to be the main sink for nutrients from the Sunbury STP.

$\text{NO}_x$  and TP concentrations at Brimbank Park were well explained by inputs from Deep and Jacksons creeks (Fig. 8), with no evidence of further significant inputs between their confluence and Keilor. It is therefore likely that, at least during low to moderate flow conditions, nutrient inputs from the Keilor Valley market gardens are small compared to loads being delivered from upstream.

Large increases in  $\text{NO}_x$  and TP concentrations between Brimbank Park and Canning St Ford (Figure 35) may have largely resulted from effluent from the Keilor STP or from urban stormwater runoff. Further analysis of data after the closure of the STP is required to assess the importance of urban runoff to nutrient loads in the lower Maribyrnong River.

### 6.3.2 Suspended solids

Suspended solids are likely to settle in the lowland reach of the Maribyrnong River during periods of low to moderate flow following storm events. This would result in loss of habitat diversity for aquatic mammals, fish and invertebrates, and reduction in primary productivity for smothered plants.

TSS concentrations in Jacksons and Deep Creeks were low on most occasions (medians less than 10 mg/L), but occasional high concentrations were associated with floods at most sites (Figure 35). Median and lower percentile concentrations increased slightly between the most downstream sites on Jacksons and Deep Creeks and the Maribyrnong River at Brimbank Park (Figure 35). This increase suggests increased mobilization of sediments between Sydenham



and Keilor during periods of moderate to low flow conditions, which may have resulted from bank and bed instability or from increased runoff of sediments in this reach. This is an alluvial section of river, so contribution of suspended solids would be expected to be greater here than in the bedrock dominated sections (see also discussion in section 2.6 and data in Table 1).

The further increase in TSS at Canning St may have resulted from areas of bank instability in this reach (although much of this section is rock beached), from stormwater runoff, or from increased phytoplankton densities downstream of the Keilor STP. Further analysis of TSS concentrations at Canning St and Brimbank Park after the closure of the STP is required to discount the last possibility.

The confluences of Arundel and Taylors Creeks with the Maribyrnong River were inspected soon after rainfall of approximately 15 mm fell over the lower catchment in 18 h. Following this event, Arundel Ck was a minor contributor of solids to the river, while Taylors Ck was a moderate contributor (Figure 38a, b and f). A small drain 50 m downstream of Arundel Ck, which drains a rock quarry and an unsealed road, had an apparently high concentration of suspended solids during the observed event (Figure 38c, d), but the overall impact on the Maribyrnong River would have been small due to the relatively small discharge of this tributary.

The stabilization works in the Arundel Road reach are likely to have reduced local bank sediment inputs. However, there are other sources of sediments within this reach. The riparian frontage of the quarries between Keilor and Arundel Road should be priority concerns. These areas normally have exposed surface sediments that are easily entrained during storm events, and they appear to drain directly to the river.

### 6.3.3 Macroinvertebrate community composition

Macroinvertebrate communities of all sites sampled in the Maribyrnong River catchment were consistently most similar to communities of the north-western and southern 'high-salinity' small rural streams (Figure 39). The community of Canning St ford was consistently more similar to the degraded metropolitan small stream communities than were sites further upstream the Maribyrnong River, suggesting some degradation from urbanization by the time the river reaches the estuary. The communities at Brimbank Park and Calder Hwy were similar to that of Canning St in 1994, a drought year, but were more similar to communities at Sydenham in 1995 (Figure 39). It is possible that the impacts of urbanization are more evident further up the river during extended low flow periods.

Although disturbance effects are evident in the macroinvertebrate communities of the lowland Maribyrnong River, the effects of urbanization on the Maribyrnong River are not as severe as on the Yarra River. The macroinvertebrate community of the Yarra at Dight's Falls, just above the head of the estuary, was degraded over the study period, consistently grouping with the degraded communities of small metropolitan streams.

The Maribyrnong River at the head of its estuary is thus less impacted by pollutants and hydrological disturbance resulting from urban run-off than is the Yarra River. Because of this, it is likely that management actions designed to improve run-off quality, or to improve instream habitat in the Maribyrnong catchment are likely to pay greater dividends in ecosystem health than in the profoundly disturbed lower Yarra River catchment.

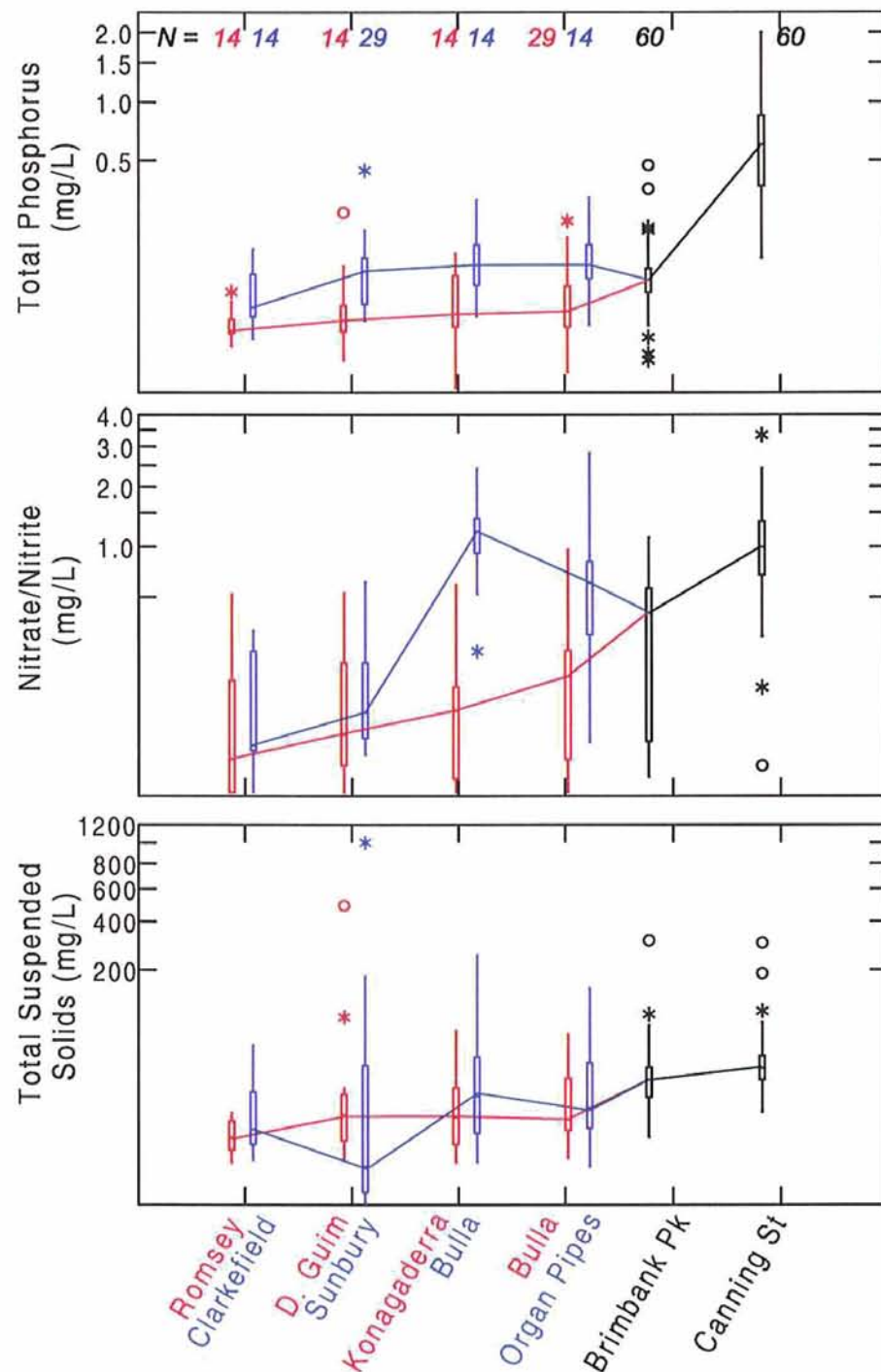
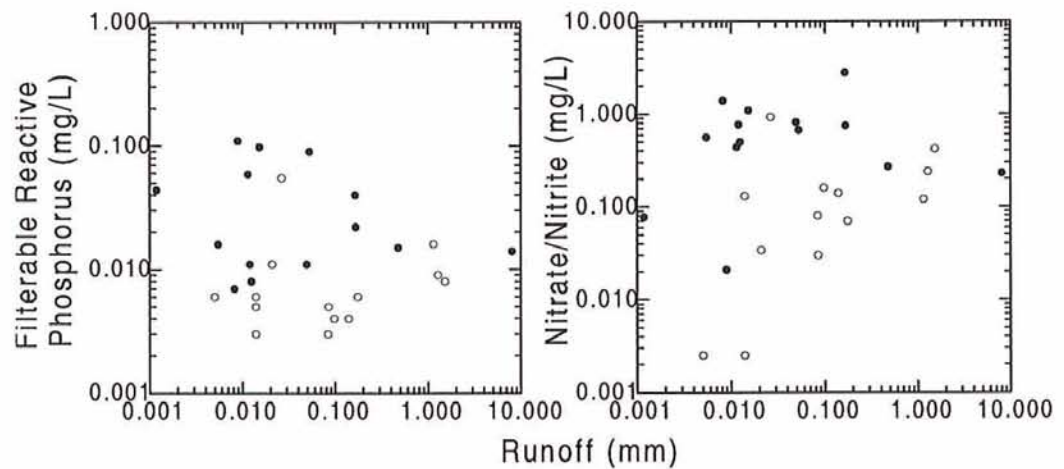


Figure 35. Total phosphorus, nitrate/nitrite and total suspended solids measured from November 1994 to December 1995 at

- four sites in Jacksons Creek in descending downstream order (*blue*) (the Bulla site is downstream of the Sunbury Sewerage Treatment Plant, and the Sunbury site is in urban Sunbury, upstream of the plant)
- four rural sites in Deep Creek in descending order (*red*), and
- two sites in the Maribyrnong River (*black*) (Brimbank Park, downstream of Keilor, and Canning Street ford just upstream of the head of the estuary). Numbers of measurements at each site are indicated. Box plots (conventions of Wilkinson, 1996) are joined by median values.

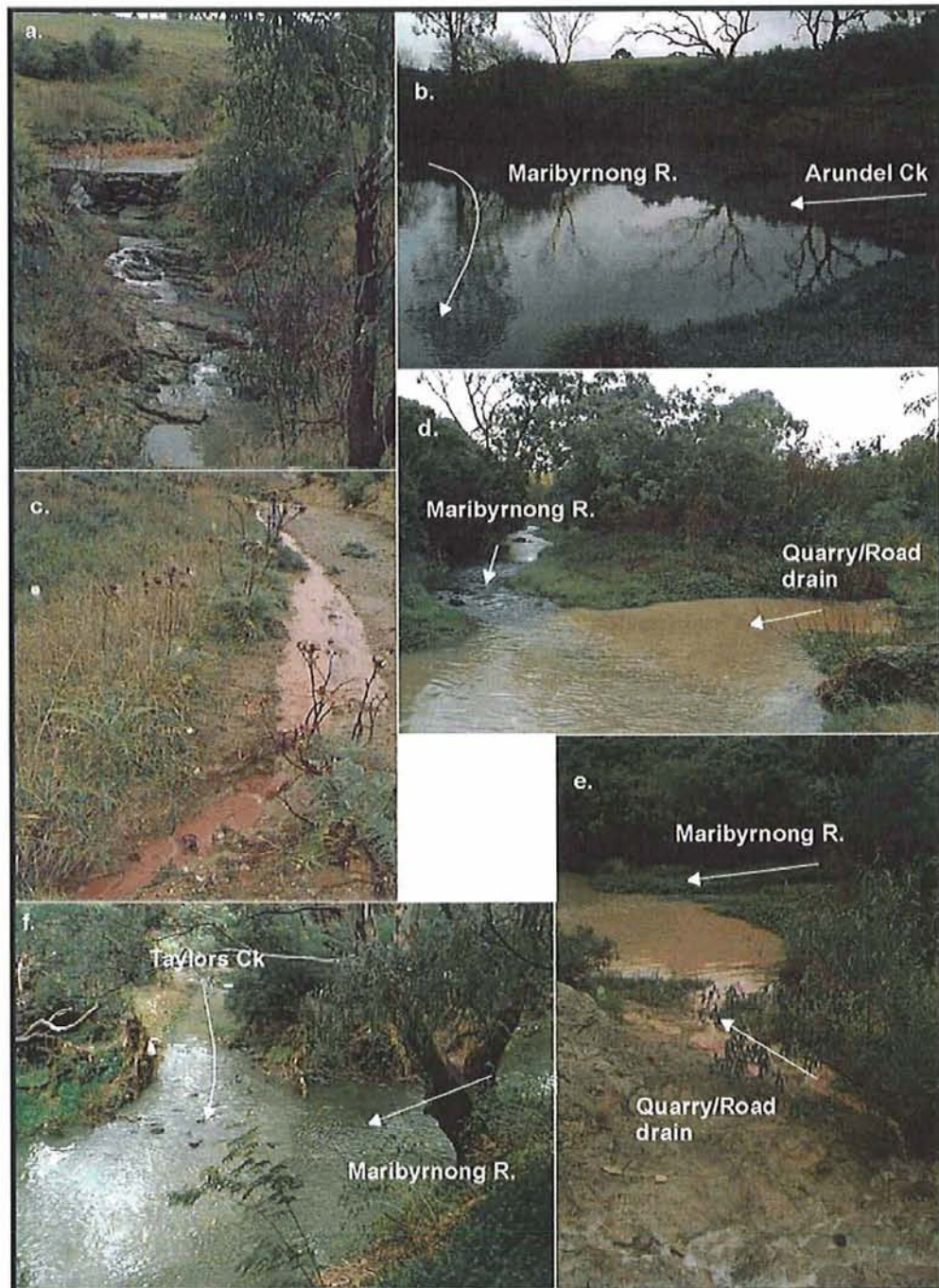




**Figure 36.** Concentrations of the major bioavailable forms of nitrogen and phosphorus in Jacksons Ck at Organ Pipes National Park (●) and Deep Ck at Bulla (○) in 1994-1995 in relation to runoff in each stream.

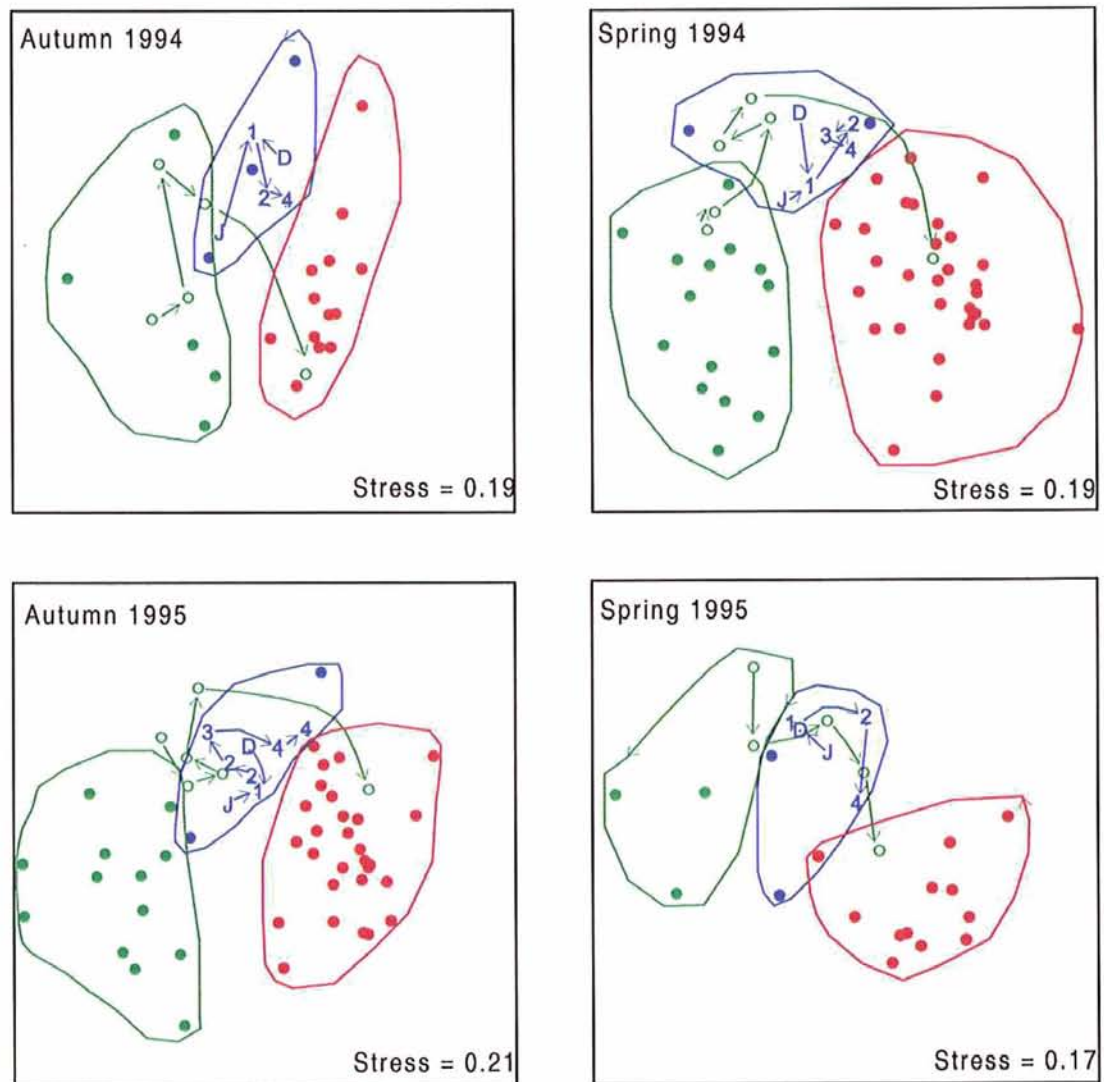


**Figure 37.** Floating mass of *Azolla filiculoides* in the Maribyrnong River at Sydenham on 10 June 1999.



**Figure 38.** Confluences of the Maribyrnong River with urban tributaries on 11 June 1999, after ~15mm of rain fell across the lower urban catchment in previous 18 h. *a.* Arundel Ck, just upstream of the confluence; *b.* confluence with Arundel Ck; *c.* Gully draining quarry and road ~50m downstream of confluence with Arundel Ck; *d, e.* confluence with the quarry drain; *f.* confluence with Taylors Ck.





**Figure 39.** MDS ordinations of macroinvertebrate community composition in streams of the Melbourne region in autumn and spring, 1994 and 1995. Filled circles are sites on small streams, separated into three groups: *green*, eastern, low-salinity, rural sites; *blue*, north-western and southern high-salinity rural sites; *red*, sites within the Melbourne metropolitan area. Sites on the Yarra River (*open green circles*) are connected by green arrows from the most upstream site (Reefton in Autumn 1994 and Spring 1995, Woori Yallock in Spring 1994, and Wonga Park in Autumn 1995) to the most downstream site (Dights Falls, just above the head of the estuary). Sites on the Maribyrnong River (*blue alphanumeric symbols*) are connected by blue arrows from Jacksons Ck at Sunbury (*J*) and Deep Ck at Bulla (*D*) to the Maribyrnong at Sydenham (*I*), Calder Hwy (*2*), Brimbank Pk (*3*) and Canning St Ford, just above the head of the estuary (*4*).

## 6.4 Notes from site inspections

### 6.4.1 Sydenham, at the end of Barbiston Rd.

The banks in this reach were largely stable, with a narrow, remnant riparian corridor of eucalypts, largely intact in places, mixed with willows in others. The understorey was dominated by exotics. At a small pumping barrage at this site, willows were growing into the channel. In most sections of the reach, large woody debris was present. A diverse assemblage of macrophytes and attached algae grew in shallow parts of the channel. A group of platypus was resident in this reach. The floating fern, *Azolla filiculoides*, was common in the littoral zones, and at a constriction in the channel, a large mat of *Azolla* covered the entire channel (Figure 37).

The dominance of exotic riparian vegetation compromises the ecological integrity of the reach. In-stream community composition was typical of streams in the rural north-west of Melbourne. However, high nutrient levels, largely arising from the Sunbury STP, make this reach vulnerable to nuisance macrophyte growth during low-flow periods. Mats such as those pictured in Figure 37 are likely to cause severe local loss of habitat and disruption to normal in-stream ecological processes.

### 6.4.2 Ionnadis farm, at the end of McNab's Rd

Riparian vegetation was very poor in this reach with few remnant Eucalypts, and highly disturbed understorey. This area is probably typical of the parts of the river described by Fisher (1999) as being "a degraded, yet at least partially stable environment".

### 6.4.3 Around Arundel Rd bridge

The works in this area appear to have achieved the aim of bank stability. The planting of the banks with indigenous plants is likely to achieve at least a partial local restoration of an allochthonous source of organic matter to the instream food web. The success of the fishway on the Arundel weir is being assessed as part of another study (Raadik, 1997).

### 6.4.4 The Arundel Ck confluence and the rock quarry downstream

The effect of Arundel Creek on the Maribyrnong requires assessment. Although land use in the Arundel Ck catchment is largely agricultural, its headwaters drain Melbourne Airport, which may be providing polluted runoff. In one moderate rain event, the suspended solids load of Arundel Creek appeared small compared to the small gully further downstream. Runoff from this gully, which drains a rock quarry and an unsealed road, requires treatment or containment. This sort of sediment source is a possible cause of observed elevated suspended solids concentrations through this section of the river.

Riparian vegetation in this reach consists of remnant eucalypts and a largely exotic understorey. Some of the eucalypts on the floodplain side of the river are dead or dying, most likely due to agricultural practices (Fisher, 1999). The pumping barrage at this site is associated with willows growing in aggrading areas in the channel.

### 6.4.5 Flora St Keilor

Deltas of fine sediment near the bridge on Flora Street, and at the quarry pumping station upstream, suggest that this quarry is also a source of sediments to the river. The drain from the Keilor Freeway is likely to be a significant source of pollutants. Macroinvertebrate community composition in this reach was similar to the degraded community at Canning St ford in the drought year of 1994, but was more similar to the community at Sydenham in 1995.

### 6.4.6 Brimbank Park to Canning St ford

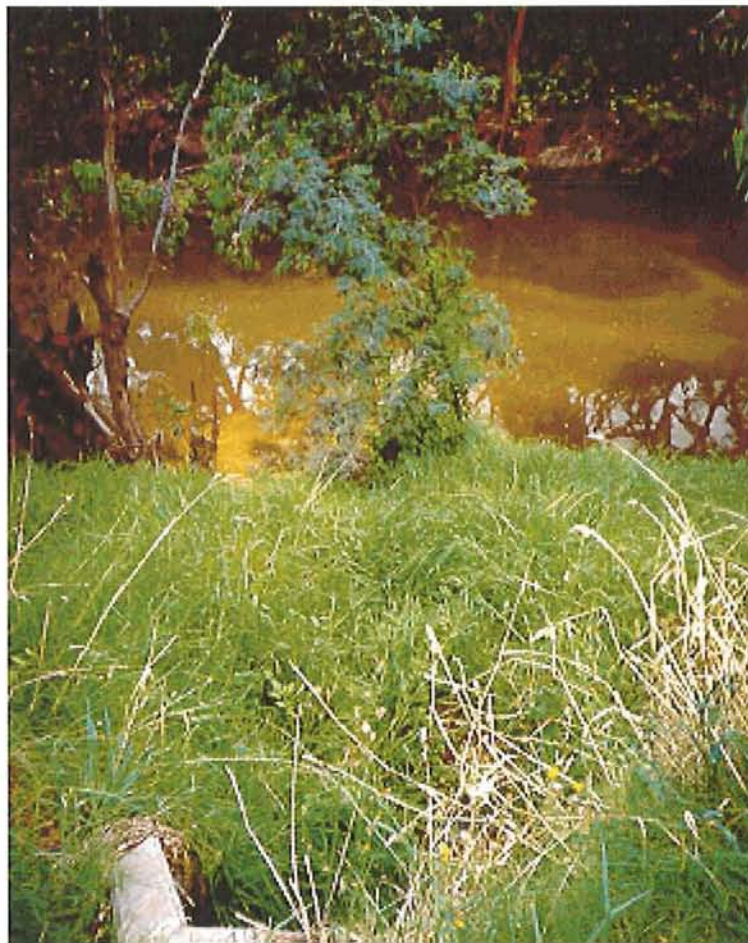
In this section of the river, the greatest source of degradation of instream condition is likely to be run-off from Taylors Creek and urban stormwater drains emptying directly into the river (Figure 40). Most of the stormwater drains descend steeply into the river, although at least



one (at Thompson St reserve, Avondale Heights) crosses a floodplain before entering the river, and may be a candidate for a pollution control pond. The gullies draining the Mountain View quarry at McIntyre Rd Kealba may also cause an impact.

A feature of this section is a number of areas of floodplain which have the potential to be restored through weed control and re-planting. Inundation of the floodplains between the Canning St ford and the railway trestle bridge would present no flooding danger to buildings. Connection between these floodplain areas and the river during floods should be encouraged.

Further physico-chemical and biological monitoring of the lower Maribyrnong River at a greater spatial intensity than current monitoring programs is required after the closure of the Keilor STP to permit clear differentiation of impacts that were caused by the plant, and those of urban runoff.



**Figure 40. Drain located 20 m downstream of the Trestle Bridge (left bank) contributing turbid runoff to the Maribyrnong River during low flow on 11<sup>th</sup> March 2000.**

## 6.5 Conclusions

Based on macroinvertebrate community composition, the lowland Maribyrnong River is in relatively good condition for an urban lowland river, certainly relative to the Yarra River, which is severely degraded by the time it reaches its estuary. Relatively undisturbed lowland river communities in urban settings are quite rare. Thus the Maribyrnong is a valuable scientific resource, in addition to its obvious values as a community resource.

Because the biotic communities of the Maribyrnong River are not severely disturbed, local-scale improvements to habitat and water quality are more likely to have measurable results in community recovery than in severely degraded systems. In severely degraded streams,

multiple disturbances acting synergistically are likely to confound the potential success of local-scale restoration efforts.

Three major groups of disturbance have been identified as potential degrading processes to the Maribyrnong River ecosystem:

**1. Land uses leading to bank and channel instability, and poor quality runoff in the Keilor floodplain area**

The local stabilization works that have been conducted in the last few years have reduced the area of exposed bank material, thereby reducing the contribution of sediment from the river banks. However, the contribution of bank material from this area as a percentage of the total material transported as suspended solids is unknown. It should be remembered that the riparian vegetation of the river in the alluvial Keilor reach was disturbed during the early years of European settlement, and is probably in better condition now than it was during the late 1800s and the early 1900s. It is doubtful that erosion is a major source of degradation to the instream habitat in this area, because the macroinvertebrate community does not show evidence of major disturbance.

There are still areas of unvegetated banks in the Keilor valley area that could be rock beached, but this may represent poor value for money. Control of runoff from soil quarries would reduce localised concentrated sediment inputs to the river. This is regarded as a matter of high priority.

Weed control and indigenous replanting in the more stable reaches of the Keilor valley can probably afford to remain lower priority given landowner indifference or worse (Fisher, 1999). The impact of Arundel Creek on the water quality of the Maribyrnong River requires assessment before recommendations on the most appropriate management approaches for this tributary can be made.

**2. High nutrient loads**

Nutrients enter the Maribyrnong River from many sources, but the most effective way to reduce loads would be improvements to the quality of effluent from the Sunbury STP. Pollution control measures on urban stormwater drains would likely be the next most effective approach to nutrient reduction in the lower Maribyrnong River.

**3. General urban stormwater pollution**

Perhaps the greatest threat to the lower Maribyrnong River remains expansion of urban settlement in the lower catchment, and the inevitable increase in urban stormwater runoff. The importance of source control in urban developments cannot be overstated. The feasibility of pollution control ponds on existing drains should be investigated. Monitoring of the lower Maribyrnong River and its drains is required at a greater spatial intensity than current monitoring programs to determine priorities for pollution control.



## 7 River Management Problems and Suggested Actions

### 7.1 Major management issues

In general, the Maribyrnong River above the Railway Trestle Bridge is in better condition than most other lowland rivers in the Melbourne Water area. This is largely because the headwaters are forested and the bulk of the catchment is rural land use. There are some urban areas in the catchment, and agriculture is practiced on the rich but narrow and relatively scarce alluvial flats. The lower parts of the catchment were settled and cleared 150 years ago, so there is a long history of land use impacts on the stream system. Early photographs indicate that the catchment and riparian zone was affected by extensive tree clearing at least 100 years ago. In fact, the current density of riparian vegetation, although poor in many places, represents a vast improvement on the situation that prevailed in the 1930s.

The Maribyrnong River is one of the two largest rivers in Victoria draining a basaltic catchment. The two main geologies represented in the Melbourne Water area are Silurian sediments to the east, and basalts to the west. The Silurian catchments and streams have received more attention in terms of understanding water quality, ecology, hydrology and geomorphology. The basalt catchments have quite different characteristics, and groundwater is a prominent but poorly understood feature. The Maribyrnong River, being in reasonably intact ecological condition, offers good opportunities for characterising the processes operating in basaltic catchments.

#### 7.1.1 Catchment land use impacts

Catchment runoff and sediment supply probably both increased following intensive development of the catchment in the early phase of settlement, but the major changes would have taken place in the early 1900s. There is no evidence in the available hydrological records that more recent land use changes have altered flooding patterns.

Increasing urbanisation will impact the runoff regime, by increasing the area of impervious surface. However, the impact of this on the Maribyrnong River will be small because the bulk of the river's runoff is sourced from the non-urban headwaters, and the area of urbanised land will never be a very high percentage of the total catchment area. Urbanisation and associated road construction will impact local tributaries, but their contribution to total discharge in the Maribyrnong River will always be minor.

Land use changes do have the potential to impact water quality. Urbanisation is known to increase nutrient and suspended solids loads. The Sunbury sewerage treatment plant appears to be a concentrated source of nutrients. Stormwater drains currently contribute polluted water to the Maribyrnong River and lower the quality of the habitat. This problem is likely to worsen as urban development proceeds.

Agriculture has been conducted on the alluvial river flats for many years. This practice probably elevates sediment and nutrient loads to the river to some degree, but this does not appear to be a serious issue. Stripping of bare floodplain soils probably occurs during major events.

The Maribyrnong River channel is incised, with localised overtopping occurring during the 1:2.5 year ARI event. More extensive inundation of the Keilor floodplain occurs for floods greater than the 1:10 year ARI event (e.g. Nov 1971 and Oct 1983 flood level). Widespread flooding occurs for floods greater than the 1:50 year ARI event (e.g. May 1974 flood level). The floodplain is cleared and has a low roughness coefficient, so that 1:50 year ARI flood flows overtopping the channel near Arundel Road, crossing south-east and re-entering near the Calder Freeway, could reach velocities sufficient to strip the floodplain soil, and threaten an avulsion. The slope of the floodplain across this area is about 0.005. The same risk applies to the meander bend upstream of Flora Street, where a soil quarry is currently operating, and the grassed right bank floodplain on the bend downstream of Flora Street, but for smaller floods of around 1:2.5-1:10 year ARI.

There appears to be a problem with drainage of stormwater runoff from the bare soil areas, as highly turbid water was observed in drains leaving the quarry below Arundel Creek and the



Flora Street soil quarry. The cleared floodplain land about 1 km upstream of the Trestle Bridge (right bank) slopes towards the Maribyrnong River and is likely to be a source of suspended solids during storm events. A few hay bales have been placed near the main drainage entry point, but their effectiveness is unknown.

### 7.1.2 Riparian vegetation disturbance

The original vegetation would have added considerable strength to the bank material. The channel would have had a high loading of large woody debris, which would have added stability to the bed. Although the Maribyrnong River would always have been fairly active in its alluvial sections (due to high stream power and active geological downcutting), disturbance of the riparian vegetation would have accelerated the rate of channel change.

The density and quality of riparian vegetation is highly variable throughout the Maribyrnong River. Some sections have very degraded vegetation, where native vegetation has been cleared intentionally by landholders and the banks invaded by weed species. This type of vegetation probably offers some degree of stability to the bank, but it does not contribute quality large woody debris to the stream.

Some sections of the river have excellent quality riparian vegetation, although it is restricted to a narrow strip along the bank. This vegetation is particularly impressive in the Brimbank Park area. This part of the channel is a clear demonstration of the potential for recovery of native vegetation in the space of approximately 25 years.

Vegetation planted in association with some of the channel stabilisation works conducted in the early to mid-1990s has also shown an impressive rate of growth and colonisation, especially considering the relatively dry climatic conditions that have prevailed over this period.

### 7.1.3 Channel instability

The Maribyrnong River is an incised stream, but this has been an active process for thousands of years. The bed of the stream is bedrock controlled, with numerous rocky outcrops acting to slow the incision rate. The bed of the stream has also been extensively stabilised by small weirs and grade control structures.

Bank erosion has been identified as a major problem in previous investigations, and considerable resources were applied during the 1980s and 1990s to control the sites that were judged to be most active. Despite the widespread perception that erosion in the Maribyrnong River is a serious problem, there is very little objective evidence available to support this view. The river has not changed its course since 1931, and only three sites showed clear evidence of significant meander bend migration (in the order of 10-20 m in 60 years).

The Maribyrnong River is a geomorphologically active stream in the incised, meandering alluvial reaches around Keilor. Although claims have been made by locals that the rate of erosion increased during the 1980s, there is no evidence to support this claim. In fact, it is possible that the rate of erosion slowed in this period in response to construction of grade control structures and rock beaching of banks in many places. Also the riparian vegetation has probably improved over this period. Stabilisation of banks with rock sometimes has the effect of shifting the point of attack downstream, rather than halting erosion. This could explain the local perception of worsening erosion.

The rate of bank erosion is unknown (there are no cross-sections available for comparison), but is probably in the order of 1-2 m per major flood event on the concave side of particular meander bends. The sites rated by Camp Scott Furphy (1990) as having the most severe erosion were subsequently stabilised. The works involved bank battering and protection using large rocks, and the more recent works incorporated native vegetation. Inspection of the sites in 1999-2000 revealed that the works have been entirely successful in stabilising the banks. The works appear to have been designed to withstand large floods, although to date the river has not experienced a period of major flood events.

Some sections of the Maribyrnong River (especially the reach 12.0-14.2 km chainage, upstream of Arundel Rd weir) currently have vertical or near-vertical banks. These sites probably erode to some extent during flood events, but the rate of bank migration is unknown.



The 11 cross-sections established as part of this study will provide a benchmark from which to determine future bank migration rates. The Arundel Rd to Browns Rd reach of the study area had the highest potential for rapid bank migration. Bankfull stream power in this area is well above  $50 \text{ Wm}^{-2}$ , so erosion should be expected during moderate and large flood events. Stream power is also quite high in the upper reaches of Brimbank Park. The alluvial section just upstream and downstream of the gauging weir has a high potential for erosion in terms of stream power, but this is cancelled to some extent by the channel's relatively straight alignment and dense vegetative cover on the banks.

There is a small risk of channel avulsion in the alluvial floodplain reach. Two small sections of channel were cutoff during the early period of settlement, so this process is not unknown here. The most likely location for channel cutoff is the bend near Flora Street, which has been cleared for soil mining, and the grassed bend below Flora Street. The other naturally likely location, the narrow neck of land near Arundel Rd, upstream of Arundel Weir, was recently stabilised with large rock.

#### 7.1.4 Fish passage

Fish passage has been recently improved by installation of fishways at Arundel Weir and weirs in Brimbank Park. There are numerous small weirs and grade control structures in the river that were not designed with allowing fish passage in mind. However, the grade control structures are low, and lack of maintenance of the weirs has resulted in their degradation, so that fish passage would be available for medium and high flows. Scott (1993) was of the opinion that three weirs above Arundel Weir (McNabs, Koroneos and Milburns Weirs) presented a barrier to all but short-fin eel and two species of lamprey.

### 7.2 Suggested management priorities

Bank erosion is a problem in two respects: landowners are concerned about loss of productive land, and the entrained sediment enters the fluvial system causing degraded water quality and deposition of sediment on habitats. The impact of bank erosion on substrate habitat quality is probably minor, as the macroinvertebrate community is in a fairly healthy condition despite bank erosion being a characteristic of this river for many years.

Water quality records suggest that the Maribyrnong River does not export an exceptionally high load of suspended sediment compared with some other rivers in the Melbourne Water area. Continued bank stabilisation works may be justifiable in terms of protection of private land or assets, but this would require a cost-benefit analysis.

The weight of evidence gathered during the course of this study points to the conclusion that a large investment in further bank stabilisation works would represent poor value for money in terms of expected waterway health benefits.

Some of the small weirs located on the river create pools that were once used for pumping irrigation water at times of very low flow or cease-to-flow conditions. It is recommended that Melbourne Water negotiate with landholders to repair or remove weirs where necessary (flow releases from Rosslynne Reservoir may now be sufficient to supply irrigation water without the weirs). The involvement of Melbourne Water in the weir repair process will ensure that fish passage is maintained. Disused weirs do not require any treatment. The weirs help to stabilise the bed, but Milburns, Koroneos and McNabs Weirs may interfere with fish passage. The recommendations of Scott (1993) should be used as a basis for reconstructing these weirs. The grade control structures are in good condition and do not require attention at this time.

The riparian vegetation is in poor to very poor condition in some of the areas that are used for intensive agriculture. Landholders have historically shown a reluctance to support re-establishment of the riparian zone. It is recommended that Melbourne Water continue to work with landholders to improve riparian vegetation, as this will bring environmental benefits, and should improve bank stability. The margins of the side-slopes and terraces (sometimes distant from the channel) are subject to potentially erosive flows during very large events (in the order of 1:50 year ARI), and the stability of these areas would be enhanced by re-vegetation.

Ecologically, the Maribyrnong River is in a relatively good condition, which is rare for a lowland river close to Melbourne. Thus, the river represents a valuable ecological resource

and should be managed as such. The major threat to the river's ecology appears to be poor quality runoff from urban stormwater drains, and turbid runoff from quarries located close to the river. Arundel Creek drains Melbourne Airport and is a possible source of contamination, but lack of data prevents assessment of this issue.

Stormwater runoff from future urban development in the catchment must be managed with tight controls on water quality. Urban stormwater probably represents the biggest threat to the integrity of the river.

The Maribyrnong River channel is incised, with localised overtopping occurring during the 1:2.5 year ARI event. More extensive inundation of the Keilor floodplain occurs for floods greater than the 1:10 year ARI event (e.g. Nov 1971 and Oct 1983 flood level). Widespread flooding occurs for floods greater than the 1:50 year ARI event (e.g. May 1974 flood level). The floodplain is cleared and has a low roughness coefficient, so that 1:50 year ARI flood flows overtopping the channel near Arundel Road, crossing south-east and re-entering near the Calder Freeway, could reach velocities sufficient to strip the floodplain soil, and threaten an avulsion. The same risk applies to the meander bend upstream of Flora Street, where a soil quarry is currently operating, and the grassed right bank floodplain on the bend downstream of Flora Street, but for smaller floods of around 1:2.5-1:10 year ARI.



## 8 Recommendations, Management Actions and Costs

### 8.1 General recommendations

1. Having relatively undisturbed hydrology and water quality, and being one of the few large basaltic plain streams in Victoria, the Maribyrnong River represents a valuable ecological resource and should be managed as such.
2. Eleven established cross-sections should be surveyed following events exceeding the 1:2 yr ARI flood event ( $225 \text{ m}^3 \text{ s}^{-1}$ ). The survey data should be plotted and compared with previous surveys to monitor the bank migration rate.
3. The most effective way to reduce nutrient loads would be improvements to the quality of effluent from the Sunbury STP. Pollution control measures for urban stormwater and freeway runoff would likely be the next most effective approach to nutrient reduction in the lower Maribyrnong River.
4. Source control of urban nutrient and sediment pollution is a high priority action. There may be opportunities for construction of wetlands for the purpose of stormwater treatment. New developments must be planned using water sensitive urban design principles.
5. Control of runoff from soil quarries and market gardens would reduce localised concentrated sediment inputs to the river. This is regarded as a matter of high priority.
6. The impact of Arundel Creek (which drains part of Melbourne Airport) on the water quality of the Maribyrnong River requires assessment before recommendations on the most appropriate management approaches for this tributary can be made.
7. It is recommended that Melbourne Water negotiate with landholders to repair or remove low level weirs where necessary. This process will ensure that fish passage is maintained. Disused and heavily degraded weirs do not require any treatment.
8. Melbourne Water should continue to work with landholders to improve riparian vegetation, as this will bring environmental benefits, and may improve bank stability. However, the history of landholder indifference or opposition to this strategy means that it may be a low priority due to the high level of effort that would be required to achieve success.
9. The weight of evidence gathered during the course of this study suggests that a large investment in further bank stabilisation works would currently represent poor value for money in terms of expected river health benefits. Channel works should be directed towards the long-term management time frame.
10. There is a risk of localised floodplain soil stripping for floods >1:5 year ARI, with much of the Keilor floodplain under threat for floods of around 1:50 year ARI. There is a risk of avulsion during these large floods. Current land use practices (market gardening and soil quarrying) increase the risk because they maintain low floodplain surface roughness and vegetative cover. Any floodplain development proposals must consider this serious risk.
11. Re-vegetation of the margins of the side-slopes and terraces would enhance the stability of these areas under infrequent, but potentially catastrophic, large flood conditions. This type of revegetation may be considered by landholders to be incompatible with the current land use. This recommendation relates to long-term planning; any major change in land use on the floodplain should involve seeking opportunities to increase floodplain stability and roughness, and the best method is re-vegetation.
12. Future geomorphic investigations should attempt to establish erosion rates, or model erosion potential. It is risky to base large investments on subjective visual assessment of erosion severity.

## 8.2 Reach-by-reach management actions and estimated costs

### 8.2.1 Priorities for management action

Priorities for the recommendations below were allocated according to the subjectively judged relative environmental, social and economic benefits that could be realised from their implementation. The three level priority ranking of Neil M Craigie Pty Ltd (1998) was used, although the descriptors 1, 2, and 3 were replaced by high, medium and low. A fourth category termed "Very high" was used to describe actions that are necessary to provide information for decision making on other actions:

- **High priority**

Actions relate to issues of concern at state or higher level, or the problem has a very high potential for escalating and imposing higher costs for correction, and prompt action is required.

- **Medium priority**

Actions relate to issues of concern at regional level. Action is required early in the works program.

- **Low priority**

Actions relate to issues of concern at local level. Action is not urgent but should be taken over the timeframe of the works program.

### 8.2.2 Catchment above Jacksons and Deep Creek junction

Item	Description	Priority	Quantities	Costs
1.	Investigate possibility of reduction of nutrient concentration in effluent from Sunbury Sewerage Treatment Plant	High	Investigation	\$5,000
2.	Any urban development and road or freeway development to require water sensitive design that minimises hydrological and water quality impacts	High	On-going enforcement of policy	-

### 8.2.3 Deep Creek and Jacksons Creek junction to Browns Road (21.7 km to 14 km chainage)

Item	Description	Priority	Quantities	Costs
1	Outside of meander bend at 14.1 km chainage has high potential for erosion. However, historical erosion rate has not been high. Also, banks are very high and steep, so cost to stabilise with rocks would be high. Alternative recommendation is to establish cross-section at 14.1 km chainage to determine bend migration rate, as locals report problematic erosion at this site	High	1 of 2 new cross-sections @ \$2,000 total	\$1,000
2	McNabs Weir is in relatively good condition but causes some local downstream bank erosion. Recommend that in consultation with landowners, rebuild with rock, using technology that allows fish passage	Medium	Repair/reconstruct weir & banks	\$25,000



3	Koroneos Weirs is in a state of disrepair, with some local downstream erosion on the left bank. Recommend that in consultation with landowners, rebuild with rock, using technology that allows fish passage	Medium	Repair/reconstruct weir & banks	\$20,000
4	Remove willows and other weed species (e.g. boxthorn) and replace with native trees and understorey where required	Medium	4 km @ \$20,000/km	\$80,000

#### 8.2.4 Browns Road to Arundel Road (14.0 km to 12.0 km chainage)

Item	Description	Priority	Quantities	Costs
1	Outside bends between at 13.43 km and 12.05 km chainage have migrated in historical times and currently have high potential for erosion. Six cross-sections were established in this reach in 1999 (at 13.43, 13.0, 12.76, 12.60, 12.52 and 12.29 km). Re-survey after 1:2 yr ARI flood events is recommended. Rock stabilisation should only be considered in the future if erosion rate unacceptable	Very high	6 cross-sections to re-survey @ \$500/site	\$3,000/2 yr
2	Inside of bend from 13.8 km to 13.4 km chainage has evidence of a previous fairly recent erosion event (within 10 years). Outside of bend is rock confined. Recommend establish cross-section at 13.6 km chainage to determine bend migration rate, as locals report problematic erosion at this site	High	1 of 2 new cross-sections @ \$2,00 total	\$1,000
3	Monitor the rock stabilisation works between 13.1 km and 12.25 km chainage after 1:2 yr ARI flood events. This area has a high natural potential for meander cutoff, but rock works constructed in 1990s should reduce chance of avulsion. Repair rock works if damaged	High	Inspect	\$500/2 yr
4	This reach has poor quality riparian vegetation. Melbourne Water should establish a cooperative strategy with landholders to remove weeds, and revegetate with native trees and understorey. In the long-term this will assist bank stabilisation and improve habitat	Medium	2 km @ \$28,000/km	\$56,000
5	Milburns Weir (13.8 km chainage) is in a state of disrepair, with some local erosion on the right bank. Recommend that in consultation with landowners, rebuild with rock, using technology that allows fish passage	Medium	Repair/reconstruct weir and banks	\$20,000

**8.2.5 Arundel Road to Calder Freeway (12.0 km to 8.9 km chainage)**

Item	Description	Priority	Quantities	Costs
1	Five cross-sections were established in this reach in 1999 (at 11.27, 11.01, 10.75, 9.62 and 8.99 km). Re-survey after 1:2 yr ARI flood events is recommended. Rock stabilisation should only be considered in the future if erosion rate unacceptable	Very high	5 cross-sections to re-survey @\$500/site	\$2,500/2 yr
2	Conduct investigation of water quality of Arundel Creek, focussing on stormwater sampling, and including analysis for heavy metals, and petrochemical pollutants	High	2 yr study	\$50,000
3	Investigate the drainage at the Flora Street soil quarry located on the left bank at 9.6 km to 10.0 km chainage. Negotiate with quarry operator to conduct works to prevent overland flow across disturbed surface directly into river	High	Investigation	Initial inspection \$2,000 (allow \$10,000 for possible works)
4	Soil is disturbed too close to the river's edge at the Flora Street soil quarry, risking bank erosion, and contributing sediment runoff directly to the river. It is recommended that a vegetative buffer strip (native trees and understorey) be established 10 m wide from the bank edge	High	0.5 km @ \$15,000/km	\$7,500
5	Investigate the drainage at the two rock quarries (Callega and Somerset) located on the left bank at 11.3 km and 11.0 km chainage. Prevent overland flow across disturbed surface directly into river by rehabilitating quarries	Medium	Investigation	Initial inspection \$2,000 (allow \$10,000 for possible contribution to works)
6	The left bank area below Arundel Rd stabilised for geotechnical reasons (chainage 11.8-11.9 km) should be monitored for stability every two years	Medium	Investigation	\$500/2yr
7	This reach has poor quality riparian vegetation. Melbourne Water should establish a cooperative strategy with landholders to remove weeds, and revegetate with native trees and understorey. In the long-term this will assist bank stabilisation and improve habitat	Medium	3 km @ \$28,000/km	\$84,000



8	The drain passing under Arundel Rd on the left bank at 11.8 km is a source of organic waste. Also, there is a possibility that the lower open section of drain will erode the river bank. It is recommended that Melbourne Water negotiate with the landholder to discourage the flushing of wastes into this drain. The drain should be inspected every 2 years for erosion	Low	Investigation	Initial inspection \$1,000 plus \$500/2yr
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### 8.2.6 Calder Freeway to Trestle Bridge (8.9 – 0.0 km chainage)

Item	Description	Priority	Quantities	Costs
1	Drainage lines, about 1 km above the Trestle Bridge, that lead directly to the river from the right bank require the establishment of vegetative buffer strips to prevent entry of suspended solids during runoff events	High	allow for treatment of 2 sites @\$2,000/site	\$4,000
2	The urban catchment drainage system presents a serious hydrological and water quality threat to the river. MW should investigate opportunities to reduce runoff and pollution from urban areas (note: this action is included as part of Taylors Creek Waterway Activity Plan – currently underway)	High	Investigation	Included in WAP
3	Gullies draining quarries located on the high right bank should be investigated to determine their contribution of suspended solids to the river	Medium	Investigation	\$3,000
4	The channel in Brimbank Park has reasonably high quality riparian vegetation, and the banks and bed appear stable. This reach only requires periodic visual inspection and response to problems as they arise	Low	Inspection	\$500/2yr

### 8.2.7 Trestle Bridge to Canning Street

Item	Description	Priority	Quantities	Costs
1	Most of the stormwater drains descend steeply into the river, although at least one (at Thompson St reserve, Avondale Heights) crosses a floodplain before entering the river, and appears to be a candidate for a pollution control pond. It is recommended that Melbourne Water investigate the opportunities for pollution control ponds in this area	High	Investigation and design (construction provisional)	\$8,000 allow \$150,000 for construction (provisional)

2	A feature of this section is a number of areas of floodplain which have the potential to be restored through weed control and re-planting. Inundation of the floodplains between the Canning St ford and the railway trestle bridge presents no flooding danger to buildings, but it holds potential for water quality and ecological benefits. MW should investigate the possibility of re-connecting these floodplain areas and the river for high frequency events (1:1 to 1:2 yr ARI), and re-establishing the floodplain ecology	Medium	Investigation and design (construction provisional)	\$10,000 allow \$200,000 for construction (provisional)
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### 8.2.8 Water quality and biological monitoring

Further physico-chemical and biological monitoring of the lower Maribyrnong River, at a greater spatial intensity than current monitoring programs, is required to permit clear differentiation of relative importance of various land uses and channel management regimes, and to monitor impact of future works. The results of monitoring will provide valuable information to improve the understanding of natural processes in basaltic catchments.

This monitoring program will help guide future river management decisions. Thus, it is important that the data be analysed and reported every 2 years.

Biological sampling (macroinvertebrates) should be conducted four times per year, and water quality (nutrients and suspended solids) sampled at least once per month. Sample storm event suspended solids transport once per year (15 samples per site per event minimum).

This is a matter of *medium-high* priority.

Suggested monitoring sites for the lower Maribyrnong River (with priority assigned) are:

- Organ Pipes National Park (Jacksons Creek) (**high priority**)
- Bulla (Deep Creek) (existing site macroinvertebrates and water quality) (**high priority**)
- Keilor Golf course, Sydenham (existing site macroinvertebrates) (**high priority**)
- Browns Road, Keilor (chainage 14 km) (*medium priority*)
- Below Arundel Rd weir, Keilor (**high priority**)
- Calder Freeway, Keilor (existing site macroinvertebrates) (**high priority**)
- Brimbank Park Weir (existing site water quality) (**high priority**)
- Trestle Bridge, Keilor East (*medium priority*)
- Canning St ford, Avondale (existing site macroinvertebrates and water quality) (**high priority**)

#### Environmental monitoring costs:

Annual storm event monitoring	\$5,000/yr
Seasonal biological monitoring	\$10,000/yr
Monthly water quality monitoring	\$10,000/yr
Reporting every 2 years	\$4,000/2 yr
Total (annual)	\$27,000



### 8.2.9 Management of low level weirs

Camp Scott Furphy (1990) identified several authorised and unauthorised weirs and fords that were constructed on the Maribyrnong River between the junction of Deep and Jacksons Creeks and the Trestle Bridge in the late 1960s. Currently these weirs are fairly innocuous with respect to geomorphology and fish passage, although they may act as bed stability control points. Most of the weirs are currently in a state of disrepair.

Below Arundel Rd there are many rock grade control structures that act as control points on the bed, and do not appear to prevent fish passage. These structures should be occasionally inspected and repaired as necessary.

It is recommended that Melbourne Water negotiate with landholders to repair or remove weirs where necessary. This process will ensure that fish passage is maintained. Disused weirs do not require any treatment.

An investigation of the issues associated with weir management should be commissioned as a matter of *medium* priority. The sum of \$6,000 should be allocated for this study, the terms of reference which should include: establishment of the current use of the weirs, the ownership (or perceived ownership) of the weirs, fish passage, the stability of the weirs, the landholder attitudes to management of weirs, and recommendations concerning management options including costs. The study of Scott (1993) can be used as a starting point for this investigation.

## 9 Acknowledgments

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## 10 References

- Anon. 1994. National River Processes and Management Program. Monitoring River Health Initiative. River Bioassessment Manual. Version 1.0. Department of the Environment, Sport and Territories; Land and Water Resources Research and Development Corporation; Commonwealth Environment Protection Authority, Canberra.
- Bray, R. 1989. Water Quality Study. Upper Maribyrnong River Concept Plan. Board of Works, Western Drainage and Waterways Section, Melbourne.
- Bray, R. 1989. Water Quality Study: Upper Maribyrnong River Concept Plan, between the Railway Trestle Bridge and the northern boundary of the Organ Pipes National Park. Western Drainage and Waterways Section, Waterways and Parks Division, Board of Works, Melbourne.
- Brookes, A. 1988. *Channelized Rivers: Perspectives for Environmental Management*, John Wiley & Sons, Chichester.
- Brookes, A. 1990. Restoration and enhancement of engineered river channels: some European experiences, *Regulated Rivers: Research and Management* 5, 45-56.
- Brookes, A. and Sear, D.A. 1996. Geomorphological principles for restoring channels. In Brookes, A. and Shields Jr, F.D. (eds) *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley & Sons, Chichester, pp. 75-101.
- Brown, V., and S. Davies. 1989. Biological Study of the Maribyrnong River. Results of Monitoring Program 1980-1982. Board of Works, Environmental Services Section, Melbourne.
- Camp Scott Furphy Pty Ltd 1990. *The Upper Maribyrnong River Erosion Survey, Vol 1 – Report, Vol 2 – Appendices, and Photographic Reference Collection*. Report to Board of Works, Melbourne, Vic.
- Carvalho, C., M. Robertson, and G. Rooney. 1997. The State of Greater Melbourne's Waterways: StreamWatch Annual Report 1996, 39 pp. Melbourne Water, Melbourne.
- Fisher, D. 1999. Urban stream rehabilitation through a decision-making framework to identify degrading processes and prioritize management actions. In I. Rutherford and R. Bartley (eds), *Proceedings of the Second Australian Stream Management Conference*, Vol. 1, Adelaide, S.A. pp. 263-266.
- Hunter, K.M. and Zampatti, B.P. 1994. *Victorian Water Quality Monitoring Network, Annual Report 1993*, State Water Laboratory of Victoria.
- Jenkin, J.F. 1989. Erosion of the Upper Maribyrnong River – Observations between the railway trestle bridge Keilor East, and McNabs Road, Keilor North. MMBW, Melbourne, Vic.
- Jenkin, J.J. 1988. Port Phillip Sunkland, in Douglas, J.G. and Ferguson, J.A. (eds), *Geology of Victoria*. Victoria Division, Geological Society of Australia Inc., Melbourne, Vic, pp. 383-387.
- Ladson, A.R. and White, L.J. 1999. *An Index of Stream Condition: Reference Manual*, Prepared for Waterways Unit, Department of Natural Resources and Environment, 2<sup>nd</sup> Ed. Melbourne, Vic.
- Lewis, C. A., N. P. Lester, A. D. Bradshaw, J. E. Fitzgibbon, K. Fuller, L. Hakanson, and C. Richards. 1996. Considerations of scale in habitat conservation and restoration. *Canadian Journal of Fisheries and Aquatic Sciences*, 53 (Suppl. 1):440-445.
- Melbourne Metropolitan Board of Works 1975a. Maribyrnong River Catchment Preliminary Environmental Study. Position Paper. Revised Draft, November. Prepared by Llewelyn-Davies Kinhill Pty Ltd, Melbourne for MMBW, Melbourne, Vic.
- Melbourne Metropolitan Board of Works 1975b. Report on Flood of May 1974 in the Maribyrnong River Basin. MMBW-D-0001, April, MMBW. Melbourne, Vic.



- Melbourne Metropolitan Board of Works 1976. Report on Flood Mitigation in the Maribyrnong River Basin: a Preliminary Hydrological Study. MMBW-D-0004, June. MMBW, Melbourne, Vic.
- Melbourne Metropolitan Board of Works 1983. Upper Maribyrnong Position Paper (Revised Draft) November. Blake T. (comp.), MMBW, Melbourne, Vic.
- Melbourne Metropolitan Board of Works 1986. Maribyrnong River Flood Mitigation Study. MMBW-D-0040. MMBW, Melbourne, Vic.
- Melbourne Water 1991. Upper Maribyrnong River Concept Plan: Railway Trestle Bridge to Organ Pipes National Park, Main Report. November. Melbourne, Vic.
- Metzeling, L. H. 1990. Biological monitoring of the Maribyrnong River and tributaries using macroinvertebrates, 93 pp. Environment Protection Authority, Victoria, Melbourne.
- Nanson, G.C. and Hicken, E.J. 1986. A statistical analysis of bank erosion and channel migration in western Canada, *Geological Society of America Bulletin* 97: 497-504.
- Schumm, S.A. 1960. The shape of alluvial channels in relation to sediment type, *United States Geological Survey Professional Paper 352B*, 17-30.
- Neil M Craigie Pty Ltd 1998. Fluvial Geomorphology of Steels Creek (Yarra River to Hunts Lane). Report prepared in association with S.O. Brizga for Melbourne Water, Richmond, Vic.
- Pittock, A.B. 1983. Recent climatic change in Australia: implications for a CO<sub>2</sub>-warmed earth. *Climatic Change* 5: 321-340.
- Raadik, T. A. 1997. Maribyrnong River Fishway Project. Phase 1, Pre-Fishway, 30 pp. Marine and Freshwater Resources Institute, Melbourne.
- Richards, K.S. 1982. *Rivers: Form and Process in Alluvial Channels*. Methuen, London.
- Rutherford, I.D. and Walker, M.R. 2000. An Approach to Predicting Rates of Bend Migration for Alluvial Meandering Streams. CRC for Catchment Hydrology, Monash University, Clayton, Vic (in press).
- Schumm, S.A. 1960. The shape of alluvial channels in relation to sediment type, *United States Geological Survey Professional Paper 352B*, 17-30.
- Scott, M. 1993. Upper Maribyrnong River native fish report: a review of the problems concerning native fish fauna. July. Unpublished draft report available from Melbourne Water.
- Sear, D.A. 1996. The sediment system and channel stability. In Brookes, A. and Shields Jr, F.D. (eds) *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley & Sons, Chichester, pp. 149-177.
- Sutherland, R. and Rumble, G. 1988. Maribyrnong River Erosion Survey – Dyson Road, Footscray to Orientation Road, Keilor North. Internal Report, Western Drainage and Waterways Section MMBW, Melbourne, Vic.
- The Federal Interagency Stream Restoration Working Group (TFISRWG) (1998) *Stream Corridor Restoration: Principles, Processes and Practices*.
- Thorne, C.R. 1992. Bend scour and bank erosion on the meandering Red River, Louisiana. In Carling, P.A. and Petts, G.E. (eds) *Lowland Floodplain Rivers: Geomorphological Perspectives*, John Wiley & Sons, Chichester, pp. 96-115.
- U.S. Army Corps of Engineers 1997. HEC-RAS River Analysis System Hydraulic Reference and Users Manual Version 2.0, April.
- Walsh, C. J., and P. F. Breen. 1999. Urban stream rehabilitation through a decision-making framework to identify degrading processes and prioritize management actions. In I. Rutherford and R. Bartley (eds.), *Second Australian Stream Management Conference*, Vol. 2, pp. 673-678, Adelaide, S.A.

- Water Resources Council 1981. Review of Victoria's Water Resources and Utilization. Part 2. Detailed Information Maribyrnong River Basin. Ministry of Water Resources and Water Supply, Victoria.
- White, L.J. and Ladson, A.R. 1999. *An index of stream condition: field manual*, Waterways Unit Department of Natural Resources and Environment, East Melbourne.
- Wilkinson, L. 1996. SYSTAT 6.0 for Windows: Graphics. SPSS, Inc., Chicago, Illinois.