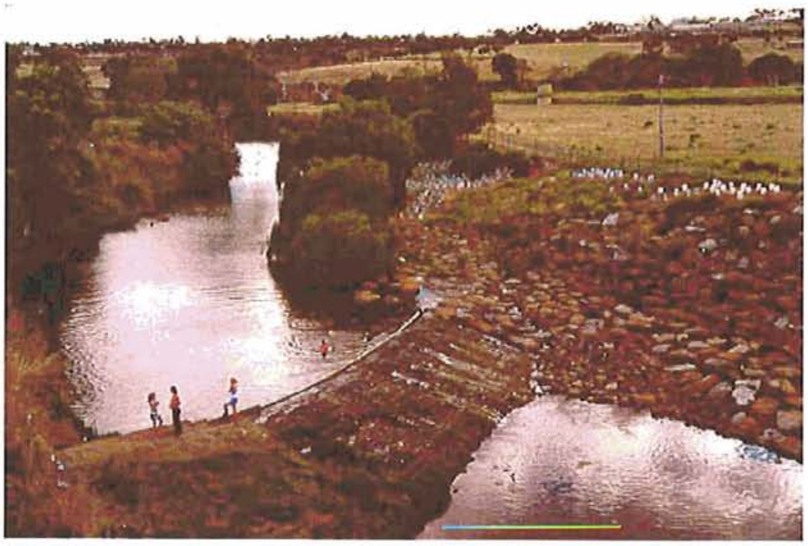
FLUVIAL GEOMORPHOLOGY
RIVER REHABILITATION
ENVIRONMENTAL FLOWS
CATCHMENT HYDROLOGY

Geomorphology of the Maribyrnong River, Victoria



A report prepared for

Melbourne Water

By

Fluvial Systems Pty Ltd

ABN 71 085 579 095

July 2000

FLUVIAL SYSTEMS PTY LTD PO Box 4117 Melbourne University Retail PARKVILLE VICTORIA AUSTRALIA 3052
Tel +61 3 9344 7780 Mobile +61 0411855 573 Fax +61 3 9344 4972 ACN 085 579 095 Email c.gippel@civag.unimelb.edu.au

Geomorphology of the Maribyrnong River, Victoria

A report prepared for

Melbourne Water

By

Fluvial Systems Pty Ltd

ABN 71 085 579 095

Box 4117
Melbourne University Retail
Parkville Vic 3010

Ph 03 83447780
Ph 0411855573
Fax 03 83444972
Email: c.gippel@civag.unimelb.edu.au

Authors:
Dr Christopher J Gippel
Dr Chris Walsh (CRC for Freshwater Ecology, Monash University) contributed Section 6 Ecological Considerationswith minor edits and additions by Chris Gippel.

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

This report should be referenced as follows:
Gippel, C.G. and Walsh C. J. 2000. *Geomorphology of the Maribyrnong River Victoria.* Report prepared by Fluvial Systems Pty Ltd for Melbourne Water Waterways and Drainage Group, East Richmond, VIC.

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 top 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 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 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 ±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 $1million 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 m^3s^{-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 fame.
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.

Table of Contents

1 Introduction

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 top 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 patters;
- 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 x 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 x 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 x 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 x 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. 300-100 x 10^6 yr BP).

Basalts were extruded during the Tertiary (peaking 20-40 x10^6 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 (6-7 x 10^6 yr BP) the Newer Volcanics were extruded over the area, with activity peaking at approximately 2 x 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^2. 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).

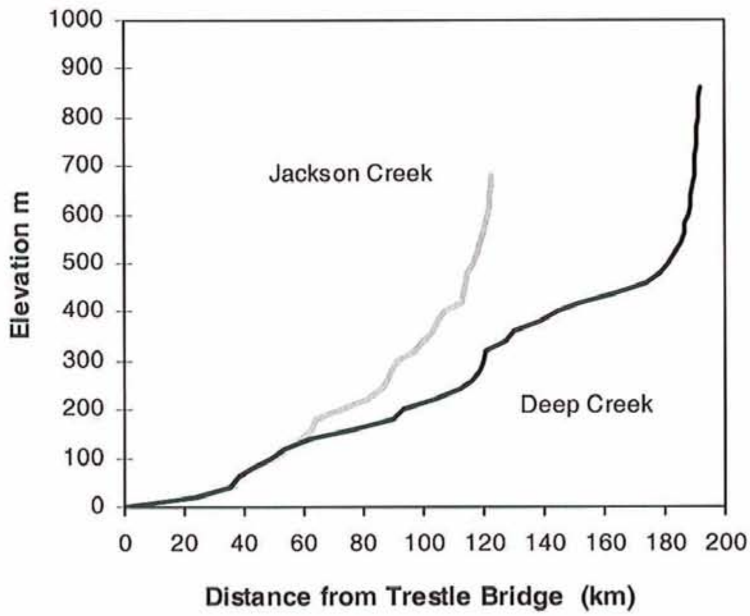


Figure 1. Long profile of Jacksons and Deep Creeks (confluence at approx. 20 km chainage).

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 m^3s^{-1} [note that MMBW (1975b) gives bankfull discharge at 270-320 m^3s^{-1} depending on tidal influence]. Houses, roads and private gardens begin to flood at a flow of 400 m^3s^{-1}, while serious damage occurs at flows above 500 m^3s^{-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 mgL^{-1} at Keilor (N = 90). At Bulla, the maximum reported was 94 mgL^{-1} (N = 41). Using EPA and MMBW data, Bray (1989) reported a maximum value of 440 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 90th 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 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 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 m^3s^{-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[1]	1871-1986[2]	1908-1933[3]	1956-1988[3]
100	ne	840	725	810
50	710	710	635	710
20	520	530	518[5]	571[4]
10	402	400	430	465
5	ne	270	340	365
2	ne	125	220	225

1. WRC (1981) threshold discharge 400 m^3s^{-1}.
2. MMBW (1986) threshold discharge 250 m^3s^{-1}.
3. Camp Scott Furphy (1990) threshold discharge 250 m^3s^{-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 Wm^{-2} above which erosional adjustments dominate, and below which the dominant process is deposition. Straightened channels with bankfull stream power above 35 Wm^{-2} actively restored their sinuosity, while those with stream power below 35 Wm^{-2} did not adjust.

Channels with bankfull stream power between approximately 15 Wm^{-2} and 35 Wm^{-2} are stable, channels with stream power between 35 Wm^{-2} and 100 Wm^{-2} are actively meandering, and channels with stream power above 100 Wm^{-2} are usually braided (or eroding). Below 15 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 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 10-50 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 Wm^{-2}, stream power is expressed as:

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

where

ρ = water density (1000 kg m^{-3})

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

R = hydraulic radius (m)

S = energy slope

V = mean cross-sectional velocity (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 m^3s^{-1}) and 1983 (450 m^3s^{-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 m^3s^{-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 m^3s^{-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 m^3s^{-1} near Koroneos Weir to 450 m^3s^{-1} near the hard rock quarry on the left bank near Milburn Rd. Over most of the reach, the bankfull discharge was between 200 m^3s^{-1} and 300 m^3s^{-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 targetted 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 ≥500 m^3s^{-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 m^3s^{-1} to 710 m^3s^{-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 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 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).

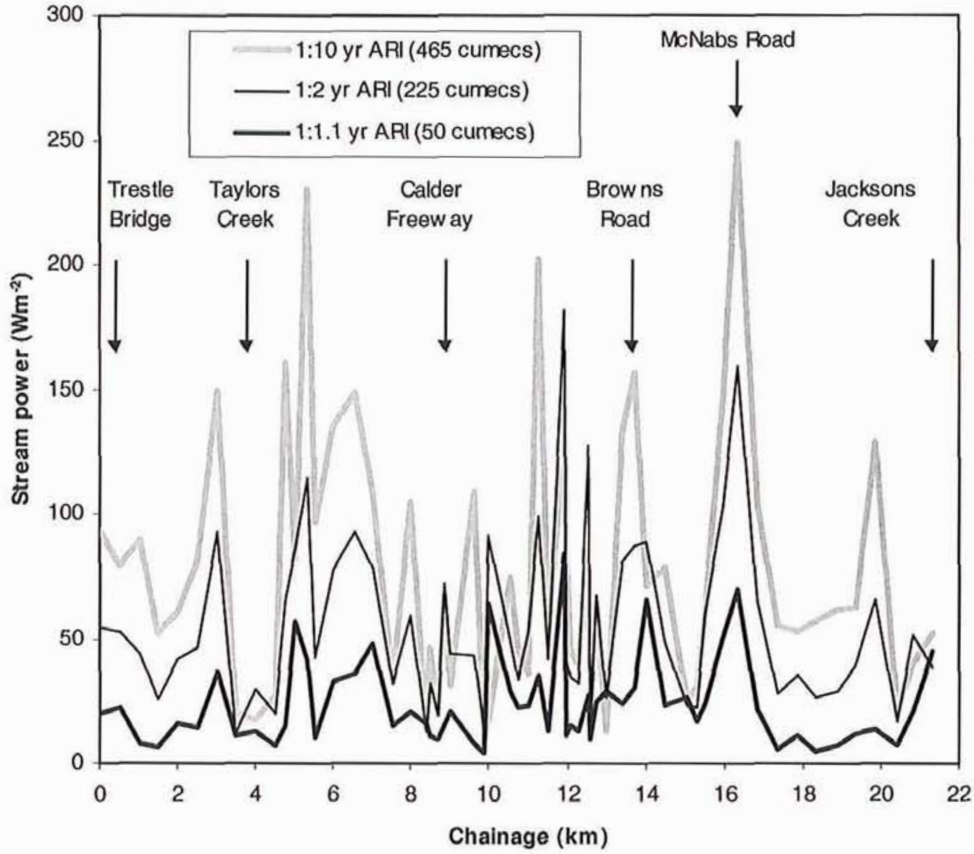


Figure 2. Variation in mean stream power for a range of discharges on the Maribyrnong River between the Trestle Bridge and the junction of Jacksons and Deep Creeks.

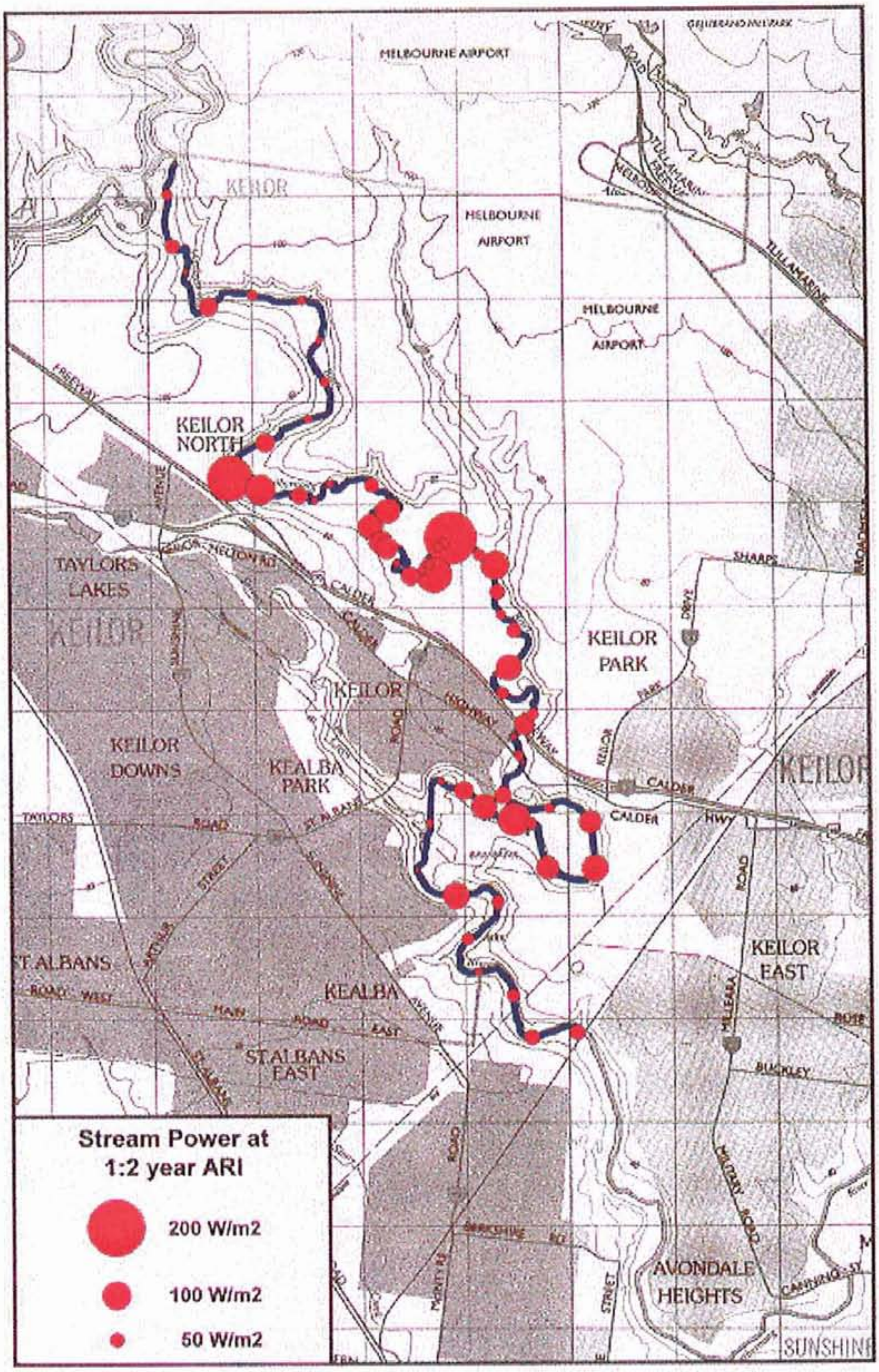


Figure 3. Modelled mean stream power at the 1:2 yr ARI event (225 m^3s^{-1}) at 62 cross-sections on the Maribyrnong River.

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 section 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 13th 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.

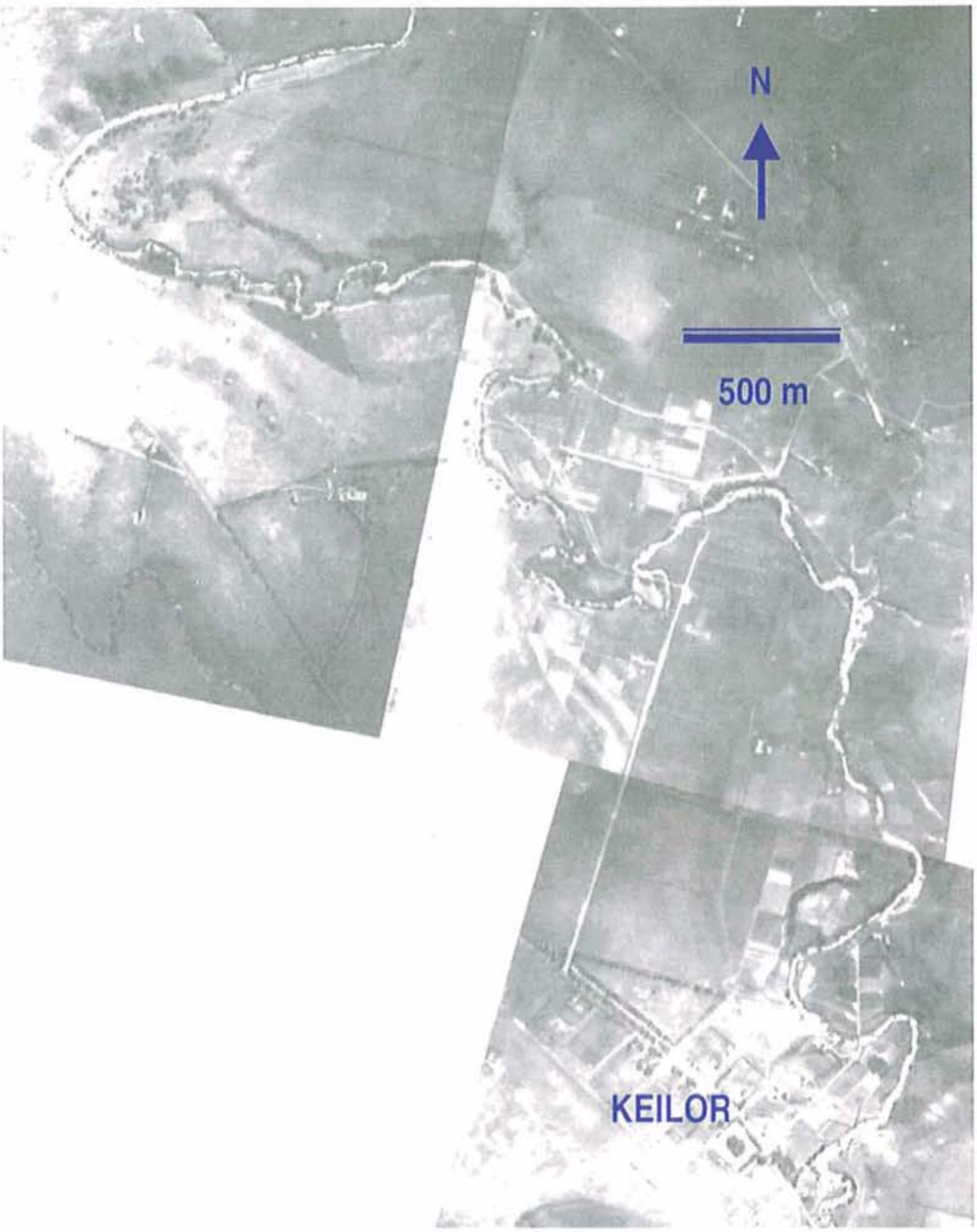


Figure 4. 1931 aerial photograph of Keilor reach of Maribyrnong River (MMBW Aero 2,13/4/1931, Runs 15, 16 & 17. 12:00 hrs No. 03452).

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.

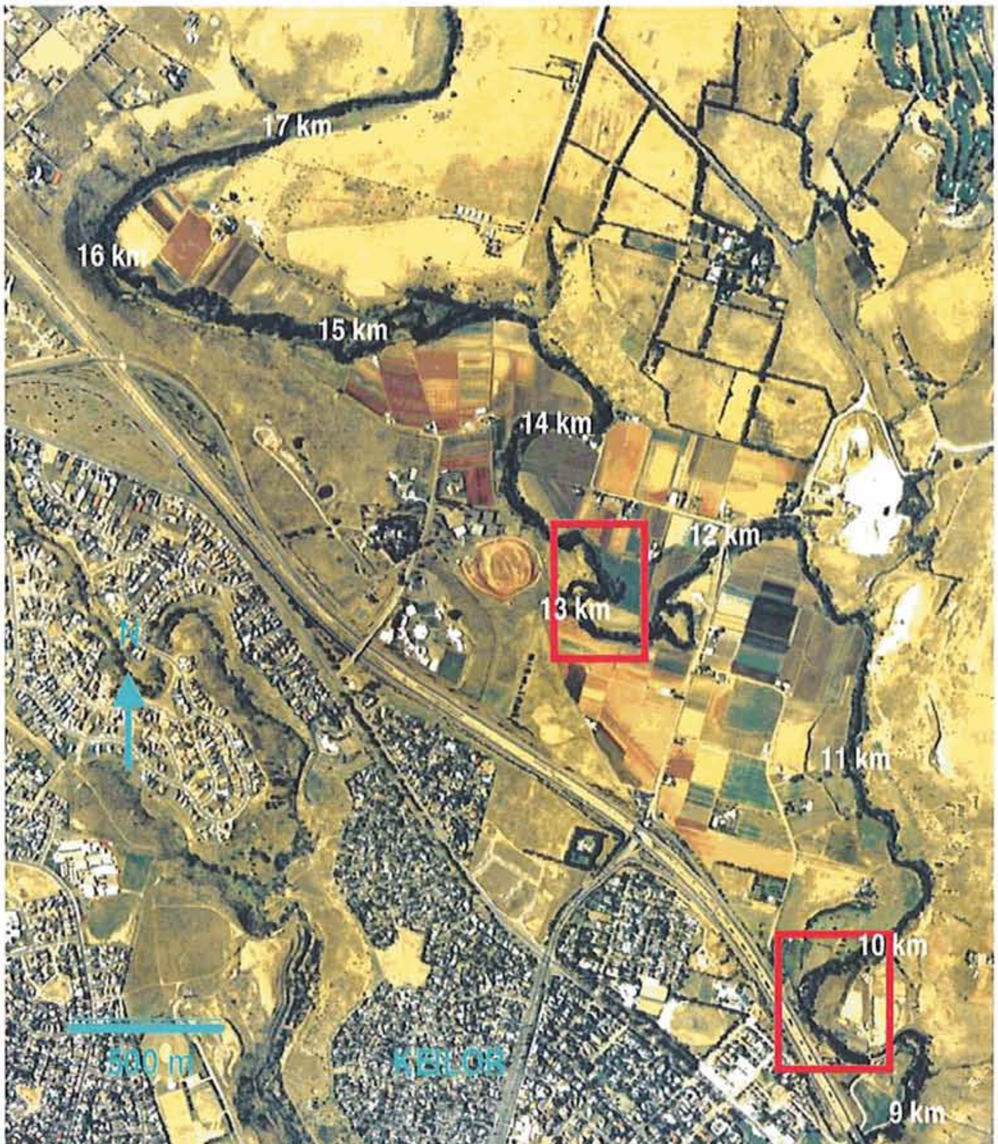


Figure 5. 1993 aerial photograph of Keilor reach of Maribyrnong River. Chainage is zero from Railway Trestle Bridge. Framed reaches are magnified in Figs 25 and 26.

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).

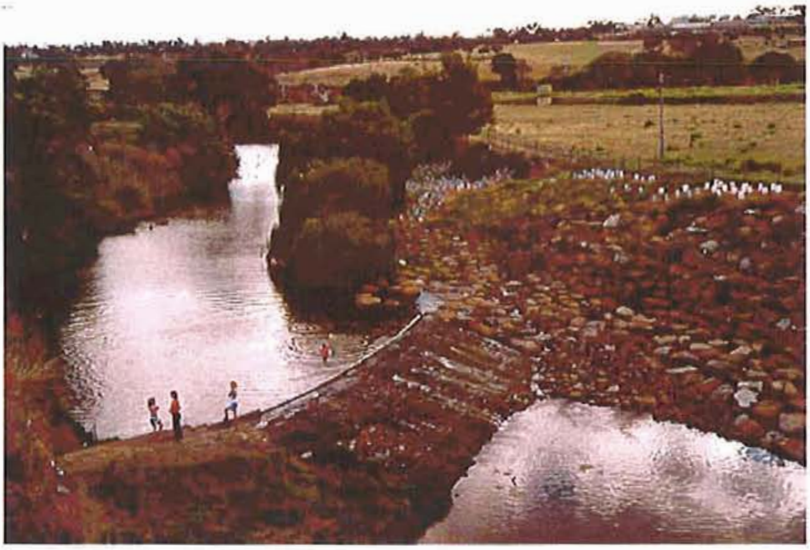


Figure 8. Arundel Street weir looking upstream (chainage 12 km), with recently installed fishway on left bank.

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^2 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^3s^{-1}, 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.