CORANGAMITE CMA

Environmental Flow Determination for the Barwon River:

Final Report - Flow Recommendations

Corangamite Catchment Management Authority

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Lloyd Environmental

FLUVIAL SYSTEMS

FLUVIAL GEOMORPHOLOGY
RIVER REHABILITATION
ENVIRONMENTAL FLOWS
CATCHMENT HYDROLOGY

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1.1 The Barwon River Environmental Flows Project

Introduction

The Barwon River Environmental Flows Project will recommend the flows required to achieve a 'healthy river ecosystem', as defined by the Victorian River Health Strategy. The project applies the FLOWS methodology for determining environmental water requirements (DNRE 2002). This project follows the recent Victorian Government White Paper, Our Water Our Future, which recognised that water in the Barwon River is fully allocated.

The FLOWS methodology involves the collation and review of the information through literature review, field assessments, consultations with agency and community members, topographic surveys of each site, hydraulic modelling, and a scientific panel workshop to make environmental flow recommendations. This document, the Issues Paper presents a preliminary assessment of the physical and ecological assets that are to be protected and promoted in the river, and makes preliminary recommendations for the flows on which they depend. It should be read in conjunction with the Site Paper that was completed earlier in the project and summarised the general characteristics of the study area and identified the river reaches on which the methodology will be based.

This report presents the final recommendations of the Environmental Flows Technical Panel (EFTP) that was established to undertake the project. The report recommends the flows required to achieve specific ecological objectives and assesses the degree to which these flows are currently provided.

Background

The Barwon River is identified as a fully-allocated catchment where the water reserve will be established initially by recognising existing entitlements, capping consumption, and applying a moratorium to new diversions. In a state-wide assessment, the Barwon has been identified as one of 21 streams which require the development of a stream flow management plan. The Victorian Government White Paper 'Securing Our Water Future Together' provides the policy underpinning for the water needs of the environment by establishing an Environmental Water Reserve.

The Corangamite CMA is responsible for the overall river health of the Barwon River and the assessment of the environmental flow needs of this river, including its internationally significant lakes and wetlands in its estuary zone. The CMA is responsible for determining ecological objectives for flow-dependent ecosystems, which will be used by DSE to set priorities and develop options for water recovery.

The Barwon is a major water supply for Geelong, the smaller urban centres, and farm water supply for the region. The system is significantly altered via extensive farm dam storages, on-stream reservoirs and many diversion licences. Inter-basin transfers occur from Lake Colac (via the Lough Calvert drainage scheme) and Lake Corangamite (via the Woady Yaloak drainage scheme) into the Barwon River.

Recent assessment of the ecological condition of the river, as part of the Corangamite River Health Strategy, has indicated that most reaches are in marginal to very poor condition, whereas a few streams in good or excellent condition are high in the catchment, above water supply storages. Wetland condition assessment (2004) has shown that most wetlands (60%) are either degraded or severely degraded, with only 15% being intact or pristine.

The estuary of the Barwon River, which includes Lake Connewarre, Reedy Lake and the lower Barwon, are internationally significant wetlands and regional, Victorian and Australian government agencies have a responsibility to protect and enhance these values.

The Corangamite CMA has commissioned Lloyd Environmental Pty Ltd, Ecological Associates Pty Ltd, and Fluvial Systems Pty Ltd to undertake this FLOWs study to gain an understanding of the role of water in the health and functioning of the freshwater and estuarine reaches of the Barwon River system. The study will classify the flows in each hydrological component, or reach, of the system, and predict the frequency, duration and seasonality of each flow band required to sustain the ecosystem. Quantification of these requirements, through a hydrological model, will allow the deficiencies between the required and current water regime to be prioritised and targeted by appropriate use of available environmental flows.

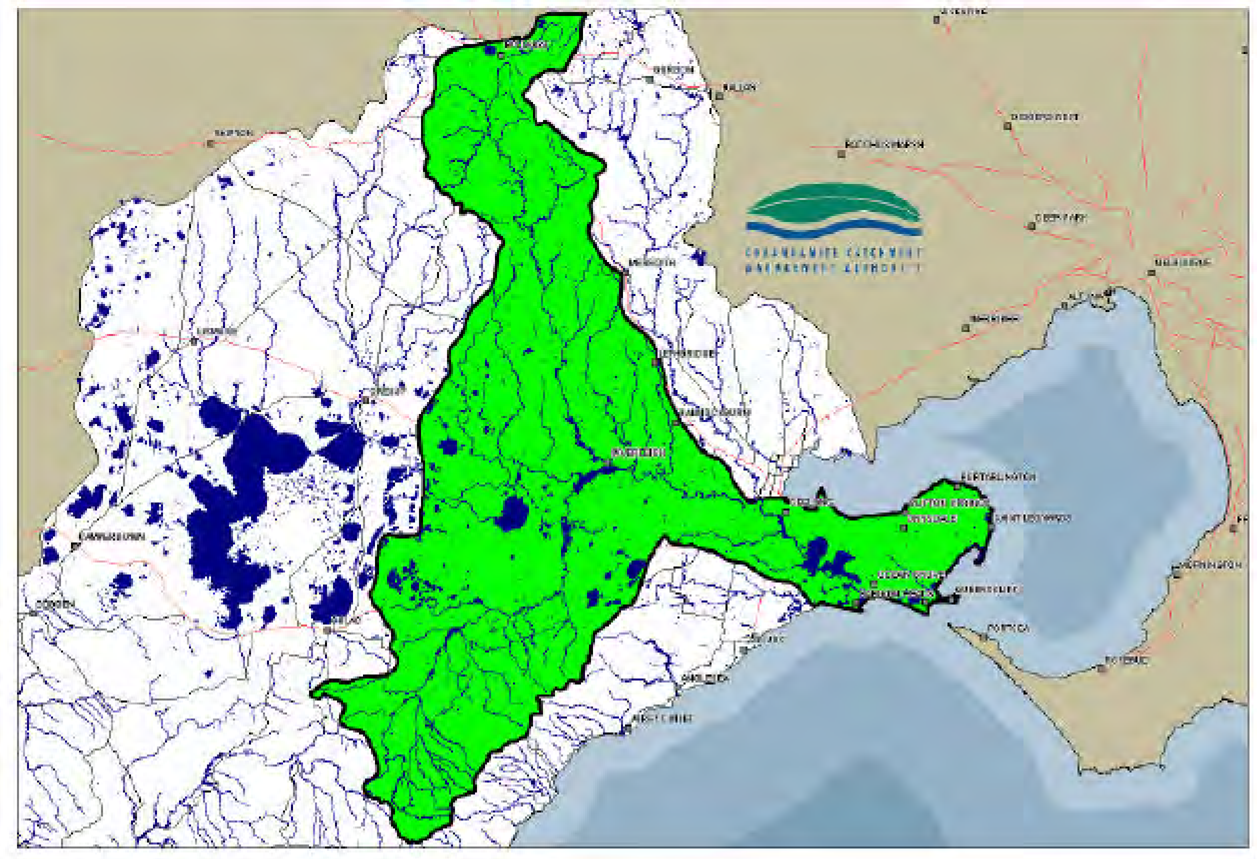

Figure 1. The Study Area

Objectives

The overall objective of this project is to determine the environmental water requirements of the Barwon River, including Lake Connewarre and the Barwon Estuary, and to develop options to meet the environmental needs.

More specifically, this investigation:

- identifies water dependent environmental and social values within each reach;
- gauges the current health of environmental values;
- identifies the flow regimes that will maintain or enhance the environmental values;
- develops Environmental Flow Objectives that take into account current social, economic and environmental values of the river; and
- recommends an environmental flow regime to meet the objectives.

The Study Area

The Barwon River rises in the Otway Ranges and flows close to the townships of Forrest, Birregurra, Winchelsea, and Inverleigh before flowing through Geelong and joining the coast at Barwon Heads. The Leigh River, a major tributary, rises near Ballarat and joins the Barwon River at Inverleigh. Two other tributaries, Birregurra and Boundary Creeks, flow into the Barwon from the western part of the catchment. The environmental flow requirements of the Moorabool River, also a major tributary of the Barwon River, have been determined in previous studies and will not be revisited in this study. The Upper Leigh River is not considered in this study (apart from the downstream effects in the mid and lower Leigh River).

The project study area comprises of nine reaches which are shown in Table 1 and Figure 2.

Table 1. Reach names and descriptions for the Barwon River Environmental Flow Study

Reach Name	Description
Upper Barwon	Barwon River from West Barwon Reservoir to Birregurra Creek confluence
Winchelsea	Barwon River from Birregurra Creek confluence to Leigh River confluence
Murgheboluc Valley	Barwon River from Leigh River confluence to Morrabool River confluence
Geelong	Barwon River from Moorabool River confluence to the Lower Breakwater
Estuary	Lower Breakwater, Lake Connewarre and Reedy Lake, lower estuary to Barwon Mouth
Birregurra Creek	Birregurra Creek
Boundary Creek	Boundary Creek
Mid Leigh River	Leigh River from Napoleons Rd to Quinney Hill
Lower Leigh River	Leigh River from Quinney Hill to Barwon confluence

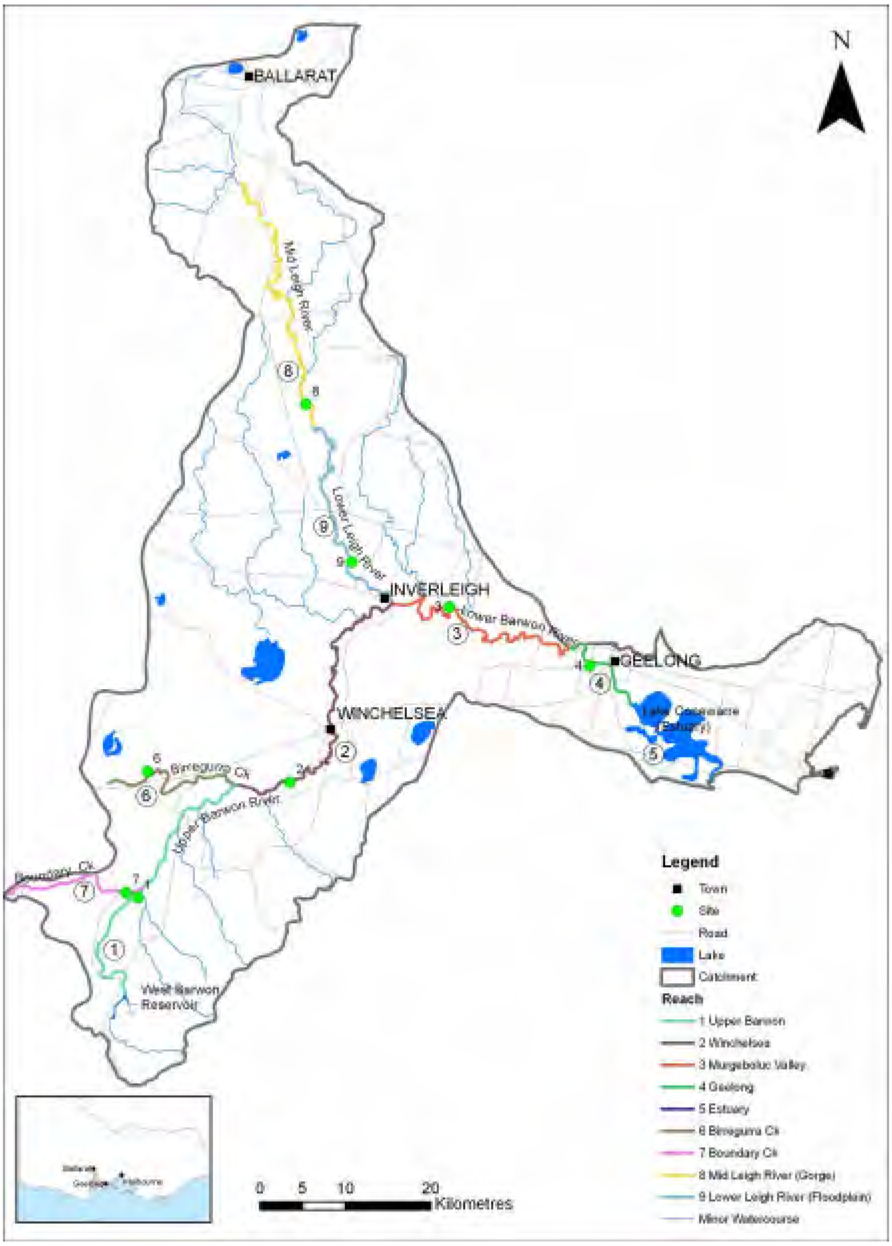

Figure 2. Map indicating delineated reaches of the Barwon River

1.2 The Adopted Methodology

This project applies the FLOWS method to determine environmental flows in rivers and streams in Victoria (DNRE 2002). The steps involved in the application of the method are presented in Figure 3.

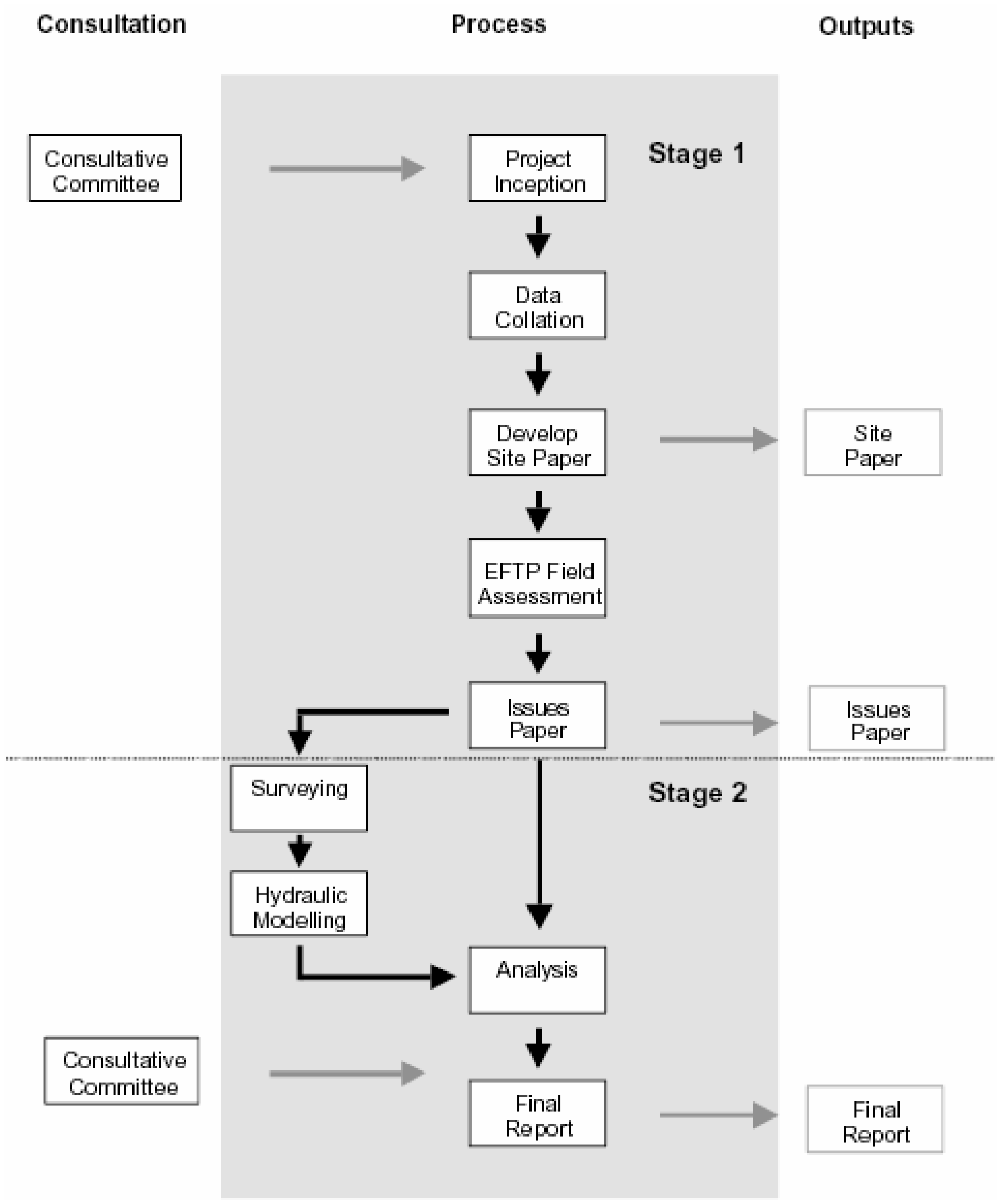

Figure 3. Flow chart illustrating the implementation of the FLOWS methodology. Note EFTP refers to the Environmental Flows Technical Panel (DNRE 2002a).

FLOWS assumes that the flow regime required to achieve the desired ecological condition in a river can be represented by a set of flow components. Flow components are defined in terms of the timing, duration and magnitude of flow events. Flow components are attributed to a representative set of ecological and physical characteristics and functions. For example, the flow component of "low flow in summer" might be attributed to the persistence of aquatic habitat in a stream bed.

Stage 1 of the project was completed with the preparation of the Issues Paper (Lloyd Environmental 2005), which presented a conceptual model of the desired condition of the study area, and assessment of the current condition. This assessment was based on existing policy and strategy statements, a review of important physical and ecological values (or 'assets' in FLOWS) and a detailed field assessment. The conceptual model is formally articulated by relating the required status of the flow components to the intended condition of each environmental asset. Within each reach, representative sites were selected for further, detailed hydrological and ecological assessment in Stage II. The key findings of the Issues Paper are summarised in Section 2 of this report.

This report, the Flow Recommendations Report, concludes Stage II of the project. It provides specific recommendations for flows that must be provided to maintain or restore the health of the Barwon River. The recommendations are based on a detailed analysis of the behaviour of the river. A hydraulic model was used to relate river flows to the depth and width of flow at a number of representative sites. This information was used to make specific links between ecological and physical processes with particular river discharges. On this basis, quantitative flow recommendations were developed.

Stage II of the project has involved:

- physical survey of a representative site in each reach to support the development of hydraulic models;
- the development of hydraulic models for the surveyed sites to relate discharge to stream depth, width, velocity and shear stress;
- setting of quantitative objectives for river health;
- recommendations for a flow regime that will provide the defined environmental water requirements.

This report also includes a preliminary assessment of the degree to which the flow recommendations are achieved under the current management regime of the river.

Later investigations, which are beyond the scope of this project, will investigate the priority of the recommended flows and the ways and means in which they can be achieved.

1.3 The Environmental Flows Technical Panel

The determination of the environmental flow requirements of the Barwon River is being undertaken by the Barwon River Environmental Flows Technical Panel (EFTP) which comprises:

- Lance Lloyd — Fish and Macro-invertebrate Ecology
- Dr Marcus Cooling — Plant Ecology
- Dr Chris Gippel — Hydrology and Fluvial Geomorphology
- Dr Brett Anderson — Hydraulics & Modelling
- Associate Professor John Sherwood — Estuarine Ecology

Dr Allen McIlwee (Ecological Associates) undertook a review of water bird ecology in relation to the water regime recommendation for the estuary reach within this report. The project was reviewed by Dr Mike Stewardson of The University of Melbourne, who is a hydrologist and environmental flows expert.

The EFTP's investigations have been assisted by the Steering Committee which comprises:

- Simone Gunn, Corangamite Catchment Management Authority
- Cameron Welsh, Southern Rural Water
- Steve Nicol, Department of Sustainability and Environment
- Cameron Howie and Mee Teng, Barwon Region Water Authority.

In addition, a Community Advisory Committee and an Expert Panel – Estuaries (consisting of the estuary and freshwater scientists and managers) have also been established to assist the Environmental Flows Technical Panel and the Steering Committee for this project. Advisory Committee members included Bob Carraill, Pat Russell, Cameron Steele, Steven McDougal, Trevor Prescott, Nellie Shalley, Stuart Mathieson, Gary Battye, Graham Perkins, Neil Pearce, Gary Wishart, and David Cotsell. The Expert Panel – Estuaries included Matt Ward, Lochie Jackson, Peter Kemp, Ian McLaughlan, Graham Perkins, Trevor Prescott as well as members of the Steering Committee and the Project team.

This is an overview of the Hydraulic Analysis Report (HAR) that was undertaken for the Barwon River FLOWS assessment. The HAR is included as an Appendix to the final report. The HAR explains the analysis in detail, and presents a summary of the results of the hydraulic simulations. The hydraulic analysis is also based in part on material presented in the Issues Paper.

2.1 Hydraulic Analysis

Numerical hydraulic models were developed for eight of the nine focus reaches on the Barwon River (the estuarine reach - site 5 - was not suitable for analysis using the FLOWS method (DNRE 2002). Hydraulic analysis provides an efficient means to estimate the relationship between flow depth and discharge for each reach. Flow data was supplied by SKM (2005). For this project models were constructed using the HEC-RAS software (U.S. Army Corps of Engineers, Version 3.1.3, May 2005: www.hec.usace.army.mil), which is designed to perform one-dimensional steady state calculations for natural and constructed river reaches. Three components are required to define a river reach within HEC-RAS: reach geometry; a downstream boundary condition; and a specification of hydraulic roughness.

2.1.1 Reach geometry defined by survey

Cross-sectional surveys were undertaken by Reed& Reed Surveying of the eight selected reaches of the Barwon Rivers and tributaries in July and August of 2005. At each reach between 6 and 10 cross-sections were surveyed at locations identified by pegs placed during field reconnaissance in Stage 1. Transects were located so as to capture the principal features of each reach, particularly geomorphic features such as pools, riffles and runs, and hydraulic features including channel constrictions, expansions and hydraulic controls.

Cross-section data was supplied in both text file format (comma separated values) and as ESRI format shape files (included on the data CD). The principal parameters provided were:

- Co-ordinates in Zone 54 AMG.66 (Easting and Northing to +-0.01 metres);
- Reduced levels to Australian Height Datum (AHD, +-0.02 metres);
- Lateral position (in East-North plane) measured from zero at the most extreme point on the left hand bank (left side facing downstream) and increasing toward the right bank.

The surveyors also surveyed the location of uniquely numbered pegs placed during the field survey conducted by scientific team to mark important physical features or vegetation assemblages. Water surface levels on the day of the survey were also noted, as were other features such as the elevation of gauging station boards.

The raw survey data was manipulated and translated into HEC-RAS geometry file format using custom written routines using the scripting language of **Matlab** (Release 14, The Math Works: http://www.mathworks.com/). The manipulations included:

- Identify longitudinal features including the thalweg and the left and right bank positions (for the main channel).
- Project points in the survey of the main channel (between the left and right banks) to a common plane so as to avoid exaggeration of the cross-section dimensions.
- Un-cross section lines (on floodplains) where the surveyed sections are overlapping[1] or need realignment with floodplain flow direction.
- Extrapolate most downstream cross-section.

Once this pre-processing is complete the cross-section data is written to a text file that can be read by HEC-RAS. Matlab routines were also written to:

- Compute the dimensional properties of each cross-section, including the variation with flow depth of wet perimeter, hydraulic radius, water surface top width and flow area.
- Estimate Manning's n roughness values using the empirical equations of Riggs (1976) and Dingman and Sharma (1997).
- Post-process flow results exported from HEC-RAS by evaluating quantitative discharge thresholds (see following section) with output written to a text file.

2.1.2 Downstream boundary condition

The flow scenarios examined during this analysis were restricted to sub-critical flows, hence only a downstream boundary condition was required (Chow, 1959). Given the information available, normal depth was specified as the downstream boundary condition, applying the so-called 'Slope-Area Method' (Sturm, 2001). Under this condition the flow depth at the outlet is determined by the geometry of the outlet cross-section, the roughness coefficient, and the local water surface slope. Water surface slope was generally unavailable so the bed slope was used as an estimate.

The uncertainty associated the specification of the downstream boundary condition revolves principally around errors in the value of roughness and the water surface slope. A sensitivity analysis was conducted where both of these parameters were perturbed around the best-estimate value. The results of this

[1] Section lines were un-crossed in two stages. First, a three dimensional surface was interpolated using the surveyed data point. Second, cross-section lines were moved so as to be parallel to the floodplain flow direction and to realign overlapping sections.

investigation are described in detail in the Hydraulic Analysis Report, however two principal conclusions were drawn:

- reaches of low slope are more sensitive to errors in the downstream boundary condition than reaches of higher slope; and
- uncertainty in the value of the friction factor is the key determining factor in the accuracy of predicted water surface profiles.

The impact of uncertainty in the specification of hydraulic roughness was explicitly considered in reporting results from the one-dimensional simulations.

2.1.3 Estimation of hydraulic resistance: Manning's n

Hydraulic resistance (also called 'stream roughness') is a measure of the friction generated between flowing water and the channel boundary. The magnitude of resistance determines the discharge at which different channel features are inundated, dictating how much flow is required to wet a vegetated bench or for flooding to commence.

It is generally accepted that the greatest uncertainty in one-dimensional hydraulic modelling is associated with estimating the value for the roughness coefficient (Aronica et al., 1998; Burnham and Davis, 1986; Coon, 1998; Western, 1994). There is no single 'best' tool, technique or equation, as numerous studies have demonstrated (Coon, 1998; Lang et al., 2004; Phillips and Ingersoll, 1998). A procedural method that builds on the recommendations of Coon (1998) was developed for assessing the roughness of each of the eight reaches assessed for in the Barwon River FLOWS study.

The accuracy to which roughness may be estimated depends primarily on the experience of the practitioner and is aided by use of various roughness estimation tools. There are four standard types of tools used to estimate the resistance of natural rivers and streams; they are: (i) procedural approaches; (ii) roughness tables; (iii) using roughness handbooks; and (iv) empirical or theoretical equations. For this project six different tools were employed, giving six Manning's n values (n^1, n^2 … n^6). The average of these estimates was selected as the 'best' estimate of reach roughness, and the spread of the values was used to estimate the likely error associated with the 'best' estimate. A more detailed description of these methods can be found in the Hydraulic Analysis Report (Appendix).

2.2 Results of hydraulic analysis

A series of standard outputs were compiled for each reach. A sample of the output is presented here for Reach 1, Upper Barwon River, with each individual product listed with a brief description in Table 2.1.

Table 2.1 List of hydraulic analysis outputs produced for each of the surveyed reaches

Hydraulic Analysis Output	Reference
Plan view of the site with each of the surveyed cross-section labelled.	Figure 2.1
List of geometric properties associated with bankfull channel stage at each cross-section, including: flow area, A; top width, B; and hydraulic radius, R.	Table 2.2
Summary of reach hydrology listing the range of flows under the natural and current flow regimes.	"Hydrology"
Commentary describing how floodplain roughness vales were assigned (and possibly other reach-specific hydraulic considerations).	"Floodplain Roughness"
Summary of the development of the estimate of in-channel Manning's n for the reach (a short description of the selection of a separate floodplain roughness value is also given, if applicable).	"Roughness Coefficient Estimation"
List of thresholds associated with sediment entrainment and vegetation removal, with the discharge estimated to breach each threshold listed in the final column.	Table 2.3
Longitudinal profile of the reach showing the elevation of the ground at the thalweg (deepest point across the channel) and a simulated water surface elevation at a very low discharge (WS).	Figure 2.2

These products were used by the technical panel to quantify each component of the environmental flow regime (low flows to overbank floods) developed at the two-day workshop.

2.2.1 Sample results: Site 1: Barwon River @ Upper Barwon.

Plan View of Reach

Eight cross-sections were surveyed over a reach length of 585 metres at the Upper Barwon site. The HEC-RAS model of these cross-sections is shown in plan view in Figure 2.1, and indicative channel dimensions are listed in Table 2.2.

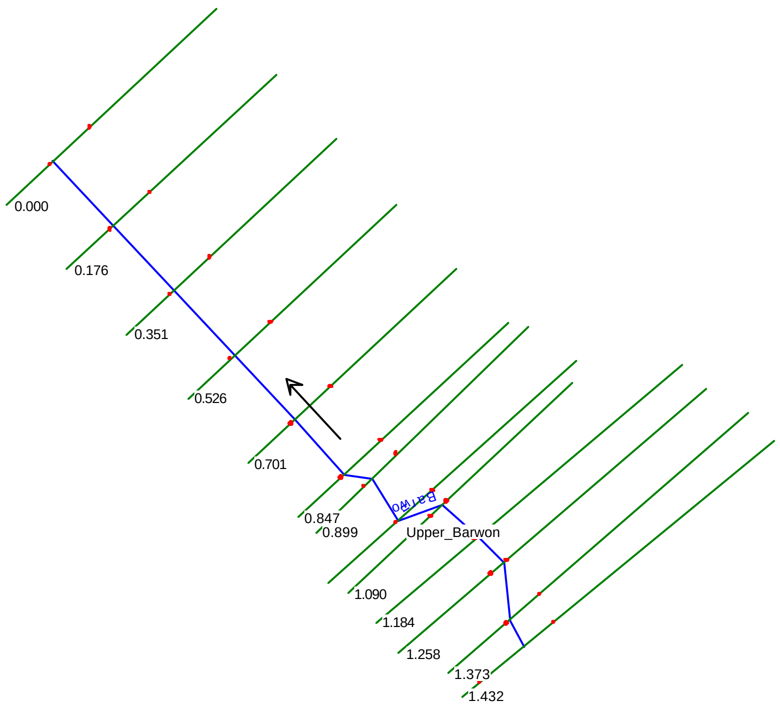

Figure 2.1 Plan view of Site 1 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.701) are extrapolated from cross-section 0.847.

Table 2.2 Summary of Channel Dimensions

XS	Distance	Elevation	Dimensions		
	(km)	(m)	A (m^2)	B (m)	R (m)
1	1.431	121.2	14.8	15.7	0.9
2	1.373	121.3	14.2	14.3	0.9
3	1.257	120.9	8.2	10	0.8
4	1.184	120.7	14.9	17.2	0.8
5	1.089	120.3	8.4	10.7	0.7
6	0.997	120.1	8.4	12.8	0.6
7	0.899	120.1	5.3	8.6	0.6
8	0.846	119.7	3.5	5.3	0.6
		Reach average:	9.7	11.8	0.8
		Std. deviation:	4.1	3.7	0.1

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)							
	Natural	1 020	1725	2 865	8 250	13 215	22 230
	Current	405	735	1 140	2 325	2 325	6 735

Floodplain roughness

The floodplain zones at Site 1 are dissected by a number of small channels. These surfaces are in places covered with scattered brush (including macrophytes and some low trees (Chow's Table: D-2.c.1) and in the remainder it is pasture with high grass (Chow's Table: D-2.a.2). An intermediate roughness was assigned: n = 0.042.

Levees

This reach is dissected by a number of channels. The main functional channel is flanked by high levees, which hydraulic modelling suggests are capable of containing a large flood (5 - 15 year ARI; 6000 - 18000 ML/day). However, the field inspection revealed that some of the secondary channels were active, presumably supplied by breaches in the levee, under Winter baseflow conditions. Consequently, the levee was considered ineffective in the numerical model.

Site 1: Roughness coefficient estimation

Method	Manning's n	Selected values		Description
Cowan's Method	0.040	n_b = 0.020	n_3 = 0.000	Silt-clay (earth) substrate with negligible irregularity (very flat profiles) with occasional cross-section shape change. Obstructions are negligible with vegetation (medium) important at lower flow stages. Meandering is considered minor in this context.
		n_1 = 0.000	n_4 = 0.015	
		n_2 = 0.005	m = 1.00	
Chow's Table	0.040	Table Ref: D-1.a.5 (minimum)		Minor stream with some weeds (#4) but also at low stage (#5) - select low end of #5 (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.030 +veg = 0.015	Slope: 0.18%	D_{50}: 0.008mm	Slope greater than threshold but finer bed material (than sand). Select intermediate roughness and add vegetation increment (n_4)
Hicks and Mason	0.054 – 0.073 0.051 – 0.061	id: 25902 (p.214) id: 45311 (p.234)	Q = 0.48 m^3/sec S = 0.0018 silt/clay	Principal matched parameters: bed material (silt), slope and especially vegetation. Mean annual discharge is too high in both cases so have selected roughness range from bottom half of discharge measurements.
Empirical Equations	0.042 – 0.047 0.050 – 0.056	Rigg's (1976) Dingman and Sharma (1997)		
FINAL ESTIMATE:	0.050 ± 0.010	(mean ± 2 SD)		SD = standard deviation

Sediment entrainment and vegetation scour thresholds

Table 2.3 lists the thresholds for sediment entrainment and vegetation scour at Site 1.

Table 2.3 Site 1 thresholds for sediment entrainment and vegetation removal expressed in terms of either a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge*
SEDIMENTS				**(ML/d)**
fines (d = 0.1 mm)	flushing from gravel	$\tau_c = 0.34\,d$	0.034 N/m^2	0.1
sand (d = 1 mm)	spherical shape normal, settled bed	$\tau_c = 0.97\,d$	0.97 N/m^2	2.8
gravel (d = 10 mm)	spherical shape normal, settled bed	$\tau_c = 0.97\,d$	9.7 N/m^2	22 000
Riffle d_{50} =0.008mm	flat shape normal, settled bed	$\tau_c = 0.49\,d$	0.004 N/m^2	< 0.1
VEGETATION				**(ML/d)**
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	> 22 230
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	97.7 > 22 230

* Median discharge (of all cross-sections excluding the outlet cross-section)

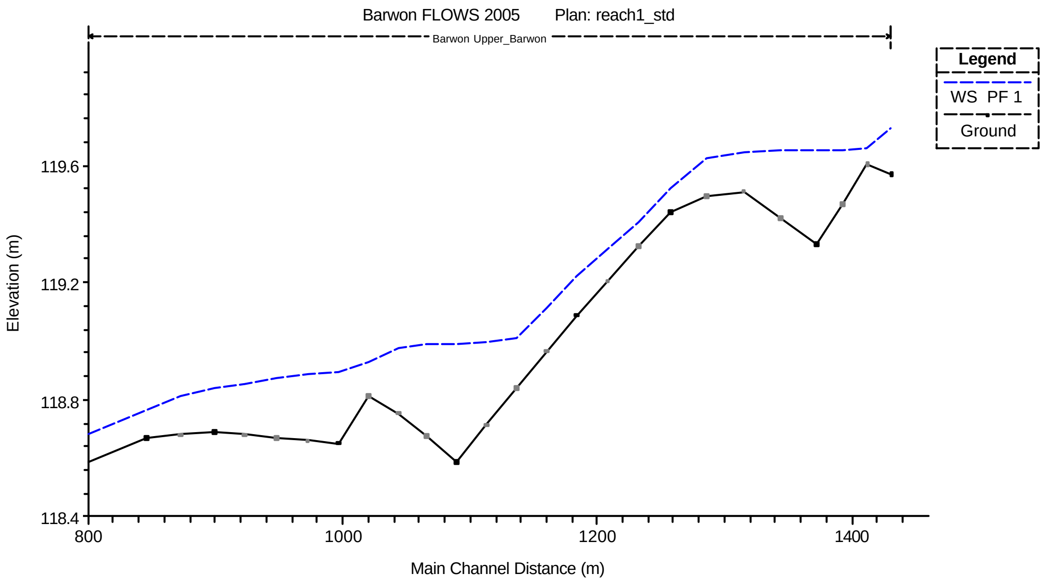

Figure 2.2 Longitudinal profile of Site 1 for very low flow (0.8 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

Site 1: Roughness coefficient estimation

Method	**Manning's n**	**Selected values**		**Description**
Cowan's Method	0.040	n_b = 0.020	n_3 = 0.000	Silt-clay (earth) substrate with negligible irregularity (very flat profiles) with occasional cross-section shape change. Obstructions are negligible with vegetation (medium) important at lower flow stages. Meandering is considered minor in this context.
		n_1 = 0.000	n_4 = 0.015	
		n_2 = 0.005	m = 1.00	
Chow's Table	0.040	Table Ref: D-1.a.5 (minimum)		Minor stream with some weeds (#4) but also at low stage (#5) - select low end of #5 (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.030 +veg = 0.015	Slope: 0.18%	D_{50}: 0.008mm	Slope greater than threshold but finer bed material (than sand). Select intermediate roughness and add vegetation increment (n_4)
Hicks and Mason	0.054 – 0.073 0.051 – 0.061	id: 25902 (p.214) id: 45311 (p.234)	Q = 0.48 m^3/sec S = 0.0018 silt/clay	Principal matched parameters: bed material (silt), slope and especially vegetation. Mean annual discharge is too high in both cases so have selected roughness range from bottom half of discharge measurements.
Empirical Equations	0.042 – 0.047 0.050 – 0.056	Rigg's (1976) Dingman and Sharma (1997)		
FINAL ESTIMATE:	0.050 ± 0.010	(mean ± 2 SD)		SD = standard deviation

Sediment entrainment and vegetation scour thresholds

Table 4 lists the thresholds for sediment entrainment and vegetation removal. A longitudinal section through the site illustrates how the channel capacity and bed level relate to the water surface at a discharge of 0.8 ML/d (Figure 3).

Table 4. Site 1 thresholds for sediment entrainment and vegetation removal expressed in terms of either a critical shear stress (N/m2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge*
SEDIMENTS				(ML/d)
fines (d = 0.1 mm)	flushing from gravel	$t_c = 0.34\,d$	0.034 N/m^2	0.1
sand (d = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\,d$	0.97 N/m^2	2.8
gravel (d = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\,d$	9.7 N/m^2	22 000
Riffle d_{50} = 0.008mm	flat shape normal, settled bed	$t_c = 0.49\,d$	0.004 N/m^2	< 0.1
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	> 22 230
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	97.7 > 22 230

* Median discharge (of all cross-sections excluding the outlet cross-section)

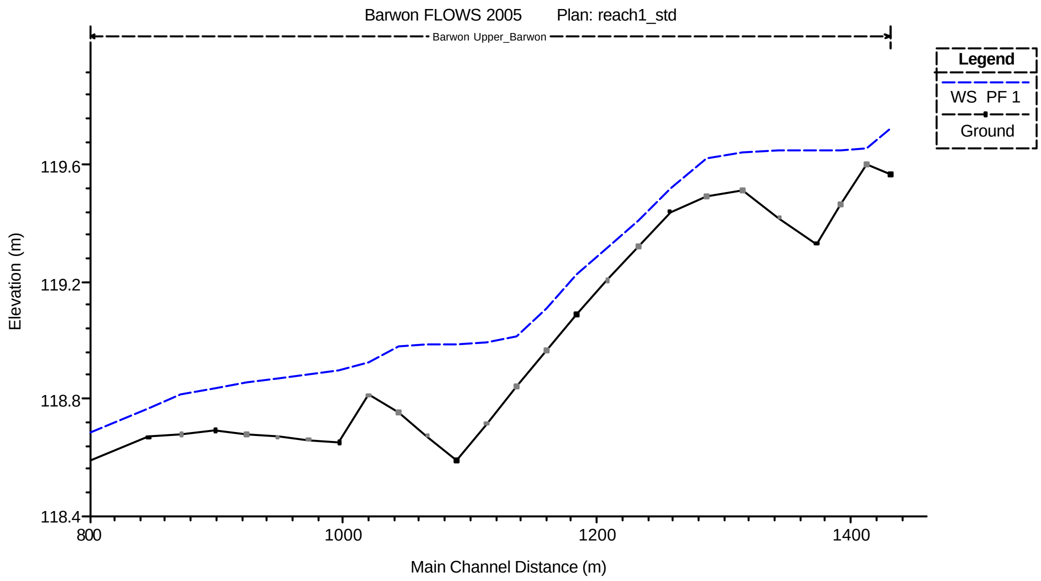

Figure 3. Longitudinal profile of Site 1 for very low flow (0.8 ML/d) with normal roughness specified (i.e. best estimate Manning's n).

Water surface elevation (m) is the br oken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

2.3 Analysis

Environmental flow recommendations were developed at a workshop held at the Corangamite CMA Geelong Offices on September 29 and 30, 2005. The EFTP developed flow recommendations on a reach by reach basis.

The analysis involved the following tasks:

- review of the environmental assets in each reach and their condition, as presented in the Issues Paper (Lloyd Environmental 2005);
- review of the relevant hydrological objectives, as presented in the Issues Paper;
- use of the hydraulic model and hydrological analysis to characterise the flows that relate to the ecological objectives; and
- discussion and agreement on the required status and flow requirement of environmental assets.

3.1 Development of Specific Flow Objectives

The EFTP reviewed the flow objectives that were identified in the Issues Paper and rationalised them on the basis of common or similar flow requirements (Table 5). The rationalised objectives were numbered for reference in the reach analysis presented in Section 4.

Table 5. Specific Flow Objectives.

Category	Sub-category	Specific Objective
Vegetation	Floodplain shrubland community	**1a** Perennial riparian shrub growth
		1b Riparian shrub community recruitment
	Submerged aquatic macrophytes	**1c** Perennial submerged aquatic macrophyte growth in pools (either in channel or low floodplain)
		1d Seasonal submerged aquatic macrophyte growth in floodplain pools or wetland areas
		1h Opportunistic growth in flooded billabongs
	Emergent macrophytes	**1e** Seasonal emergent macrophyte growth
		1i Summer macrophyte and grass colonisation of stream bed
	Drought-tolerant emergent macrophytes	**1j** Temporary inundation of saline floodplain
	Floodplain woodland community	**1f** Growth and recuitment of Red Gum, Blackwood and other floodplain woodland species
	Halophytes	**1g** Presence of salt indicator plants (e.g. Sea Club Rush, *Selliera radicans*)
2. Fish	Dwarf Galaxids	**2a** Maintain permanent populations in reach
		2b Provide breeding trigger and recruitment in reach by prolonged seasonal inundation of vegetation beds and Instream benches.
	Climbing Galaxiids	**2c** Longitudinal connectioin in channel for Galaxias olidus dispersal and G. brevipinnis juvenile upstream migration (late hydrological winter)
		2d Downstream migration of G. brevipinnis (early hydrological winter)
	Blackfish	**2f** Permanent pool habitat
		2g Submerged woody debris for breeding and / or hard and clean substrate
		2h Longitudinal connection in channel
	Mountain Galaxiids	**2i** Provide flow over sandy islands and benches
	Australian Grayling	**2j** Maintain permanent deep pool of minimum depth 3 m
		2k Provide breeding trigger and recruitment in reach, flush reach between February to May and inundation of vegetation beds and Instream benches is required
		2l Longitudinal connection in channel for adult grayling movement
		2m Juveniles migrate upstream from sea between October and December
		2n Downstream migration of larvae between May and July (early hydrological winter)
3. Geomorphology	Maintain capacity to mobilise sediment and shape channel and habitat features	**3a** Prevent excessive macrophyte colonisation of the bed leading to channel capacity reduction and potential erosion
		3b Disturb riparian vegetation to provide new habitats and regeneration and to control riparian vegetation encroachment into stream channel
		3c Maintain channel form and key habitats, including undercuts, in-

Category	Sub-category	Specific Objective
		channel benches, and flood runners where present
		3d Maintain channels and inlets for connectivity of main channel with important floodplain and wetland zones (where present)
		3e Maintain downstream sediment transport processes to prevent incision and aggradation of the bed, and consequent accelerated bank erosion and changed flood frequency
		3f Movement of sand bed material to maintain bed morphological and hydraulic diversity
		3g Scour sediments from base of pools to maintain quantity and quality of pool habitat.
		3h Scour surficial and interstitial fine sediment from riffles and overturn bed substrate (gravels and cobbles where present)
		3i Form large woody debris accumulations and scour pools around large woody debris.
		3j Disturb shrub layer vegetation on floodplain to create a mosaic of habitats
4. Macro-invertebrates		**4a** Sustain macroinvertebrate communities during Summer and Autumn
		4b Create and extend aquatic habitat for macroinvertebrate growth (flourish of life)
		4c Create and extend aquatic habitat for macroinvertebrate growth
		4d Support main growth and reproductive season for macroinvertebrates in Spring
5. Water Quality		**5a** Avoid prolonged stratified conditions in pools

3.2 Criteria to Evaluate Flow Objectives

To assess the flows required to achieve ecological objectives, quantitative physical indices of specific physical processes were sought. The indices identify the physical events in the stream, such as substrate mobilisation or velocity, which support ecological objectives and allow the required discharge to be objectively calculated. This process provided consistent and objective guidance for the assessment of flow requirements by the EFTP. Table 6 summarises the flow indices that were related to the flow objectives. The method used to develop and apply the indices is provided below.

Cease to Flow

Periods of cease to flow in summer and autumn are a natural characteristic of the small tributaries Boundary Creek and Birregurra Creek. They provide a dormant period for some emergent macrophytes such as *Bolboschoenus caldwellii* and allow grasses, sedges and herbs to colonise the stream bed, contributing to habitat diversity for fish and macroinvertebrates (Objective 1i). If these reaches do not cease to flow, sustained flows may promote the growth of perennial emergent species such as *Typha* and *Phragmites*, which will replace other vegetation assemblages and may degrade habitat for Platypus, larger fish species, such as River Blackfish, and macroinvertebrates.

Groundwater Discharge

Groundwater discharge was not quantitatively assessed in this study, but it was recognised as an important process in some reaches. Groundwater discharge is interpreted to contribute to flow in the Barwon River below the Upper Barwon Reservoir and in Boundary Creek. Additionally, groundwater discharge contributes to seasonal variation in soil salinity in the watercourse in Birregurra Creek and in the Barwon River at Murghebuloc (Objective 1g). Evaluation of groundwater discharge and salt fluxes are beyond the scope of this study.

Lateral Flow Extent

In-stream emergent and submerged plants require waterlogged soils or inundation during the main growing season, which extends approximately from August to December (Objective 1e). This was related to the discharge at which water reaches the toe of the channel bank. Inundating riffle cross sections is also an important indicator of the availability of habitat for benthic macroinvertebrates. The flows required to fully wet the perimeter of riffles (Objective 4a) were interpreted from the surveyed cross sections and referral to field notes and photographs. These were related to discharge using the hydraulic model.

Table 6. Flow Indices and Objectives

Index Type	Index	Objectives
Cease to Flow	Cease to flow duration	**1c** Perennial submerged aquatic macrophyte growth
Groundwater Discharge	Saline groundwater discharge to watercourse	**1g** Presence of salt indicator plants
Lateral Flow Extent	Water extends to toe of bank	**1e** Seasonal emergent macrophyte growth
	Perimeter of riffles fully wetted	**4a** Habitat for macroinvertebrate communities during summer and autumn
Velocity	Pool volume replacement	**5a** Avoid prolonged stratified conditions in pools
Flow Depth	Hydraulic depth at riffles (flow required to cover d50 particles + 50 mm)	**2c** Longitudinal connection in channel for *Galaxias olidus* dispersal **2d** Downstream migration of *G. brevipinnis*
	Hydraulic depth over shallowest riffle thalweg d50+100 mm	**2h** Flow to connect Blackfish pool habitats **2l** Longitudinal connection in channel for adult Grayling movement
	Inundate some macrophyte beds to at least 200 mm	**4d** Main growth and reproductive season for macroinvertebrates in spring
	Pool depth	**2a** Maintain permanent Dwarf Galaxiid populations in reach **2f** Permanent pool habitat for Blackfish >500mm **2j** Permanent deep pool of minimum depth 3 m for Australian Grayling (Reach 4 only)
	Flow passes lower breakwater	**2m** Juvenile Grayling migrate upstream from sea
	Inundation of woody debris	**2g** Submerged woody debris for Blackfish breeding
	Inundation of benches	**1b** Growth and recruitment of riparian shrubby vegetation **2i** Flow over sandy islands and benches for Mountain Galaxids breeding **4c** Create and extend habitat for aquatic macroinvertebrates
	Inundation of low floodplain wetlands	**1d** Seasonal submerged aquatic macrophyte growth in floodplain pools or wetlands areas **1i** Summer macrophyte and grass colonisation of stream bed
	Inundation of floodplain	**1f** Growth and recruitment of floodplain woodland vegetation **1h** Opportunistic aquatic plant growth in flooded billabongs **1j** Temporary inundation of saline floodplain **2b** Inundation of floodplain vegetation for Dwarf Galaxias breeding **4b** Create and extend habitat for aquatic macroinvertebrates
	Water table within 500 mm of surface of floodplain shrub habitat	**1a** Perennial riparian shrub growth
Sediment Mobilisation	Flush fines (0.0034 N/m2)	**2g** Hard clean surface at the edge of pools for Blackfish breeding
	Entrain sands (0.97 N/m2)	
	Mobilise fine gravel (97 9.7 N/m2)	
	Mobilise fine gravel (97 N/m2)	
	Mobilise riffle material – d16	
	Mobilise riffle material – d50	
	Mobilise riffle material – d84	
Vegetation Removal	Velocity x Depth in channel exceeds 0.15	**3a** Prevent excessive macrophyte colonisation of

	(Q95)	the bed of leading to channel capacity reduction and potential erosion
	Q99.9	**3b** Disturb riparian vegetation to provide new habitats and regeneration and to control riparian vegetation encroachment into stream channel
Channel Dimensions and Form	Q99.9	**3c** Maintain channel form and key habitats including undercuts, in-channel benches and flood runners where present **3d** Maintain channels and inlets for connectivity of main channel with important floodplain and wetland zones where present
	Mobilise riffle material – d50 Mobilise riffle material – d84	**3e** Maintain downstream sediment transport processes to prevent incision and aggradation of the bed and consequent accelerated bank erosion and changed flood frequency
	Grass removal (80 N/m2 shear stress)	

Flow Depth

The depth of water in riffles connecting pools during baseflow can limit the movement of fish between pools. For movement of *Galaxias olidus* and *G. brevipinnis* between pool habitats, there needs to be a minimum depth of around 50 mm at the thalweg (deepest point) of the shallowest riffle (Objectives 2c, 2d). A deeper threshold of d50 +100 mm over the shallowest riffle thalweg was applied for the movement of the larger species River Blackfish and Australian Grayling (Objectives 2h, 2l) where d50 is the diameter of the fiftieth percentile of substrate particles. The optimum value for this depth is uncertain, but it is reasonable to assume that fish will make effective use of such avenues for movement as long as they remain wholly submerged and there is sufficient cover available. When food is scarce or the water level in pools is low, fish may attempt to move or disperse across riffles so shallow that their backs are exposed, however, they are particularly vulnerable to predation by birds at this time. For this reason the EFTP have recommend thalweg depths sufficient to keep the whole fish submerged. River Blackfish spawn from November to January and the fry are ready to disperse and feed after a few weeks.

Flow depth was also used to define the discharge required to support emergent macrophyte growth over spring (Objective 4d). The adopted threshold provides inundation of some of the emergent macrophytes in the reach to a depth of 200 mm.

The discharge required to maintain pools was used to evaluate the availability of permanent habitat for Dwarf Galaxiid, River Blackfish and Australian Grayling (Objectives 2a, 2f and 2j, respectively).

The population of Australian Grayling in the lower Barwon River depend on opportunities to migrate between the weir pool in Geelong and the estuary. This means that flows must be sufficient to flow over and drown out the upper breakwater and flows sufficient to allow the fishway on the lower breakwater to operate effectively or that this weir is drowned out.

Woody debris or hard, rocky surfaces are used by River Blackfish to lay eggs (Objective 2g). Once laid, the eggs must remain flooded for a period of 21 days until the larvae are released. During the field assessment the distribution and level of woody debris and rocky surfaces, where present, where noted, and minimum discharges determined from the hydraulic model accordingly.

The inundation of benches in winter and spring supports the seasonal growth of aquatic macrophytes and other riparian plant species (Objectives 1b, 4c). Flow over sandy islands provides sites for Mountain Galaxias to breed (Objective 2i). The flows required to inundate benches (where present) were interpreted from cross sections that showed benches, using the hydraulic model.

The discharges required to inundate floodplain wetlands and the greater floodplain was determined from the hydraulic model and used to establish the achievement of objectives relating to aquatic macroinvertebrate habitat, Dwarf Galaxias breeding habitat and vegetation growth and reproduction.

In general, the baseflow or low flow level is expected to closely reflect the water table under the adjacent floodplain. Periods of shallow water below the floodplain are believed to support the seasonal growth of plant communities dominated by *Callistemon sieberi, Leptospermum lanigerum* and *Lomandra longifolia*. The flow depth which corresponded to a depth to groundwater of 500 mm was applied in reaches where these communities were significant.

Sediment Mobilisation

For sediment mobilisation, shear stress thresholds were computed by applying Shields Critical Shear Stress Method (Gordon et al., 2004, p.194). Three generic sediment thresholds were computed, specifically the shear stress required to: a) flush fines (d = 0.01m) from a gravel surface ($\tau_c = 0.34\ d$); b) entrain (mobilise) a normal, settled bed of sand; and c) to mobilise fine gravel. Three thresholds were also computed relating to the riffle sediments measured at each site. The shear stress required to mobilise the 16%, 50% and 84% of the riffle sediments were computed (i.e. sediment calibre equal to the median and two standard deviations either side of the median particle size - see Hydrology Report).

Vegetation Removal

For vegetation, thresholds for the removal of grasses and rupture ('lodging') of macrophytes. The minimum shear stress required to impact the least hardy of grasses (i.e. poorly established bunch grass) is 80 N/m2. The discharge required to rupture macrophytes was computed by application of Groeneveld and French's (1995) relationship. The diameter of the macrophyte stems tested was set, as recommended by Groenveld and French (1995), to 0.0119m (11.9mm). Two thresholds were then evaluated to represent a 95% and 99.9% chance of stem rupture respectively. The thresholds are reported as a discharge required for the product of flow depth and velocity to exceed either 0.152 (Qm95% - referred to as Q95) or 1.52 (Qm99.9% - referred to as Q99.9). Shrubs are present in many of the channels, and it is ecologically desirable to occasionally check their growth. There are no published data available on which to base an index for removing shrubs, so here we assumed that the shear stress to remove grass and macrophytes would disturb shrubs, as shrubs are less flexible and present a greater drag on the flow (due to larger projected area) - countering this is the possibility of greater rooting strength. It is emphasised that the removal of vegetation can only be predicted as a probability, and that for any given event only a proportion of vegetation will be disturbed. Vegetation may remain undisturbed due to variations in flow velocities within a stream, the stability provided by the substrate in which plants grow or the path taken by debris entrained by the flow. For this reason, this criterion is expressed in terms of 'checking the growth of' or 'disturbing' shrubby vegetation. It is not intended to represent the removal of all shrubby vegetation.

Channel Dimensions and Form

Channel maintenance means maintaining the overall structure of the stream bed, banks and morphological features within the channel, such as benches, bars, riffles, pools and undercuts. Bankfull flow, which is the flow that corresponds to the top of the bank (in an un-incised stream) is widely regarded as a reasonable index for the flows that maintain the overall channel form, although it is also recognised that channel form is the product of a wide range of flow frequencies and durations. The flow required to maintain channel dimensions and form was assessed with regard to the Q99.9 threshold.

Note that one day is specified as the duration for flows that maintain the physical habitat of the stream, although flows less than this duration will achieve the objective. One day is the minimum time step in the flow model.

3.3 Flow Threshold Interpretation

Flow Magnitude

In the flow recommendation tables flow magnitude is the daily average of the flow including the peak of the event. We need to specify the rate of rise and recession. The duration represents the entire event, including the rise, peak and fall.

This is the daily average of the flow including the peak of event. The instantaneous peak would be higher.

– need to specify rate of rise and recession use triangle – peak, duration rate of rise and fall - t

Low Flow and Baseflow

The timing or duration of Low flow and Baseflow events is not specified in each reach. These are generally specified to occur throughout the hydrological summer and winter respectively. They are the minimum to which flows may be reduced by water managers, but should fall lower if natural was lower. Therefore, intervention is not required to increase flow if the low flow or baseflow recommendation is higher than natural at any time.

Flow Duration

The hydraulic analysis reports discharge for a given height (or shear stress or velocity) in the channel. When this is converted to a flow recommendation, it is implicit that this discharge is over a certain time period. The recommendations state the frequency and duration for a given discharge magnitude. In doing this, reference was made back to the hydrological analysis, which was based on mean daily discharge. So, for example, if a magnitude of 30 ML/d was required to inundate a bench, then the hydrological analysis of mean daily discharge was referred to in order to determine how frequently (and for what duration) this discharge was achieved as a mean daily discharge.

Some processes may not require the threshold discharge to be achieved as a daily average. For example, if stones just need to be turned over (i.e. not rolled for a whole day), then a day long duration is not required and the specification can be as an **instantaneous discharge**. If the stone turning recommendation is made as a mean daily discharge, then unless the operator holds the flow very steady, the discharge on that day will be sometimes above 30 ML/d (stones turning) and sometimes below 30 ML/d (stones not turning).

Flows are often **managed** (for water supply) over a daily time step (although conventionally **measured** over a 6 minute time-step), so we specified the environmental flows as mean daily flows. So, a recommendation of 30 ML/d for one day means a mean daily flow of 30 ML/d. On that day, the operator can vary the flow around 30 ML/d, but the mean should be 30 ML/d. In some smaller streams where the dam control is just upstream the discharge can be controlled over short time steps (such as hourly). In these situations it might be appropriate to specify some environmental flows as instantaneous flows – provided the threshold only needed to be crossed for a short period in order to achieve the objective.

The above discussion applies to all environmental flow processes. For removing vegetation for example, plants can withstand a certain shear stress for a period of time before failure (the literature does not indicate how long is this period). Bed mobilisation, formation of undercut banks, re-working sand bars, scouring pools etc. – in practice these processes are not achieved instantaneously, even though the process may be defined theoretically as being achieved once a critical shear stress is reached. This is an area of process understanding that is weak. The exact durations required to complete these physical processes are unknown, but intuitively, maintaining a discharge for say 3 hours will probably allow most of them to be achieved. An exception might be processes that require mass transport of sediment in a river, such as reshaping benches and bars and scouring undercuts. These processes might require durations in the order of one whole day. In most cases expert judgement cannot reliably determine the required duration, and the exact specification of the duration will require adaptive management.

When it comes to future assessment of the flow regime to check for compliance with the agreed environmental flow regime, the analysis must be done on an appropriate time step. If flows are recommended as mean daily discharge values, then this is straightforward. For those objectives that have flow durations specified over minutes or hours, then the analysis will have to be done on a sub-daily time step – a data intensive exercise.

4.1 Reach 1 – Barwon River at Upper Barwon

Environmental Flow Objectives

Flow recommendations for Reach 1 are provided in Table 7. This reach extends from the Barwon River from West Barwon River Reservoir to upstream of the Birregurra Creek junction.

The representative site selected in this reach resembles a modified wetland habitat. Under natural conditions flow would have been dispersed over a broad floodplain in which multiple, poorly defined flow paths may have existed. This has since been modified to a narrow constructed channel which drains the broad floodplain. The EFTP determined that a healthy stream in this reach would retain the natural vegetation communities, including a Tea Tree shrubland on the floodplain and wetland habitats associated with the main flow path. These environments could not be restored without changes to current drainage practices and land uses, particularly works to promote floodplain inundation and the exclusion of stock from the watercourse.

Cease to flow is not recommended in this reach. While it occurs for a period of two weeks approximately once every three years, this is not sufficient to dry out wetlands or channel pools. No ecological role for cease to flow was identified.

Persistent, low flow during summer and autumn is important in this reach for the continued growth of aquatic plants and animals throughout the year. Low flows of 5 ML/d will maintain a depth of 30 to 50 cm in pools in the stream channel, which will provide a permanent habitat for the small fish and macroinvertebrates expected in this reach. This discharge will also fully wet the stream perimeter, providing habitat for aquatic macroinvertebrates. Perennial flow will also maintain a shallow watertable under the floodplain which will support the growth of shrubby floodplain vegetation, such as *Leptospermum lanigerum*.

Low flow freshes are required to periodically inundate floodplain pools and wetlands and to sustain perennial growth of aquatic macrophytes such as Milfoil. This objective could be achieved at a lower discharge than the recommended 215 ML/d if the drain were less effective.

Baseflow is required to support the seasonal growth of submerged and emergent macrophytes and for the seasonal growth and reproduction of aquatic fauna. The recommended discharge of 50 ML/d will maintain flow in the channel sufficient to inundate adjacent wetlands and floodplain pools. It also provides sufficient hydraulic depth in the channel for small fish to disperse.

Macro-invertebrate production increases during periodic increases inflow as additional habitat becomes available. These events supply additional prey for larger aquatic fauna and waterbirds. Discharges of 153 ML/d inundate low-lying floodplain areas and activate all floodplain channels and is recommended as the threshold for high flow freshes. This threshold exceeds the discharge required to transport sediment and remove sand in all cross sections (76 ML/d).

The inundation of the floodplain with a recurrence interval of one year is recommended. A discharge of 1600 ML/d will inundate the entire floodplain and will achieve bank full level iin all floodplain channels.

This will support a seasonal flush in growth and will support the recruitment of floodplain plant species and would provide habitat for small fish to breed. Dwarf Galaxias require events lasting 5 to 7 days to recruit while other Galaxiids and Pygmy Perch require 5 to 7 days to recruit.

It is assumed that the low levee alongside the excavated channel is ineffective. Therefore all geomorphological objectives are achieved by high flow freshes and no recommendation is made for bankfull or overbank flows.

The pools in this reach are shallow and frequently flushed by low flows. No flow recommendation is made to address pool water quality (5a).

Table 7. Flow objectives for Reach 1 – Barwon River at Upper Barwon.

Flow				Rationale
Season	**Magnitude**	**Frequency**	**Total Event Duration**	
summer	Low Flow 5 ML/d	continuous		1a Perennial riparian shrub growth 1c Perennial submerged aquatic macrophyte growth 2a Permanent Dwarf Galaxid population 4a Habitat for macroinvertebrate communities in summer and autumn
summer	Low flow freshes 215 ML/d	2-3 per year	2 days	1d Seasonal submerged aquatic macrophyte growth in floodplain pools or wetlands
winter	Baseflow 50 ML/day	continuous		1d Submerged aquatic macrophyte growth in floodplain pools and wetlands 1e Seasonal emergent macrophyte growth 2c Longitudinal connection in channel for *Galaxias olidus* dispersal 2d Downstream migration of *G. brevipinnis* 4d Support main growth and reproductive season for macroinvertebrates
winter	Small High Flow Fresh 153 ML/d	2-3 per season	5 days	4b Create and extend habitat for aquatic macroinvertebrates 3c 3d 3e Geomorphological features
winter	Large High Flow Freshes 1600ML/d	annual	7-10 days	1b Riparian shrub community growth 2b Inundation of floodplain vegetation for Dwarf Galaxid breeding 3c 3d 3e Geomorphological features 4b Create and extend habitat for aquatic macroinvertebrates

Achievement of Recommendations

The recommendations for this reach are only partially achieved under currently flow conditions due largely to the influence of the West Barwon Dam upstream of this reach. The influence of the dam is stronger in the upper sections of this reach. Given, we have only flow records at the beginning and end of the reach we cannot say how much of the reach achieves these recommendations. The low flows in the summer and high flow freshes in winter are met meaning that fish and aquatic vegetation populations may be maintained but growth and expansion of macro-invertebrates and aquatic macrophytes will not occur nor will regular longitudinal connections will not be available for fish migration (Galaxiid species). Some of the geomorphological functions will also not occur.

Table 8. Analysis of the current frequency and duration of the recommended flows for Reach 1.

Season	Recommendation	Current	Achievement
Summer	Low continuous flows of 5 ML/d	Currently exceeded 85% of the time which is close to natural flow series	Flow recommendation largely met
Summer	Low flow freshes of 215 ML/d 2-3 times per year for 2 days	Currently occurs 1-2 times per year (always over 2 days)	Flow recommendation not currently met
Winter	Baseflow of 50 ML/d	Currently exceeded 50% of the time when naturally it would have occurred about 80% of the time	Flow recommendation not currently met
Winter	Small high flow freshes of 153 ML/d 2-3 times per season for 5 days	Currently occurs 7-8 times per season with over 3 events of over 5 days	Flow recommendation met
Winter	Large high flow freshes of 1600 ML/d	Current occurs 3-4 times per y ear for with at least one event of over 7 days	Flow recommendation met

4.2 Reach 2 - Winchelsea

Environmental Flow Objectives

The flow objectives for Winchelsea are presented in Table 9.

Cease to flow is not a natural phenomenon in this reach and no recommendation was made for cease to flow.

During summer and autumn, low flows are required to maintain permanent pools in this reach. Low flows are also required to sustain some riffle habitat between the main growing period of winter and spring. This flow is determined by the lowest flow that provides a pool detph of more than 50 cm at two out of three cross sections and wets the stream bed perimeter at all cross sections.

Low flow freshes are recommended on the basis of the habitat requirements of River Blackfish. Freshes inundate hard surfaces, such as woody debris on which eggs are layed. They also allow fish to meet and breed and for larval fish to disperse to pools throughout the reach. This threshold was set by the flow required to cover woody debris at the island cross section (section number 5). Only one event of this duration is required to trigger breeding, but two are specified to ensure that breeding occurs.

The baseflow recommendation is based on the flows to promote seasonal growth of emergent macrophytes and to provide sustained aquatic habitat for aquatic macroinvertebrates. The recommended flow wets the toe of the bank, and will either waterlog or inundating emergent vegetation on sandy benches or fringing the stream.

Periods of elevated baseflow are recommended to provide additional temporary habitat for macroinvertebrates. This discharge will inundate the majority of the island at cross section 5 and will completely inundate all other benches in the reach. Periods of two weeks are required to provide significant breeding and growth opportunities.

High flow freshes are required 3 to 5 times per year over a period of seven days each. The channel in this reach is steeply incised into the floodplain. This discharge will inundate shrubby vegetation growing on the steep banks of the channel, such as *Leptospermum lanigerum* and *Callistemon sieberi* and will reach the upper extent of *Phragmites australis*. This discharge connects pool and riffle habitats throughout the reach and provides migration opportunities for *Galaxias olidus* and *G. brevipinnis*. Sandy bench habitats are also inundated, which provides breeding habitat for *G. olidus*. Large high flow freshes will have sufficient energy to disturb vegetation from the stream channel, thereby maintaining habitat diversity and areas with an open stream environment. Woody debris will also be moved, to create snaggy accumulations.

At bankfull levels, morphological features will be maintained by scouring pools, creating sandy benches and maintaining the downstream movement of sediment.

Overbank flows are recommended primarily to provide periodic, temporary inundation of the scattered remnant Red Gum and Blackwood vegetation on the floodplain. Overbank flows will also have sufficient energy to remove any accumulated macrophyte beds in the stream channel, and are therefore recommended every 5 years.

Table 9. Flow objectives for Reach 2 - Winchelsea

Flow				Rationale
Season	**Peak Magnitude (Mean Daily)**	**Frequency**	**Total Event Duration**	
summer	Low Flow 12 ML/d	continuous		2f River Blackfish require sustained low flows to maintain permanent pools in this reach 4a Low flows sustain the macroinvertebrate community in summer
summer	Low flow freshes 175 ML/d	2 per year	4 days	2g Submerge woody debris or hard, clean surfaces for River Blackfish breeding 2h Flows to connect pools for River Blackfish movement
winter	Baseflow 120 ML/d	continuous		1e Seasonal growth of emergent macrophytes 4d Aquatic macroinvertebrates activity
winter	Elevated Base Flow 240 ML/d	1-2 per year	14 days	4c Macroinvertebrate growth and reproduction
winter	Large High Flow Freshes 2,400 ML/d	3-5 times per year	7 days	1b Riparian shrub community growth 2c Upstream migration of Galaxias olildus 2d Downstream migration of Galaxias brevipinnis 2i Inundate sandy benches for Mountain Galaxias habitat 3b 3d 3f 3g 3i Geomoroplogical features
winter	Bankfull Flows 12,000 ML/d	1 per year	12 days	3c 3e Geomorphological features
winter	Overbank flows >12,000 ML/d	One 30,000 ML/d event every 5 years	16 days	3a Disturb emergent macrophyte beds 1f Support growth and recruitment of floodplain woody vegetation

Achievement of Recommendations

The recommendations for this reach are largely achieved with current flows. This indicates however any further reduction in frequency or duration of these flow events will lead to a decline of the values of the reach.

Table 10. Analysis of the current frequency and duration of the recommended flows – Reach 2.

Season	Recommendation	Current	Achievement
Summer	Low flows of 12 ML/d	Currently and natural occurs 70% of the time or more	Flow recommendation largely met
Summer	Low flow freshes of 175 ML/d 2 times per year for 4 days	Currently occurs 2-3 times per year with several events over 4 days in duration	Flow recommendation met
Winter	Baseflows of 50 ML/d	Currently occurs 50% of the time which exceeds the natural occurrence	Flow recommendation met
Winter	Elevated base flows of 240 ML/d 1-2 times per year for 14 days	Currently occurs for approx. 18% of the time whereas naturally occurred about 25% of time	Flow recommendation largely met
Winter	Large high flow freshes of 2,400 ML/d 3-5 times per year for 7 days	Currently these occur 2-3 times per year for mostly over 7 days which is similar to natural which occurred 3 times per year	Flow recommendation largely met
Winter	Bankfull flows of 12,000 ML/d once per year for 12 days	This flow occurs once every 1.5 years with at least 1 or 2 events over 12 days in length	Flow recommendation largely met
Winter	Overbank flows of 30,000 ML/d for 16 days every 5 years	This currently occurs over 5 years with some events of about 15 days 16 days	Flow recommendation largely met

4.3 Reach 3 – Murgheboluc Valley

Environmental Flow Objectives

Flow objectives for the Murgheboluc Valley reach are presented in Table 11. This reach represents the Barwon River from Leigh River confluence to Buckley's Falls.

Cease to flow does not occur either naturally or currently in this reach. No related ecological objectives were identified and no recommendation is made for cease to flow.

The presence of resident population of River Blackfish requires low flow to be sustained throughout the hydrological summer period. At a discharge of 22 ML/d, the channel width is completely wetted, all pools are maintained. This flow is currently exceeded 80% of the time, which creates a low likelihood of stratified anoxic or saline conditions in pools. This discharge will sustain aquatic macroinvertebrate fauna. A low flow period is important to allow groundwater to recharge the stream. The water table is interpreted to be saline, and the presence of salt tolerant plants in the riparian zone, such as *Selliera radicans*, requires periodic saline conditions.

Low flow freshes support breeding by River Blackfish which occurs over the period from November to January. The woody debris on which fish lay eggs is inundated at several locations at 498 ML/d, and this is the flow recommended for the freshes. This discharge exceeds the level required for fish to move between pools during the breeding period, which occurs at 20.4 ML/d.

The recommended baseflow discharge represents the flow required to create waterlogged conditions in the lowest benches adjacent to the channel bed. This will support the seasonal growth of emergent macrophytes growing on the channel fringe will provide habitat in riffles, pools and vegetation for aquatic macroinvertebrates.

One to two periods of elevated baseflow are recommended to occur each year to provide additional habitat for aquatic macroinvertebrates. This discharge will inundate benches at the upstream end of the main pool in the modelled stream section and will inundate most riffles.

Two sustained high flow freshes are required in most years to support the seasonal growth of shrubby vegetation on the floodplain, including *Callistemon sieberi* and *Lomandra longifolia*. The flow threshold of 11,000 ML/d was determined as the level required to provide a shallow water table for floodplain vegetation and to activate flood runners. Freshes will also allow the migration of Galaxias and Grayling. High flow freshes will maintain geomorphological features in the reach such as bench formation, sediment transport, woody debris movement and the formation of pools.

Bankfull flows are required primarily to maintain geomorphological features such as pools, benches, undercuts and floodplain channels. The current frequency and duration is recommended to maintain the existing stream geomorphology. This exceeds the requirement to disturb reedy vegetation from the stream channel every 5 years to maintain an open cobble habitat for fish and macro-invertebrates.

The objective to periodically remove shrubby vegetation from floodplain benches is achieved by the overbank flow discharge of 40,000 ML/d. This achieves a flow depth of 1.4 m over the floodplain delivering a velocity of 1.1 m/sec. It is required every ten years, with the duration of such events naturally spanning 17 days.

Table 11. Flow objectives for Reach 3 – Murgheboluc Valley

Flow				Rationale
Season	**Peak Magnitude (Mean Daily)**	**Frequency**	**Total Event Duration**	
summer	Low Flow 22 ML/d	continuous		1g Presence of salt indicator plants 2f River Blackfish require sustained low flows to maintain permanent pools in this reach 4a Low flows sustain the macroinvertebrate community in summer 5a Avoid prolonged stratified conditions in pools
summer	Low flow freshes 498 ML/d	2 per y ear	5 days	2g Submerge woody debris or hard, clean surfaces for River Blackfish breeding 2h (20.4 ML/d) Flows to connect pools for River Blackfish movement
winter	Baseflow 56 ML/d	continuous		1e Seasonal emergent macrophyte growth 4d Support main growth and reproductive season for macroinvertebrates in spring
winter	Elevated Base Flow 196 ML/day	1-2 times per year	2 weeks	4c Create and extend habitat for aquatic macroinvertebrates
winter	High Flow Freshes 11,000 ML/day	2 per year	10 days	4c Create and extend habitat for aquatic macroinvertebrates 1b Perennial riparian shrub growth 2c Longitudinal connection in channel for Galaxias olidus dispersal 2d Downstream migration of G. brevipinnis 2g Submerged woody debris for Blackfish breeding 2i Longitudiinal connection in channel for adult Grayling movement 2i Flow over sandy islands and benches for Mountain Galaxias breeding 3b 3d 3f 3g 3h 3i Geomorphological features
winter	Bankfull Flows 28,000 ML/d	Every 1.5 years	15 days	3a 3c 3e 3h Geomorphological features
winter	Overbank flows 40,000 ML/d	Every 10 years	17 days	3j Disturb shrub layer vegetation on floodplain to create a mosaic of habitats

Achievement of Recommendations

The recommended flow are mostly met in the lower flow ranges but bankfull and overbank flows do not occur with the required frequency or duration under current conditions. This means that many geomorphological functions are not catered for including vegetation disturbance required for a diverse floodplain habitats. Some of the high flow functions may not be met each year under current conditions therefore limiting the growth and population size and diversity of riparian vegetation, macroinvertebrates, and fish.

Table 12. Analysis of the current frequency and duration of the recommended flows at Reach 3.

Season	**Recommendation**	**Current**	**Achievement**
Summer	Lows flows of 22 ML/d	This flow is currently exceeded 95% of the time	Flow recommendation met
Sumer	Low flow freshes of 498 ML/d twice per year for 5 days	This flow currently occurs about twice per year for approx. with durations of event for at least 5 days	Flow recommendation met
Winter	A baseflow of 56 ML/d	This flow is currently exceeded 95% of the time	Flow recommendation met
Winter	An elevated baseflow of 196 ML/d once or twice per years for 2 weeks	This flow is currently exceeded 55% of the time slightly exceeding natural flow events	Flow recommendation met
Winter	High flow freshes 11,000 ML/d twice per year for 10 days	These flows currently occur only once per year with several events are over 10 days	Flow recommendation only partially met
Winter	Bankfull flows of 28,000 ML/d every 1.5 years for about 15 days	This flow currently only occurs every 3 years but no event occur more than 12 days	Flow recommendation not met
Winter	Overbank flows of 40,000 ML/d over 10 years for 17 days	This currently happen every 5 years but no event currently exceeds 7 days	Flow recommendation not met

4.4 Reach 4 - Geelong

Environmental Flow Objectives

Flow objectives are presented in Table 13. This reach represents the Barwon River from Buckley's Falls to the Lower Breakwater.

Limited habitat is available for aquatic macroinvertebrates in the emergent vegetation fringing the weir pool in this reach. The water level is largely controlled by the lower breakwater (the weir) so a flow as low as 8 ML/d is sufficient partially inundate this fringing vegetation during summer. Similarly, a baseflow of 8 ML/d is recommended in winter. This value is provisional, and should be refined through additional investigations into the discharge required to maintain the pool water level after stormwater, groundwater and evaporative fluxes are taken into account.

Further work is required to determine an appropriate discharge for low flow freshes. These events must regularly mix the pool to prevent stratification and associated risks of anoxia and algal blooms. The flow to achieve destratification can only be determined through a specialist study of the hydraulics of the pool. The requirement for such a flow should also be considered in the light of alternative mixing strategies by aeration or mechanical means.

Sustained low flow freshes are required in the reach to enable Australian Grayling to breed between February and May in most years. These flows will allow for a well mixed and oxygenated water column and that aquatic vegetation beds and Instream benches to be inundated providing required habitat and food items for larvae and juveniles.

High flow freshes are recommended to partially inundate low floodplain areas and billabongs near the river. This occurs at a discharge of 4153 ML/d and supports the seasonal growth of floodplain and wetland vegetation and provides habitat for floodplain fauna including macroinvertebrates, small fish and waterbirds. Four events per year are recommended to maintain wetland habitat throughout the season. This flow is also sufficient to maintain the physical form of floodplain channels and inlets.

The bankfull discharge is based on the geomorphological bankfull level and will maintain the downstream movement of sediment and will maintain physical habitat features such as pools, undercuts and benches.

These flows are noted as these recommendations are only provisional at this stage pending assessment of downstream flow requirements and adaptive management results. This reach is subject to specific impacts and changes which need to be considered in these assessments, including:

- storm water management and impacts
- risks of algal blooms
- continued modification of the Reach e.g. through further revegetation
- flows to support recreation and tourism (as already foreshadowed by the CCMA)

Table 13. Flow Objectives for Reach 4 - Geelong

Flow				Rationale
Season	**Peak Magnitude (Mean Daily)**	**Frequency**	**Total Event Duration**	
summer	Low Flow 8 ML/d			4a Low flows sustain the macroinvertebrate community in summer
summer	Low flow freshes 250 ML/d	2 events per year	14 days	5a Avoid prolonged stratified conditions in pools 2k Grayling breeding trigger
winter	Baseflow 80 ML/d			1e Seasonal emergent macrophyte growth 2j Permanent deep pool (min depth 3 m) for Grayling 2l Connecting flow between pools for Grayling 2m Connecting flow to estuary 4d Support main growth and reproductive season for macroinvertebrates in spring
winter	High Flow Freshes 4,153 ML/day	4 per season	6 days	1b Growth and recruitment of riparian shrubby vegetation 1f Growth and recruitment of floodplain woodland vegetation 1h Opportunistic aquatic plant growth in flooded billabongs 3g (Ml/d[2]) Scour sediments from base of pools 3d Maintain floodplain channels and inlets 2b Inundate floodplain vegetation for Dwarf Galaxias breeding 4b Extend habitat for aquatic macroinvertebrates
winter	Bankfull Flows 40,000 ML/d	Every 1.2 year	16 days	3c Maintain channel form and key physical habitat features 3e Downstream sediment transport

Note: These recommendations are only provisional at this stage pending assessment of downstream flow requirements

[2] Sufficient for scour holes etc check flow measure flow concentration

Achievement of Recommendations

The recommendations for this reach are largely achieved with current flows. Bankfull flows are not currently met. However this assessment indicates that further reductions in frequency or duration of these flow events will lead to a decline of the values of the reach.

Table 14. Analysis of the current frequency and duration of the recommended flows at Reach 4.

Season	Recommendation	Current	Achievement
Summer	Low flow of 8 ML/d	Currently this occurs nearly 100% of the time which is slightly more frequent than naturally	Flow recommendation met
Summer	Low flow freshes of 250 ML/d twice per year for at least 14 days	This flow is currently occurs 3-4 times each year with at least two events over 15 days in length	Flow recommendation met
Winter	Baseflow of 80 ML/d	This flow currently occurs 85% of the time which is similar to the natural frequency	Flow recommendation met
Winter	High flow freshes of 4153 ML/d which occur 4 times each season for about 6 days	This flow currently just 4 times per season (previously was 7-8 times per season) for durations mainly above 6 days	Flow recommendation met
Winter	Bankfull flows of 40,000 ML/d 6 times every 5 years for 16 days	Currently this flow occurs only once every 3 years with no events longer than 15 days	Flow recommendation not met

4.5 Reach 6 – Birregurra Creek

Environmental Flow Objectives

Flow objectives for Reach 6 (Birregurra Creek) are presented in Table 15.

Birregurra Creek is a significantly modified stream environment. The hydrology and salinity regime has been altered by releases made to the watercourse and the clearance of native vegetation from the catchment. The vegetation the stream supports are affected by the altered hydrology and salinity regime, as well as land clearance, weed invasion and continued stock access. Under these circumstances, where the stream is a managed and highly modified ecosystem, it was not reasonable for the EFTP to recommend a flow that would sustain the components of the original stream ecosystem. Instead, objectives were set to maintain the current community of salt-tolerant emergent macrophytes and associated fauna.

The salt-tolerant species *Bolboschoenus caldwellii* occurs in watercourses subject to seasonal drying and temporary salinisation. A cease to flow period of 22 days, occuring twice per year (which is the current regime), was recommended to provide a dormant period for *Bolboschoenus* and *Eleocharis acuta* and to allow the salinity of the soil and shallow groundwater to increase.

No baseflow recommendation was made. Instead frequent high flow freshes are recommended to maintain the waterlogged soils and temporary inundation that supports the seasonal growth of emergent macrophytes. The recommended discharge of 24 ML/d will provide a depth of 200 mm throughout the reach will support fish movement. Between 5 and 6 events per year was recommended as sufficient to provide a minimum growing period for the existing plant assemblage.

Bankfull flows will temporarily increase the habitat for aquatic macroinvertebrates, increasing the food available for fish and waterbirds. By maintaining the current frequency and total event duration, they will also continue to maintain geomorphic features and maintain the movement of sediment downstream.

Overbank flows will spread on to the flats in the upstream section of this reach, inundating the low shrubland community of *Halsoarcia* spp., *Juncus* spp. and *Distichlis disticophylla*. Events occurring every second year will help maintain the current soil moisture and salinity regime and will help exclude terrestrial vegetation from the watercourse. They will provide temporary additional habitat for macroinvertebrates, waterbirds and fish.

Table 15. Flow objectives for Reach 6 – Birregurra Creek

Flow				Rationale
Season	**Magnitude**	**Frequency**	**Total Event Duration**	
summer	Cease to flow	2 per year	22 days	1g Presence of salt indicator plants
winter	High Flow Freshes 24 ML/d	5-6 events per year (current is 8)	15 days	1e Seasonal emergent macrophyte growth 4d Main growth and reproductive season for aquatic macroinvertebrates 2c *Galaxias olidus* dispersal 2d Downstream migration of *G. brevipinnis*
winter	Bankfull Flows 136 ML/d	1 every 0.8 of a year	9 days	3c Channel form and key physical habitats 3e Downstream sediment transport 4b Extend aquatic macroinvertebrate habitat
winter	Overbank flows 321 ML/d	1 in 2 years	7 days minimum	1j Temporary inundation of saline floodplain vegetation

Achievement of Recommendations

As outlined in the Issues Paper, the flow regime of this reach has been significantly impacted with increased flows meaning that most of these flows being exceeded under current conditions and more frequently than under natural conditions. Biodiversity, growth and reproduction are likely to be limited by increased frequency of flow events and the salinity range of discharged water.

Table 16. Analysis of the current frequency and duration of the recommended flows for Reach 6.

Season	Recommendation	Current	Achievement
Summer	2 Cease to flow events per year for 22 days each	This currently occurs 70% of the time	Flow recommendation met
Winter	High flow freshes of 24 ML/d 5-6 per year	Currently occur 8 times per year	Flow recommendation met
Winter	Bankfull flows of 136 ML/d 4 times very 5 years	This now occurs very frequently, well above this threshold and more frequently under natural conditions	Flow recommendation met
Winter	Overbank flows of 321 ML/d every 2 years for a minimum of 7 days	This now occurs very frequently, well above this threshold and more frequently under natural conditions	Flow recommendation met

4.6 Reach 7 – Boundary Creek

Environmental Flow Objectives

Flow objectives for Reach 7 (Boundary Creek) are presented in Table 17.

The channel in this reach has been artificially deepened and straightened drain cut into the floodplain. The channel has steep sides with little bench development. It is desirable to promote bench development to provide additional habitat complexity, the geomorphological objective 3g, to scour sediments from the base of pools was not included. Objective 3a, to create open water habitat by disturbing emergent vegetation, was also considered irrelevant as open water is not a natural characteristic of this stream.

A healthy stream in this reach would support dense, reedy vegetation, although this has largely been replaced by exotic grasses and forbs. A cease to flow period of 2 weeks, twice per year, is recommended to support the growth of grasses and reeds on the stream bed.

A baseflow of 1 ML/d is recommended to maintain semi-permanent aquatic habitat for small fish and macroinvertebrates. This discharge will fully wet the channel perimeter. Groundwater discharge is likely to contribute significantly to this flow requirement. Similarly in summer, a baseflow of 1 ML/d is recommended to promote the growth of emergent macrophytes growing at the channel edge. Inundation of this vegetation will provide habitat for aquatic macroinvertebrates.

A discharge of 64 ML/d provides 200 mm inundation over vegetation on the bench in the channel. Freshes of this discharge will provide temporary additional habitat for macroinvertebrates.

The channel is artif icially and deeply incised. Therefore no bankfull level can be defined. Overbank flows are intended to contribute to (or reflect) the presence of a shallow water table under the floodplain, which is required to support the growth of waterlogging-dependent vegetation. Although it has been cleared from the floodplain, Tea Tea would formerly have been the dominant vegetation type. A discharge of 137 ML/d corresponds to a water table lying 0.5 m below depressions on the floodplain, and would allow Tea Tree communities to be restored.

Table 17. Flow recommendations for Reach 7 – Boundary Creek

Flow				Rationale
Season	**Magnitud**	**Frequency**	**Total Event Duration**	
summer	Cease to flow	2 per year	2 weeks	1i Summer macrophyte and grass colonisation of stream bed
summer	Low Flow 1 ML/d			2a Semi-permanent aquatic habitat for Dwarf Galaxid 4a Macroinvertebrate habitat in summer and autumn
winter	Baseflow 1 ML/day			1e Seasonal emergent macrophyte growth 2b Inundation of vegetation for Dwarf Galaxias breeding 4d Main growth and reproduction season for aquatic macroinvertebrates
winter	High Flow Freshes 64 ML/d	4 per season	6 days	4b Extend aquatic macroinvertebrate habitat
winter	Overbank flows 137 ML/d[3]	1 in 2 years	9 days	1a Perennial riparian shrub growth 3b Disturb riparian vegetation 3c Maintain channel form and key habitats 3e Main downstream sediment transport

Achievement of Recommendations

Flow recommendations in this reach are mostly achieved however these flow recommendations could be easily curtailed with increasing catchment dam development.

Table 18. Analysis of the current frequency and duration of the recommended flows for Reach 7.

Season	Recommendation	Current	Achievement
Summer	2 Cease to flow events per y ear for 2 weeks	This currently occurs 30% of the time which is slightly more frequent than natural	Flow recommendation met
Summer	A summer low flow of 1 ML/d	This occurs about 40% of the time during summer which is about the same as the natural frequency	Flow recommendation met
Winter	A baseflow 1 ML/d	This occurs about 80% of the time during summer which is about the same as the natural frequency	Flow recommendation met
Winter	High flow freshes of 64 ML/d 4 times each season for 6 days	This occurs about 3-4 times per year with many events longer than 6 days	Flow recommendation largely met
Winter	Overbank flows of 137 ML/d once every two years for 9 days	This flow occurs every 1.5 years with several events over 9 days	Flow recommendation met

[3] Half a metre of groundwater under the depressions on the floodplain required – which is met by this flow

4.7 Reach 8 – Mid-Leigh River

Environmental Flow Objectives

Flow objectives for Reach 8 are presented in Table 19. This reach represents the Leigh River from Cambrian Hill to Quiney Hill.

Under natural conditions cease to flow events occurred only rarely, approximately once every year for five days. Cease to flow no longer occurs due to discharges to the stream higher in the catchment. There is no ecological basis for recommending that cease to flow is restored.

Low flows are required to maintain the extensive pool habitats that occur in this reach. The pools will support River Blackfish and macroinvertebrates over summer and autumn. A flow of 12 ML/d will entirely wet the channel width and will provide up to 300 mm inundation in the active parts of the riffles and most riffle beds. This will provide perennial habitat for aquatic macroinvertebrates and will maintain. The requirement for permanent pools for River Blackfish is met at a discharge of 6 ML/d and will also be achieved. Currently this flow is exceeded 90% of the season, and will also protect pool water quality from risks associated with salinity and anoxia.

Low flow freshes are required to support River Blackfish breeding. Sediment is removed from the substrate on which eggs are layed, snags and other hard surfaces, at key locations in the reach at 5.6 Ml/d. However, the threshold for this flowband is based on the requirement for connectivity between pools for Blackfish adults and juveniles to move during and after breeding, which occurs at flows of 44.5 ML/d. Two freshes are required each year to provide a reasonable certainty of breeding occurring.

Baseflows support the main growth and reproductive period for aquatic macrophytes. A discharge of 49 ML/d provides waterlogged conditions for the lowest benches adjacent to the channel bed on which Phragmites australis and Eleocharis acuta occur. These conditions will also support the seasonal activity of aquatic macroinvertebrates. This discharge will allow the migration of small fish up and downstream.

Two periods of elevated baseflow, each lasting two weeks are recommended to support the growth of riparian shrubs growing in a broader zone than the channel perimeter. At a discharge of 248 ML/d, the stream level corresponds to a water table less than half a metre below the floodplain surface at several sites. This would support the seasonal growth of *Callistemon sieberi* and *Leptospermum lanigerum* and other deep-rooted floodplain plants such as *Lomandra longifolia* and *Phragmites australis*. This discharge will also inundate benches on which emergent macrophytes grow, providing addtional temporary habitat for aquatic macroinvertebrates.

The lowest flood runners crossing the floodplain are activated at a discharge of 1658 ML/d. This has been set as the threshold for high flow freshes which will provide breeding habitat for Mountain Galaxias by inundating sandy islands and benches and will maintain the physical environment of the stream channel and floodplain.

The threshold for bankfull events of 3744 ML/dwas set to inundate and promote recruitment in floodplain shrub communities and to maintain the channel and floodplain form. This threshold reflects the geomorphological bankfull level and will have sufficient energy to remove emergent macrophytes from the stream channel, which occurs at a discharge of 2025 ML/d. The recommended discharge will disrupt and open up patches of vegetation on the floodplain by achieving the Q95 threshold at at least one cross section, thereby maintaining a mosaic of environments. It will also maintain downstream sediment movement and maintain undercuts, pools and benches.

Table 19. Flow objectives for Reach 8 – Mid-Leigh River

Flow				Rationale
Season	**Peak Magnitude (Mean Daily)**	**Frequency**	**Total Event Duration**	
Summer	Low Flow 12 ML/d			2f (6 ML/d) Permanent pool habitat for Blackfish 4a (12 ML/d) Sustain macroinvertebrates during summer and autumn
Summer	Low flow freshes 44.5 ML/d	2 per year	2-3 days	2g (5.6 ML/d) Inundate woody debris or hard surfaces as a Blackfish 2h (44.5 ML/d) Longitudinal connection in channel
winter	Baseflow 49 ML/d			4d Main growth and reproductive season for macroinvertebrates 2c (44.5 ML/d) Connect pools for small fish migration 2d Downstream migration of G. brevipinnis 1e Seasonal emergent macrophyte growth
winter	Elevated Base Flow 248 ML/day	2 times per year	2 weeks	1a Perennial riparian shrub growth 4c Extend aquatic macrophyte habitat
winter	High Flow Freshes 1,658 ML/day	2 per season	7 days	2i Flow over sandy islands and benches 3b 3d 3f 3g 3h[4] (93 ML/day) Geomorphological objectives
winter	Bankfull Flows 3,744 ML/d	Every 1.2 years	10 days	1b Riparian shrub community recruitment 3a (2,025 ML/day) 3c (depth) 3e 3j Geomorphological objectives

[4] provisional

Achievement of Recommendations

The recommended flows for this reach are largely met under the current regime although high flow freshes are only marginally achieved indicating further flow extraction is unsustainable.

Table 20. Analysis of the current frequency and duration of the recommended flows for Reach 8.

Season	Recommendation	Current	Achievement
Summer	No cease to flow	No cease to flow	Flow recommendation met
Summer	Low flow of 12 ML/d	This flow is currently exceeded 90% of time which is slightly more frequent than natural	Flow recommendation met
Summer	Low flow freshes of 44.5 ML/d twice per year for 2-3 days	Currently occurs more than 8 times per year for up to 15 days	Flow recommendation met
Winter	Elevated baseflow of 49 ML/d	Currently occurs 65% of the time	Flow recommendation met
Winter	Elevated baseflow of 248 ML/d twice per year for 14 days	Currently occurs between August and December 5% of the time	Flow recommendation met
Winter	High flow freshes of 1,658 ML/d twice per season for 7 days	This occurs 1-2 times per year with durations for some events over 7 days	Flow recommendation largely met
Winter	Bankfull flows of 3,744 ML/d every 1.2 years for 10 days	This flow occurs every 1.2 years with several events exceeding 10 days	Flow recommendation met

4.8 Reach 9 – Lower-Leigh River

Environmental Flow Objectives

Flow objectives for Reach 9 are presented in Table 19. This reach represents the Leigh River from Quiney Hill to the Barwon River confluence.

Under natural conditions cease to flow events occurred only rarely, approximately once every two years for three days. Cease to flow no longer occurs due to discharges to the stream higher in the catchment. There is no ecological basis for recommending that cease to flow is restored.

The requirement to maintain pools for aquatic fauna and macroinvertebrate habitat during the hydrological summer is met by a low flow of 8 ML/d. This discharge provides a trickle flow between pools and completely wets the channel width in all channel pools.

Emergent macrophyte growth in this reach is limited to a narrow zone near the baseflow level and sparse patches on low sandy benches. Baseflow is required to support the growth of this vegetation and to provide habitat for aquatic macroinvertebrates. The recommended discharge of 52 ML/d provides waterlogged conditions for the lowest benches adjacent to the channel bed at cross sections 2 and 4 and provides sufficient flow for small fish to migrate through the reach.

High flow freshes that support breeding breeding events for Dwarf Galaxias are recommended to occur twice per year to provide a reasonable certainty of successful breeding. Shrubby vegetation (*Leptopsermum lanigerum* and *Callistemon sieberi*) grow half-way up the bank on this reach The recommended discharge of 2217 ML/d will inundate this level and is interpreted to support growth and reproduction of vegetation in this zone. This discharge will also achieve geomorphological objectives to maintain physical habitat features in the watercourse.

Bankfull flows is geomorphologically defined, i.e. it is the flow required to reach the top of the bank. The current discharge of 11000 ML/d currently occurs once every five years with a total event duration of 22 days, and should be continued to maintain the current stream geomphorphology.

The billabongs and woodland vegetation on the floodplain are dependent on overbank flows. A discharge of 11000 ML/d will fill billabongs, providing temporary habitat for submerged aquatic macrophytes such as Milfoil, habitat for macroinvertebrates and small fish. When flooded, the billabongs are likely to support waterfowl and possibly piscivorous waterbirds. Overbank flows will also increase floodplain soil moisture, promoting the growth of Red Gum and Blackwood and promoting tree recruitment. These events only occur intermittently in this reach and it is recommended that the current event frequency of one in five years, with total event duration of 22 days is maintained.

Table 21. Flow objectives for Reach 9 – Lower Leigh River

Flow				Rationale
Season	**Peak Magnitude (Mean Daily)**	**Frequency**	**Total Event Duration**	
summer	Low Flow 8 ML/d			2a (ML/d) Semi-permanent aquatic habitat for Dwarf Galaxid 4a Macroinvertebrate habitat in summer and autumn
winter	Baseflow 52 ML/d			1e Seasonal emergent macrophyte growth 2c Flow connects pools to allow *Galaxias olidus* dispersal and *G. brevipinnis* migration upstream 2d Downstream migration of *G. olidus* 4d Main growth and reproduction season for aquatic macroinvertebrates
winter	High Flow Freshes 2217 ML/day	2 per year	8 days	1b Riparian shrub community recruitment 2b Inundation of vegetation for Dwarf Galaxias breeding 3a (48.8 ML/d) Disturb stream-bed macrophytes 3b (48.8 ML/d) Disturb riparian vegetation 3g (90.2 ML/d) Scour sediments from pools 3i (1.9 Ml/d[5]) Form woody debris accumulations
winter	Bankfull Flows 8476 ML/d[6]	Every 5 years	17 days	3c Maintain channel form and physical habitat features 3eDownstream sediment transport
winter	Overbank flows >11000 ML/d[7]	Once every 5 years	22 days	1f Growth and recruitment of floodplain woodland species 1h Submerged aquatic macrophyte growth in billabongs

[5] Sufficient for scour holes etc check flow measure flow concentration

[6] This level is the geomorphological bankfull 7 Nov 1995 flood was 7884 ML/d mean daily

[7] Flood billabongs and floodplain redgums for opportunistic growth & recruitment

Achievement of Recommendations

The flow recommendations for this reach are mostly met but large flows are slightly reduced in frequency and duration.

Table 22. Analysis of the current frequency and duration of the recommended flows for Reach 9.

Season	Recommendation	Current	Achievement
Summer	Low flow of 8 ML/d	Currently this flow occurs 95% of time	Flow recommendation met
Winter	Baseflow of 52 ML/d	Currently this flow occurs 50% of the time	Flow recommendation met
Winter	High flow freshes of 2217 twice per years for 8 days	This flow occurs twice per year with events up to 15 days	Flow recommendation met
Winter	Bankfull flows of 8476 ML/d every 5 years for 17 days	This flow currently occurs once every five years for up to 17 days	Flow recommendation met
Winter	Overbank flows of over 11,000 ML/d once every 5 years for 22 days	This flow currently occurs every 30 years or so which is about the same frequency as the natural frequency	Flow recommendation met but flow series indicates some doubt about this flow recommendation

4.9 Reach 5 – Estuary

The Estuary is a complex of habitats, such as:

- Salt Swamp
- Hospital Swamp
- Reedy Lake
- Lake Connewarre including the estuarine sections of the lower River Channel

Each has a range of values for waterbirds, vegetation, fish and aquatic fauna, despite modific ation of the water regime of three of these, with only Lake Connewarre fully connected to the estuary.

Reedy Lake is approximately 550 ha in area and is reported to be the largest freshwater wetland in central Victoria (Yugovic 1985). Prior to European settlement, Reedy Lake was an ephemeral wetland that received minor flow from a small local catchment and major flows from peaks in the Barwon River. The Barwon River was originally estuarine upstream beyond the lake and the lake would have received a combination of saline and freshwater inflows, depending on the contribution of high tides and high river flows.

A regulated channel was cut between the Barwon River and Reedy Lake in 1953, upstream of the lower breakwater. The channel provided a regular input of freshwater to the lake. Initially, water entering the lake rapidly drained to the estuary. In order to maintain water levels in the lake during the 1967-1968 drought, the bank at the outlet was raised.

These works have important implications for the groundwater environment of the lake. Like the other lakes fringing the estuary, the lake is a natural discharge site for shallow groundwater. Under natural conditions, the salinity of the lake would have increased when water was absent, as groundwater discharge to the surface, or when sea water entered the lake. The salinity of the lake would have declined when the lake was inundated by fresh water from the Barwon River. The greater the depth of flooding, the greater was the potential for fresh surface water to have freshened the soil profile.

This water regime is likely to have created a similar plant habitat to conditions currently found in Hospital Swamp. Shallow saline groundwater would have supported a zone of salt tolerant macrophytes a the fringe, such as *Muehlenbeckia florulenta, Gahnia sieberi, Poa labillardieri* and *Distichlis distichophlla*. Shallow, seasonal inundation by freshwater would have occurred at the fringes of the wetland, at the limit of normal flooding from the Barwon River. This would have created waterlogged, flooded soils with some degree of freshening in winter and spring, but more saline in summer and autumn. These conditions are tolerated by the emergent macrophytes *Typha* sp., *Phragmites australis, Schoenoplectus validus, Eleocharis sphacelata* and *Bolboschoenus medianus. Schoenplectus validus* and *Eleocharis sphacelata* tend to occur in deeper water (a normal seasonal range of 0.2 to 0.8 m) that does not normally dry out. *Phragmites australis* and *Typha* sp. tend to occur in soils that dry out seasonally, but are flooded seasonally by 0.2 to 1.5 m of water, ideally for 9 months. *Bolboschoenus caldwellii* is highly salt tolerant and will grow in areas that are seasonally inundated by up to 0.8 m for as little as 2 months per year. Sandy soils at the wetland fringe would provide favourable habitat for *Baumea juncea*. It is possible that well-flushed soils with low salinity may have supported sedgelands of other *Baumea* species.

Emergent macrophytes are likely to have been excluded from the lower bed of the lake by deep flooding in winter and spring. Regular seasonal flooding to more than 1 m will exclude most emergent macrophytes, particularly when flooding depth represents an additional stress to saline soils. When flooded, the lake is likely to have supported a variety of salt tolerant semi-emergent and submerged macrophytes such as *Ruppia* sp., *Lepilaena* sp., *Myriophyllum* sp., *Vallisneria gigantea*, and *Triglochin procerum*. Falling lake levels in late spring / early summer would have provided a saline marsh habitat for herbs such as *Triglochin striata, Mimulus repens, Pratia concolor, Apium annuum* and *Cotula* spp.

If the lake dried out, the deepest lake bed may only have provided bare soil, but would have been colonised by opportunistic terrestrial grasses, particularly *Agrostis avenacea*. These broad concentric zones of vegetation were observed by Yugovic (1985) in the 1980s.

The balance between these plant habitats has been altered by a gradual freshening of the lake and the introduction of a more stable and permanent freshwater regime. Since 2000, a new water regime has been introduced with the objectives of controlling carp and maintaining the quality of habitat for waterbirds. The flow thresholds relevant to the current water management regime are:

- 0 m AHD - inlet sill at the channel between the Barwon River and Reedy Lake upstream of the lower breakwater;
- 0 m AHD – lake bed level;
- 0 m AHD – sill of outlet channel between Reedy Lake and Lake Connewarre;
- 1.7 m AHD - overtop level of bank between Barwon River and Reedy Lake; and
- 0.9 m AHD – overtop level of bank between Reedy Lake and Lake Connewarre.

The water regime as recommended by PPK (2000) is presented in Table N.

Table 14. Recommended Water Regime for Reedy Lake (PPK 2000).

Month	Water Level (m AHD)
May	0.5
June	0.6
July	0.6
August	0.7
September	0.75
October	0.8
November	0.8
December	0.6
January	0.4
February	0.2
March	0.2
April	0.4
May	0.5

The key expected outcomes of this regime were:

- to provide deep water feeding and breeding habitat for waterfowl and habitat for eels and other fish between May and December;
- to exclude emergent macrophytes from most of the seasonally inundated area;
- to expose the lake margins between November and February to provide mudflat habitat for wading birds;
- to attract ducks and provide access by shooters to a range of locations with flooding of 0.4 m AHD in April and May.

In addition to this annual cycle was recommended that the lake is completely dried from time to time to eliminate carp. The recommended regime was to completely dry the lake for three months from February.

It was also recommended that in years when large numbers of Ibis breed that higher lake levels are maintained until fledging occurs.

This water regime has not had the intended result. The extent of open water habitat has been extensively replaced by reeds (particularly *Typha orientalis* and *Phragmites australis*) such that only a small area of open water remains. Furthermore, the reed habitat has a low floristic diversity and many of the plant communities described by Yugovic (1985) have declined or been lost.

The main causes of the change in vegetation are likely to relate to the relatively stable water levels under the current water regime (particularly during the growing season of plants between September and January) and the relatively deep water levels.

While the current water regime floods and exposes a significant proportion of the lake bed June and December, this corresponds to a change in water level of only 0.2 m. It is likely that the area that is exposed by falling water levels will remain damp and will therefore provide similar plant habitat to areas flooded by up to 0.4 m. This is particularly true for summer-growing generalist species such as *Typha orientalis* and *Phragmites australis* which will readily grow in a range of water depths ranging from waterlogged soils to depths of 0.5 m. The current water regime provides these conditions over a large proportion of the lake between October and January, which is the main growing period for these species.

The current water regime also maintains a water depth of 0.5 m or more for 8 months of the year in Reedy Lake. This will exert a downward pressure on the naturally saline groundwater that lies beneath the lake. Saline groundwater is a significant controlling factor on the structure of plant communities in the Barwon River estuary. This water regime will create fresh soil conditions over a large proportion of the lake, which will favour species that grow in low salinity soils, such as *Typha orientalis* and *Phragmites* sp.

Lake Connewarre State Wildlife Reserve consists of an extensive estuarine and saltmarsh system drained by the Barwon River. It includes a large permanent freshwater lake, a deep freshwater marsh, several semi-permanent saline wetlands and an estuary. Water is supplied from the Barwon River, local catchments and estuarine flows.

This wide variety of wetland habitats supports large and diverse waterbird populations. A total of 135 bird species (72 waterbird species) have been recorded in the reserve (Pescott 1983). This includes 29 species listed by JAMBA and CAMBA, two species listed only by CAMBA and two species listed only by JAMBA (NRE 1995).

Reedy and Middle Lakes have supported large populations of Sharp-tailed Sandpipers and Marsh Sandpipers (Watkins 1993). Up to 2830 Straw-necked Ibis, 1230 Australian Shelduck, 2500 Pacific Black Duck, 2805 Grey Teal, 609 Purple Swamphens and 5508 Eurasian Coots have also occurred here (NRE 1995). The lakes have also supported threatened waterbirds such as Freckled Duck and Blue-billed Duck (listed under the Flora and Fauna Guarantee Act) (NRE 1995). Reedy Lake also supports the largest breeding population of Swamp Harrier in Victoria (DCNR 1993).

A number of rare and threatened waterbird species have been recorded at Lake Connewarre. These include Great Egret, Fairy Tern, Blue-billed Duck and Australasian Bittern (NRE 1995a). The lake has support large numbers of Curlew Sandpipers and Sharp-tailed Sandpipers (Watkins 1993). Up to 5000 Black

Swans and 2500 Eurasian Coot also have been observed (NRE 1995). Up to 2000 Black Swans, 980 Sharp-tailed Sandpipers, 1550 Red-necked Stints and 2800 Curlew Sandpipers have been counted at the Barwon Estuary (NRE 1995).

4.9.1 Waterbird Breeding

Waterbirds require successful nesting sites for successful breeding. Colonial nesting waterbirds such as Little Egret, White-necked Heron, White-faced Heron, Great Cormorant, Little Black Cormorant, Pied Cormorant, Little Pied Cormorant and Yellow-billed Spoonbill build stick-nests in trees next to lakes or wetlands (page 55). These nests are often built in branches overhanging open water. This group of waterbirds feed in wetlands within the reserve but are not likely to breed, due to a lack of large trees.

Some duck species nest in tree hollows near water. While the Australian Wood Duck is only waterbird dependent on tree hollows, other species such as Pink-eared Duck, Blue-billed Duck, Chestnut Teal, Grey Teal, Australian Shelduck, Pacific Black Duck may nest in tree hollows or on the ground amongst dense vegetation. These species may breed at Lake Connewarre State Wildlife Reserve during periods of high food availability.

Three groups of waterbirds are likely to breed in Lake Connewarre State Wildlife Reserve. Colonial nesting species such as the Straw-necked Ibis and Glossy Ibis build their nests in bushes of lignum. Large breeding populations of Straw-necked Ibis, Australian White Ibis, Glossy Ibis and Royal Spoonbills have been recorded from Reedy and Middle Lakes (NRE 1995). The lakes have supported more than 10% of the regional breeding population of Straw-necked Ibis and Australian White Ibis and more than 5% of the State's breeding population of Royal Spoonbill (ANCA 1996). A colony of 10 000 plus Straw-necked Ibis nested in 1977, 1978 and 1979 and a colony of 500 Australian White Ibis was observed in 1983 (Marchant & Higgins 1991).

Most colonial nesting waterbirds only breed successfully when their nests are surrounded by water. If water levels drop before the young birds fledge, adult birds often abandon their nests (Scott 2001). Flood magnitude and duration is may be important determinant of the size and success of breeding events for colonial nesting waterbirds in Lake Connewarre State Wildlife Reserve.

Another group of waterbirds likely to breed in reserve are those that create platform nests on or near water by trampling down rushes, reeds or cumbungi. Freckled Duck, Black Swan and Musk Duck. Australasian Grebe and Great Crested Grebe form a platform nest at water level in dense stands of reeds and rushes by collecting together a mass of submerged and floating water plants. Buff-banded, Rail Dusky Moorhen and Purple Swamphen build platform nests under the cover of dense emergent water plants.

A third group of waterbirds likely to breed in Lake Connewarre State Wildlife Reserve are those that build shallow ground scapes amongst various dense vegetation or debris near the edge of waterbodies. This includes a range of small waders such as Red-necked Avocet, Black-fronted Dotterel, Red-capped Plover and Black-winged Stilt.

Use of Water Regime Classes by breeding waterbirds

Common Name	Breeding Stimulus	Nest Type	Principal Breeding Site
Red-necked Avocet	Flooding, Seasonal	Ground scrape in flooded reeds	Temporary Wetland
Black-fronted Dotterel	Flooding	Ground scrape in flooded reeds	Temporary Wetland
Masked Lapwing	Flooding	Ground scrape in flooded reeds	Temporary Wetland
Red-capped Plover	Flooding	Ground scrape in flooded reeds	Temporary Wetland
Black-winted Stilt	Flooding	Ground scrape in flooded reeds	Temporary Wetland
Freckled Duck	Flooding, Seasonal	Platform in reeds or shrubs 1 m above water	Temporary Wetland
Black Swan	Flooding	Mattress of vegetation near reeds	Temporary Wetland
Musk Duck	Seasonal	Mattress of vegetation near reeds	Temporary Wetland
Australasian Grebe	Flooding	Raft of reedy vegetation over deep water	Temporary Wetland
Great Crested Grebe	Flooding	Raft of reedy vegetation over deep water	Temporary Wetland
Buff-banded Rail	Flooding, Seasonal	Platform in or on flooded reeds	Temporary Wetland
Dusky Moorhen	Flooding	Platform in or on flooded reeds	Temporary Wetland
Purple Swamphen	Flooding	Platform in or flooded reeds	Temporary Wetland
Darter	Flooding	Stick nest in flooded trees	Red Gum Forest
Little Egret	Flooding, Seasonal	Stick nest in flooded trees	Red Gum Forest
While-necked Heron	Flooding, Seasonal	Stick nest in flooded trees	Red Gum Forest
White-faced Heron	Flooding	Stick nest in flooded trees	Red Gum Forest
Great Cormorant	Flooding	Stick nest in flooded trees	Red Gum Forest
Little Black Cormorant	Flooding	Stick nest in flooded trees	Red Gum Forest
Pied Cormorant	Flooding	Stick nest in flooded trees	Red Gum Forest
Little Pied Cormorant	Flooding	Stick nest in flooded trees	Red Gum Forest
Yellow-billed Spoonbill	Flooding, Seasonal	Stick nest in flooded trees	Red Gum Forest
Australian Wood Duck	Flooding	Tree hollows near water	Red Gum Forest
Pink-eared Duck	Flooding	Tree hollows or reedy platform	Red Gum Forest
Blue-billed Duck	Flooding	Tree hollow or reedy platform	Red Gum Forest, Temporary Wetland
Chestnut Teal	Flooding	Tree hollow or reedy platform	Red Gum Forest, Temporary Wetland
Grey Teal	Flooding	Tree hollow or reedy platform	Red Gum Forest, Temporary Wetland
Australian Shelduck	Flooding, Seasonal	Tree hollow or reedy platform	Red Gum Forest, Temporary Wetland
Pacific Black Duck	Flooding	Tree hollow or reedy platform	Red Gum Forest Temporary Wetland

Floods are likely to play a major role in waterbird breeding in Lake Connewarre State Wildlife Reserve. Flooding initiates a productive succession of potential food resources, which attracts waterbird species and stimulates breeding (Maher and Carpenter 1984; Crome 1986). Wetland productivity is tied to wetting and drying cycles associated with the growth and decay of aquatic plants (Maher and Carpenter 1984). On reflooding, the vegetation is drowned, and the rich organic substrate and decaying vegetation supports the development of complex wetland flora and large invertebrate populations (Crome, 1986). In contrast, permanent water bodies with little fluctuation in water level do not promote large scale breeding of waterbirds (Frith, 1982).

There is no hydrological hydraulic or systematic, long-term water level records for the three main wetlands of the estuary to reliably relate water levels to ecological outcomes. The following recommendations are based on discussions with Field and Game representatives and the land and water resource managers responsible for managing the estuary.

4.9.2 Reedy Lake

Discussions with local stakeholders have identified the following objectives for Reedy Lake:

- the lake should support a diverse range of waterfowl, reed-dependent birds, fish eating birds and large and small waders;
- the lake should support a range of aquatic plant communities including open water, semi-emergent macrophytes and emergent macrophytes;
- carp populations should be minimised;
- water should have sufficient clarity to support the growth of submerged macrophytes;
- the lake should support waterfowl hunting in late autumn and early winter.

The lake does not currently achieve these objectives, particularly due to the increasing dominance of emergent reeds, particularly *Typha* sp. and *Phragmites australis*. Consequently there has been an increase in the abundance of reed-dependent waterbirds and decline in species dependent on open water. The habitat available for waterfowl and opportunities to hunt them have declined. Carp have become increasingly dominant and are thought to limit the growth of submerged aquatic macrophytes. Reedy Lake also supports beneficial uses such as water extraction, a commercial eel fishery and game hunting as it is a game reserve and all of these beneficial uses are also not supported by the current regime as access to the Lake is gradually excluded by reed growth.

The current water regime provides conditions that promotes emergent reeds at the expense of other species. The current regime also provides limited opportunities for carp to be controlled (a drawdown every 6-7 years only). It is recommended that the following principles are used to alter the water regime and to achieve the management objectives. A proposed water regime is presented to apply the principles (Table 23).

The majority of the lake bed should dry out completely over summer and autumn. *Typha* and *Phragmites* are summer-growing plants that grow best in flooding up to 500 mm deep between October and February. Dry conditions from November to March will check the growth of these plants and lead to an eventual decline. There may be short term conflicts with the beneficial uses of the Lake at these times but the proposed regime will lead to a longer term improvement for each of the beneficial uses.

Dry conditions over summer and early autumn will also restore a more saline water table beneath the lake. The vegetation and water regime of the lakes fringing the estuary indicate that a saline water table lies close to the surface (but groundwater monitoring would be required to confirm this). At Reedy Lake, permanent flooding will have exerted downward pressure on the aquifer, reducing groundwater salinity. Higher soil salinities occur where groundwater evaporates from a dry lake bed, such as at Salt Swamp, and these conditions are too saline for *Typha* and *Phragmites* to grow. Higher soil salinities would further limit the growth of *Typha* and *Phragmites*. They would promote salt-tolerant shrubs and herbs (such as Samphire) when the lake is dry and would promote semi-emergent macrophytes and open water when the lake is flooded. Dry conditions will also reduce the population of resident carp.

A large proportion of the lake should be to a depth of more than 1 m during winter and early autumn. Seasonal flooding will provide habitat for waterbirds, fish and submerged aquatic macrophytes. If the water level is maintained at a fairly stable level for most of this time, emergent macrophytes will be limited to a narrow zone at the perimeter of the flooded area. Active control of these water levels would be required and it is believed that the current infrastructure is not able to provide this level of control to create the desired water regime.

Central to this conceptual model of lake water requirements is an understanding of the response of the aquifer to flooding and drying. Monitoring bores are required in the lake bed and the lake perimeter to assess the potential for these principles to be applied and to modify the conceptual model if required. Deep and shallow bores located in the lake bed and the lake perimeter would provide information on the vertical salinity gradient in salinity, water table responses to flooding and drying, response times and local groundwater gradients and flows. Monthly records of surface water levels should also be kept.

It may not be possible to apply the proposed water regime without modifications to existing structures and flow paths. In particular, the current density of reeds significantly slows water movement. Upgrade to the water distribution infrastructure is required to achieve the necessary level of control over water regime to ensure water regime objectives to be me and to enable timely response to unforeseen or undesirable ecological or environmental changes.

Due to the resilience of reeds to seasonal flooding conditions, an amended flow regime would have to be applied for at least five years for significant changes in their distributions to appear. If this time frame was unacceptable, it would be possible to accelerate change by introducing a complete drought (permanent drying) for an initial period of three years to initiate the restoration of the desired ecosystem structure. This suggestion however would impact upon the beneficial uses of duck hunting and the commercial eel fishery for this period, so it is likely that the first or second option in Table 23 is more likely allow these uses to continue (even if it is with some impacts initially),

Table 23. Recommended Water Regime for Reedy Lake

Month	1st Option Water Level (m AHD)	2nd Option Water Level (m AHD)	3rd Option Water Level (m AHD)
May	0.4	0.4	0.4
June	0.4	0.4	0.4
July	0.6	0.6	0.6
August	0.9	0.9	0.9
September	0.9	0.9	0.9
October	0.5	0.9	0.9
November	0.3	0.5	0.9
December	0.1	0.3	0.5
January	0	0.1	0.3
February	0	0	0.1
March	0	0	0
April	0	0	0

Three options are proposed for the management of Reedy Lake:

- The first option is most conservative and has a strong chance of resulting in a change in the vegetation structure to the desired system of open water with submergent macrophytes and diverse fringing vegetation.
- The second option could be applied every year with the likelihood that the preferred vegetation objectives occur but the change may take a longer time to re-adjust. There is a increased , but still low, risk of summer growing macrophytes (such as *Typha* & *Phragmites*) becoming more prevalent. This might better support waterbird breeding and an ideal water regime might see this option applied four out of five years and option one in the remaining year (with a low rainfall).
- The third option could be applied but would have a low likelihood of change to the preferred ecological condition. It is perhaps an option that could be applied in high rainfall years only – based on a rainfall trigger of something like the 75th percentile rainfall, which might co-incide with large waterbird breeding events once in a decade or similar frequency.

Broadly the water regime will result in:

- Flooding in early winter and drying out in mid-spring before the main growing season of reeds;
- Reeds would be excluded from the central area by saline groundwater, by flooding that is too deep for them in spring and by the absence of flooding in their main summer growth period;
- A drying phase to control exotic fish species and allow nutrient processing in the wetland bed;

- The central lake area would be flooded to a depth of more than 1 m for 3 to 6 months, in which would grow emergent and semi-emergent water plants like milfoil, *Potamogeton, Triglochin and Lepilaena*. This will allow for aquatic invertebrates and fish populations to breed and expand with Reedy Lake;
- Reeds would persist, but in a zone near the seasonal upper limit of water levels in winter and spring;
- High level intermittent flooding in winter and spring by rainfall and river flows every 2-3 years to allow extensive flooding, aquatic habitat creation and fish breeding events.

This would probably provide the greatest diversity in waterbird, fish and plant habitats, but has the limitation of not having water present during the duck shooting season. Note however, the infrastructure currently is not able to provide this option and would need upgrading to enable it to proceed. Without such changes the values and beneficial uses of Reedy Lake may be lost or diminished.

4.9.3 Hospital Swamp

The water regime of Hospital Swamp has been regulated for approximately 20 years. The wetland features a range plant assemblages that correspond to soil the various soil moisture, salinity and flooding environments present. According to local wetland managers, the existing water regime supports the desired ecological community. The following articulates the existing relationship between water regime and ecology so that management may be formalised.

Hospital Swamp comprises 5 basins which receive water both from the Barwon River estuary and from local runoff. The wetland is isolated from the estuary by a bund. Water is diverted from the Barwon River via a regulated channel through Sparrowvale Farm, which has an invert of 0.3 m AHD. Other unregulated channels become active at Barwon River levels greater than 1.4 m AHD.

The wetland overflows to Lake Connewarre at a level of 0.5 m AHD. The wetland can be drained using a regulated pipe with an invert of 0.2 m AHD.

The regulator is opened when the Barwon River exceeds 0.7 m AHD. Barwon levels greater than 0.9 m AHD allow Hospital Swamp levels to reach 0.5 m AHD, the normal full level.

The limit of wetland vegetation is defined by *Muehlenbeckia florulenta* shrubland which occurs in association with *Distichlis distochophylla* and *Juncus kraussii*. This association lies at an elevation of more than 1 m AHD is rarely flooded. It is likely to occur in soils that are seasonally waterlogged. Flooding would be tolerated, but is not a requirement to sustain this vegetation.

Elevations between the Lignum and the normal full level of the wetland (0.5 m AHD) support salt tolerant sedges and herbs. *Bolboschoenus caldwellii* was observed growing over *Sarcocornia quinqueflora* and *Selliera radicans*. Other species likely to be present include *Mimulus repens, Schoenoplectus pungens, Triglochin striata* and *Distichlis distichophylla. Bolboschoenus caldwellii* grows in saline areas subject to inundation with fresh or brackish water for a period of 1 month to 4 months in most years. The vegetation in this area most likely reflects a zone of permanent waterlogging where saline groundwater discharges to the surface, but soil salinities are reduced seasonally by flooding.

The normal full level of the wetland is marked by emergent macrophytes, particularly *Phragmites australis* and *Bolboschoenus caldwellii. Schoenopletctus validus* is also likely to be present. This association occurs at the fringe at the wetland at at islands within the wetland that emerge above 0.5 m AHD.

Between elevations of 0.5 and 0.1 m AHD (the base of the wetland) the vegetation comprises a marshland assemblage. This area is regularly inudated to a largely stable maximum depth of 0.5 m AHD and supports a range of submerged and semi-emergent herbs and shrubs. Common species observed during the site inspection include *Sarcocornia quinqueflora, Ruppia maritima, Distichlis distichophylla, Mimulus repens* and *Cotula coronopifolia.* Other species likely to be present include *Potamogeton* sp., *Crassula helmsii, Rumex bidens, Triglochin procerum, Triglochin striata, Schoenoplectus pungens* and *Lilaeopsis polyantha.* This assemblage reflects the brackish conditions of the wetland, which are likely to be least saline when freshwater enters from the Barwon River, but becomes progressively more saline as water levels fall and groundwater discharge increases. Species such as *Triglochin procerum, Ruppia* and *Lilaeopsis* will tolerate permanent inundation or seasonal flooding. Species such as *Sacrocornia, Distichlis, Mimulus, Rumex* and *Triglochin striata* are favoured by seasonal inundation but will tolerate permanent waterlogging. The presence of the latter species suggests that drawdown of the wetland in late spring is important to this vegetation structure. Low water levels in November and December will provide an opportunity for these low-growing species to flower and set seed before excessive temperatures, high salinities or insufficient moisture in January and February inhibit further growth.

Water management specifically involves:

- maintenance of a saline water table at or near the surface of the wetland bed. This will allow some areas of permanent low level pools providing fish habitat in which to over summer;
- fresh water inundation between June and November for a period of at least 3 months in most years to a depth of more than 0.4 m to support the growth of submerged aquatic plants such as *Lilaeopsis, Potamogeton* and *Ruppia*;
- fresh water inundation for 2 to 4 months to an elevation of 0.5 m AHD in winter and spring in most years to support the growth of emergent aquatic macrophytes such as *Phragmites australis* and the creation of extensive aquatic habitat, stimulate fish breeding and enable recruitment of fish larvae;
- intermittent inundation (events of 1 to 2 weeks, 2 to 4 times per year) of the *Bolboschoenus* sedgeland and to enable extensive breeding events of fish such as galaxiids within the sedgelands;
- drawdown in November or December in most years to provide a growing opportunity for lake bed herbland species; and
- drawdown of the wetland in late summer and all of autumn to maintain the salinity of soil water and to restrict emergent macrophytes to the wetland fringe.

Flooding is not required by *Muehlenbeckia* shrubland growing at the fringes of the wetland. However this plant association tolerates temporary inundation and probably reflects a water regime involving soils that are seasonally waterlogged by saline groundwater and inundated by surface water for 2 months 1 year in 10.

4.9.4 Salt Swamp

Salt Swamp is a shallow basin located to the south of Lake Connewarre, extending south-west from the Lower Barwon Channel. The Barwon Heads Road intersects the southern corner of the swamp. The site has previously been impacted by grazing and shell-grit extraction, but it retains diverse and largely intact native vegetation.

Estuarine water is excluded from the lake at normal levels by a low bund. The lake receives runoff from a local catchment which accumulates in the lake bed and is lost to seepage and evaporation. High levels in the estuary can spill into the swamp with a reported recurrence interval of 2 years (Yugovic 1985). The site appears to be a groundwater discharge zone and supports a waterlogging-tolerant halophytic plant community.

The central, lowest lying part of the lake supports an extensive (approximately 40 ha) *Wilsonia* herbfield. The dominant species in this assemblage is *Wilsonia humilis,* but the species *W. backhousei* and *W. rotundifolia* are also present. The herbfield is subject to annual inundation, approximately from June to December. The extent of the herbfield corresponds to the extent of regular inundation. When flooded the swamp supports *Ruppia maritima, Lepilaena preissii* and *Chara* sp.

A *Sarcocornia quinqueflora* herbfield occurs in seasonally waterlogged, saline soils at the perimeter of the area subject to regular inundation. Component species of this association are *Triglochin striata* and *Samolus repens*.

A samphire shrubland, dominated *Sclerostegia arbuscula* and *Halosarcia pergranulata* occurs on well-drained saline soils at the at the perimeter of the *Sarcrocorina* herbfield. Rainfall in winter and spring promotes seasonal growth and flowering of *Disphyma clavellatum*, *Frankenia pauciflora* and *Cotula coronopifolia*.

Gahnia filum sedgeland occurs at the perimeter of the wetland in association with *Distichlis distichophylla, Enchylaena tomentosa, Dysphyma clavellatum, Wilsonia humilis* and *Poa poiformis*. It appears to be associated with seasonally waterlogged soils that lying over a saline water table.

Water management at Salt Swamp specifically involves:

- a saline water table that lies at or near the surface of the wetland bed;
- drying of the wetland bed in summer and autumn to maintain the dominance of *Wilsonia* spp. by curtailing the growth of aquatic plants and providing a recovery period for *Wilsonia* spp.; and
- flooding the wetland to the limit of the *Wilsonia* herbfield on an annual or biannual basis for 4 to 6 months to provide surface water and soil water and salinity requirements for *Wilsonia* spp. and to provide growing conditions for aquatic plants (e.g. *Ruppia maritima*). This will also create habitat, trigger breeding and allow for recruitment of macroinvertebrate and fish species.

Flooding of areas higher in the wetland are probably not essential to maintaining the vegetation communities of the wetland. However, they are tolerant of flooding and would tolerate the following water regime:

- flooding in the Samphire shrubland for up to 2 months 1 year in 5; and
- flooding in the *Gahnia* sedgeland for up to 2 months 1 year in 10.

The flooding in the fringing shrubland and sedgelands for 1- 2 months every 3 years will enable extensive breeding events for fish species such as Common Jollytail, Blue-Spot Goby, Congolli, and Silverside.

4.9.5 Lake Connewarre including the estuarine sections of the lower River Channel

Lake Connewarre, the current active estuary of the Barwon, is characterised by dynamic changes in water levels and salinity – this variability is required to maintain the diverse fish and macroinvertebrate fauna.

The principles of the water regime to support the aquatic ecosystem and its habitat for Lake Connewarre are:

- Complete flushing during winter to maintain salinities at or below seawater;
- Spring flushes of freshwater from upstream to lower salinity and flood marginal zones of the lake to trigger fish breeding and recruitment;
- Low discharge in autumn to minimise flushing; and,
- Flows over the fishway at Lower Breakwater to enable fish movement along the lower Barwon.

Specifically, the following flow recommendations are made for the current active estuary:

- Late winter to early spring flushing flows

A flow of at least 600 ± 200 ML/day measured at McIntyres Bridge (Geelong) should be maintained for at least 3 months in late winter/early spring (between July and October) as a flushing flow to maintain freshwater conditions. This flow should occur at least once annually.

This estimate is based on a logarithmic relationship found between disxcharge and salinity in Lake Connewarre and on a hydrodynamic model developed for the lake (Sherwood *et al*. 1987)

- Summer/Autumn Low Flows

Salinity in Lake Connewarre should not exceed 35ppt during summer and autumn low flow conditions and this maximum level should not be maintained for more than 2 months. The minimum environmental flow needed to achieve this is 30 ± 10 ML/day at McIntyres Bridge

- Flow variability

Temporal variability in the input of freshwater flow is an inherent component of a functioning estuarine environment. Such variability, for example, results in variations in salinity that advantage euryhaline species adapted to highly variable salinity regimes. Loss of this variability has the potential to drastically alter community structure, with euryhaline estuary species replaced by stenohaline species adapted to either truly marine or freshwater environments. A minimum flow (Recommendation 2) will provide flows to ensure that a salinity gradient is maintained in the upper estuary. However, a minimum flow will not provide the variability required to maintain the estuarine ecological community. It is recommended, therefore, that the managed flow regime include periods of low flow (or cease to flow conditions) and freshes to mimic natural levels of flow variability. The frequency and timing of the recommended flows, and any independence rules related to meeting the recommendations, have not been specified here and will need to be formulated via further analysis of modelled flow data.

Flows less than the minimum flow established in Recommendation 2 (including cease to flow conditions) should be allowed to occur at their natural frequency and timing. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

Periods of higher flow should occur during summer and autumn at their natural frequency and timing to mimic natural freshes. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

- 4.5 Maintenance of Connectivity

The Upper and Lower Breakwaters (or Barrages) present barriers to fish migration in the Barwon River. Such barriers break the connectivity between the sea, estuary and river essential for the lifecycles of diadromous fish including galaxids, tupong , eels and, potentially, the threatened Australian grayling.

Fish passage should be provided to allow migration of diadromous species between freshwater and the estuary/sea.

5.1 Conclusions

Recommended and Current flows

The flow recommendations for the main stem of the Barwon River are largely met under current flow conditions. The effects of the West Barwon Dam upstream of this reach in the upper section of the first reach and may be evident in other reaches in terms of the high flows (bankfull and overbank flows) not being met in reaches 3 and 4. However, it is also clear that further reductions in frequency or duration of these flow events will lead to a decline of the values of the mainstem of the Barwon. The values at risk are geomorphological functions of flows (i.e. creation and maintenance of the form of the river channel and its habitats) and large breeding events the lack of which will limit the growth and population size and diversity of riparian vegetation, macroinvertebrates, and fish.

The flow recommendations for the tributaries of the Barwon are largely met by the current flow but Birregurra Creek and the Leigh River are subject to additional flows due to interbasin transfers or STP discharges. These additional discharges, in themselves, do not seem to have large adverse impacts but do create risks from additional saline or eutrophic conditions. These means that increases in the duration or frequency of cease to flows may provide additional threats to the values of these systems. High flows in these tributaries are generally only marginally met under the current flow regime. These flows and the ecological or geomorphological objectives they support are under risk with increasing catchment dam development or flow diversions.

Interpretation of Flow Recommendations

Where spell frequencies are recommended, they are the minimum required to achieve stream health. Therefore it is appropriate to deliver more spells than recommended, provided they do not exceed the natural maximum. Similarly longer durations can be delivered, as long as they do not exceed the natural maximum.

Most spells are recommended for a particular season. However the seasonal cutoff is arbitrary and designed to reflect general seasonal patterns in hydrology and ecological requirements. Spells that overlap the start or end of a specified season should be treated as belonging to the season.

The recommendations provided in this report are based on long-term statistics that describe an 'average year'. Over the long term, a range of spell frequencies and durations would occur. When developing rules to implement the recommendations, consideration should be given to the scope (and operational necessity) to vary spells implementation in 'wet' and 'dry' years so that the long term average is achieved.

A long term compliance period is required to evaluate:

- the incorporation of variability in flow delivery; and
- adherance to the recommended average flow.

A period of 10 to 20 years might be most appropriate from an ecological point of view in order to describe long term (5 to 10 year) cycles in hydrology and ecological responses. However a shorter compliance period, say 5 to 10 years, might be more appropriate from an operational point of view to allow management to be adapted within the current management and policy framework.

Comparing Recommendations between Reaches

Flow recommendations are not necessarily consistent between reaches. The recommended baseflows, low flows, freshes and flood flows vary in consecutive reaches. When viewed as a whole, the recommendations may appear inconsistent and impossible to apply, particularly where higher flows are recommended in upstream reaches than in downstream reaches, at the same time. This is not a condition that could occur in a natural system.

The reason for these inconsistencies is that the adopted FLOWS methodology considers the water requirements of reaches in isolation from each other. Flows are recommended on the basis of hydraulic modelling at a single representative site and field observations and existing data elsewhere in the reach. The behaviour of the river system outside the reach is not considered.

In general this approach is appropriate, because in regulated systems there is normally scope to manage the flow regime of reaches individually. However, the inconsistencies do highlight a real limitation of the method. The degree to which a single site can represent an entire reach depends on the variability within the reach. If additional sites were modelled, different, and perhaps more representative, flow recommendations would be made. It is likely that some of the inconsistencies between reaches would also be reduced.

5.2 Recommendations

It is recommended that the feasibility of implementing the flows recommended in this study is investigated.

The recommendations of this study will be used in a review of river management that seeks to balance environmental, social and economic requirements for water. In making allocations to the environment, it should be recognised that this study recommends the minimum flows required to achieve river health. Partial implementation of the recommended flows may not achieve river health.

There are constraints on the delivery of the flow recommendations presented in this report. In some cases the water management structures (weirs and reservoirs) have physical constraints that, without modification, do not enable flows of the recommended magnitude to be provided. The delivery of water for environmental purposes may represent safety risks or risks to property. Environmental requirements for water may conflict with the requirements of other consumers. The process to implement environmental flow recommendations must account for these factors.

While this study is based on the best available information and the opinions of experts, more detailed and site specific information would increase the confidence (and reduce the risks) with which the recommendations are made. The recommended flows should be considered as hypotheses that will be tested in an adaptive management framework through implementation, monitoring and periodic review.

References

ANCA (1996). A Directory of Important Wetlands in Australia Second Edition. Australian Nature Conservation Agency, Canberra.

Aronica, G., Hankin, B. and Beven, K., 1998. Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. Advances in Water Resources, 22(4): 349-365.

Burnham, M. and Davis, D., 1986. Accuracy of computed water surface profiles. Research Document 26, The Hydrologic Engineering Centre, U.S. Army Corps of Engineers, Davis, California.

Chow, V.T., 1959. Open channel hydraulics. McGraw Hill, New York.

Coon, W.F., 1998. Estimation of roughness coefficients for natural stream channels with vegetated banks. 2441, U.S. Geological Survey, Denver, CO, U.S.A.

Crome, F.H.J. (1986). Australian waterfowl do not necessarily breed on a rising waterlevel. Australian Wildlife Research 13:461-80.

Dingman, S.L. and Sharma, K.P., 1997. Statistical development and validation of discharge equations for natural channels. Journal of Hydrology, 199: 13-35.

DNRE (2002). FLOWS. A method for determining the environmental water requirements in Victoria. Department for Natural Resources and Environment, Victoria.

Frith, H.J. (1982) Waterfowl in Australia. Third edition. Augus and Roberston, Sydney.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. and Nathan, R.J. 2004. Stream Hydrology: An Introduction for Ecologists. Second Edition, John Wiley & Sons, Chichester.

Groeneveld, D.P. and French, R.H. 1995. Hydrodynamic control of an emergent aquatic plant (Scirpus acutus) in open channels. Water Resources Bulletin 31: 505-514.

Lang, S., Ladson, A. and Anderson, B., 2004. A review of empirical equations for estimating stream roughness and their application to four streams in Victoria. Australian Journal of Water Resources, 8(1).

Lloyd Environmental (2005). The Environmental Flow Determination for the Barwon River - Issues Paper. Report for Project LE5023 prepared for Corangamite CMA, Colac.

LYDEFTP 2004. Environmental Flow Determination For The Little Yarra And Don Rivers: Final Recommendations. Prepared by the Little Yarra and Don Rivers Environmental Flow Technical Panel for Melbourne Water Corporation, Melbourne.

Mahher, M.T. and Carpenter, S.M. (1984). Benthic studies of waterfowl breeding habitat in south-western NSW. II Chironomid Populations. Australian Journal of Marine and Freshwater Research 35:97-110.

Merchant, R. and Higgins, P. Eds. (1989) Handbook of Austalian, New Zealand and Antartic Birds. Vol 1. Oxford University Press, Melbourne.

NRE (1995). Wetland Database, Parks, Flora and Fauna Division, Department of Natural Resources and Environment, East Melbourne.

PPK Environment & Infrastructure P/L. (2000). Reedy Lake, Geelong - Water Level Management Plan. Report to Parks Victoria, July 2000.

Phillips, J.V. and Ingersoll, T.L., 1998. Verification of roughness coefficients for selected natural and constructed stream channels in Arizona. 1584, U.S. Geological Survey, Denver, CO, U.S.A.

Pescott, T. (1983). Birds of Geelong. Neptune Press.

Riggs, H.C., 1976. A simplified slope-area method for estimating flood discharges in natural channels. U.S. Geological Survey Journal of Research, 4(3): 285-291.

Scott, A.C (2001). Waterbirds: In Rivers as Ecological Systems: The Murray Darling Basin. Editor Young, W.J. CSIRO Land and Water, Canberra.

SKM 2005. Environmental water requirements of the Barwon System: preparation of daily stream flow data for the Barwon River, Draft A. Corangamite Catchment Management Authority, May.

Sturm, T.W., 2001. Open channel hydraulics. McGraw-Hill, Boston, USA.

US Army Corps of Engineers (2004). HEC-RAS software Version 3.1.2: www.hec.usace.army.mil

Western, A.W., 1994. The Behaviour of Salinity and Density Stratified Flows in the Wimmera River, Australia. PhD Thesis, The University of Melbourne, Melbourne, Australia.

Watkins, D. (1993). A National Plan for Shorebird Conservation in Australia. Australasian Wader Studies Group, Royal Australasian Ornithologists Union, Melbourne.

Yugovic, J.Z. (1985) The vegetation at the Lake Connewarre State Game Reserve. Arthur Rylah Institute for Environmental Research, Heidelberg.

Hydraulic Analysis of the Barwon River

Companion report to the 2005 FLOWS study to establish the environmental water needs of the Barwon River.

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October 2005

Table of Contents

1 Introduction

This report describes the hydraulic analysis conducted for the Barwon River FLOWS study, 2005. The first section of the report details the methodology and software tools applied in the study to develop one-dimensional hydraulic models for each of the eight surveyed reaches. In particular, this section focuses on the rigorous approach taken to estimate the roughness coefficient of each reach. The second section then presents a detailed description of the input parameters (reach geometry, downstream boundary condition and hydraulic roughness coefficient) used to construct HEC-RAS models of each reach.

Environmental flow recommendations were made by working interactively with HEC-RAS simulations. As an extra tool to assist with model interpretation the discharge required to satisfy a series of quantitative ecological and geomorphological thresholds (e.g. shear stress required to initiate sediment motion) were precomputed and tabulated. Indicative tables of threshold discharges are also presented herein.

2 Methodology

Numerical hydraulic models were developed for eight of the nine focus reaches on the Barwon River (the estuarine reach - site 5 - was not suitable for analysis using the FLOWS method (SKM et al., 2002)). Hydraulic analysis provides an efficient means to estimate the relationship between flow depth and discharge for each reach. For this project models were constructed using the HEC-RAS software (U.S. Army Corps of Engineers, Version 3.1.2, April 2004: www.hec.usace.army.mil), which is designed to perform one-dimensional steady state calculations for natural and constructed river reaches. Three elements are required to define a river reach within HEC-RAS: reach geometry; a downstream boundary condition; and a specification of hydraulic roughness. The following sections describe the methods used to quantify each of these elements, including consideration of uncertainty where relevant.

2.1 Reach geometry

The channel shape was measured by surveying between 6 and 10 lateral transects for each reach (transects are lines that cut across the stream perpendicular to the flow direction). Surveys provided the geometric data required to define a reach within HEC-RAS. Transects were located so as to capture the principal features of each reach, particularly geomorphic features such as pools, riffles and runs, and hydraulic features including channel constrictions, expansions and hydraulic controls.

2.2 Determination of Hydraulic Roughness

Hydraulic resistance (also called ‘stream roughness’) is a measure of the friction generated between flowing water and the channel boundary. Higher values of resistance are associated with rough-textured boundaries, with highly sinuous channels, and with turbulent flows down rapids and through vegetation. Flows through high resistance channels move more slowly and at a higher stage than through lower resistance channels at the same discharge. The magnitude of resistance determines the discharge at which different channel features are inundated, for example the bankfull flow at which flooding commences, and the speed at which flows are conveyed and accumulate down the network.

The overall value of flow resistance in a natural river comprises contributions from many interdependent sources, including: bed and bank roughness, bend losses, secondary flow resistance as well as the contribution of vegetation (Bathurst, 1993). There are four standard approaches used to estimate the various contributions to resistance in natural rivers and streams; they are: (i) procedural approaches; (ii) roughness tables; (iii) using roughness handbooks; and (iv) empirical or theoretical equations.

A procedural method that builds on the recommendations of Coon (1998) was developed for assessing the roughness of each of the eight reaches assessed for in the Barwon River FLOWS study. Coon's (1998) procedure is recommended by the United States Geological Survey and therefore is relevant for North American conditions that are somewhat different from those in Australia. Southern hemisphere data and techniques, for example Hicks and Mason's (1991) work, were therefore adopted in place of some of the references recommended by Coon (1998). There is no single best approach for the estimation of hydraulic resistance. In the absence of calibration data (measured discharge and stage), it is best practice to employ a range of methods (Coon, 1998; Lang et al., 2004). For this project, each of the four approaches (listed earlier) were employed, with the specific methods described in the following sections.

A note on the spatial variation of hydraulic roughness

In reality hydraulic roughness varies with both lateral position over a cross-section and longitudinally down a reach. However, the determination of roughness with available estimation techniques is imprecise. Therefore, roughness coefficients are estimated to find a reach-average value, with most of the effort expended defining in-channel roughness characteristics. As a result, for this modelling roughness coefficients are in general held constant in the longitudinal and lateral directions. The only exception to this rule is where well-defined floodplains exist. Floodplains are known to exhibit very different roughness to the channel, hence these zones are assigned roughness values independently to the main channel. Floodplain flows are however less critical in the FLOWS assessment, hence values were estimated using only Chow's (1959) table (Section D-2).

2.2.1 Procedural Approach – Cowan's Method

Cowan's (1956) method attempts to capture the essence of professional judgement in a procedural method. Cowan notes that while the value of resistance could depend on 8 or 10 factors, he suggests the five most important channel features to be: surface irregularity; cross-section variability; obstructions; vegetation resistance; and channel sinuosity. Using his approach a base value of Manning's n is selected according the bed and bank material (n_b), with corrections for each factor (n_1, n_2, n_3, n_4, and m). Once the correction factors are selected, an estimation for the net section resistance can be computed using (0.1) (in Table 2.1). An indication of the relative importance of the correction factors is implied by the maximum recommended adjustment increment (listed in Table 2.1).

Table 2.1 Cowan's Method: Equation and Correction Factors

Equation: $n = (n_b + n_1 + n_2 + n_3 + n_4) \times m$ (0.1)

Factor	Description	Maximum Values channel[a]	floodplain[b]
n_b	base value of n for a straight and uniform channel	0.070	
n_1	correction for surface irregularity	+0.020	+0.020
n_2	correction for cross-section size and shape	+0.015	n/a
n_3	correction for obstructions	+0.015	+0.030
n_4	correction for vegetation	+0.100	+0.200
m	correction for sinuosity	× 1.3	n/a

Table Notes:
a - Values recommended by Cowan (1956) b - Values listed by Arcement and Schneider (1989)

Cowan's (1956) approach has attracted some criticism. Cowan himself described two limitations: firstly, the method is not applicable to streams with mobile beds; and secondly, the data set from which recommended corrections were derived does not include large channels. In addition, the theoretical basis of the method has been questioned, as the assumption that the resistance corrections may be applied independently implies that the principal of superposition applies, a proposition examined and rejected by numerous subsequent fluvial studies (see pages 77-103 of review by Yen, 1991). However, despite these detractions, Cowan's method provides a useful tool for approximation. Indeed, it is a core component of the approach to roughness selection recommended by the USGS (Coon, 1998).

Estimates of roughness using Cowan's method are made in this project by reference to the tabulation provided by Chow (Chow, 1959, Table 5-5, p. 109).

2.2.2 Roughness Tables - Chow

Roughness coefficients are also estimated by reference to tables, most reproducing the table produced by Chow (1959), although a similar tabulation has also been produced in South African by Rooseboom et al. (1986). Chow's table provides indicative low, medium, and maximum Manning's n values for open channel types ranging from constructed drains (lined or built-up) to flows down natural streams and across floodplains. Chow constructed the table using the best available experimental data from published and unpublished studies (Horton, 1916; Ramser, 1929; USDA, 1955 in Chow, 1959, p.114).

Values of Manning's n are selected by matching the properties of the reach under investigation with the type of channel and description provided by Chow (1959).

2.2.3 Roughness Tables - Bathurst

More recently, Bathurst (1993) proposed a method for bracketing channel roughness based on differentiating streams according to the calibre of bed material and the prevailing channel slope. His method is founded on the presumption that the dominant factors controlling flow resistance vary along the channel network, and in many cases with discharge. He identified four principal channel types based on hydraulic considerations:

- In sand-bed channels resistance varies principally with bedform types, although suspended sediment concentration may also have an effect.
- In gravel-bed rivers bed material relative roughness and ponding in pool-riffle sequences are the important factors.
- In boulder-bed rivers flow resistance is determined by form drag of boulders.
- In step pool/fall channels, ponding is the critical factor.

It is worth noting that while changes in resistance mechanisms and coefficients occur along the river system, resistance at a site is also variable. For example with increased discharge, ponding effects may be drowned out while bank vegetation may come into play. Data compiled by Bathurst (1993) shows the typical parameter values and ranges for each of his stream types (Table 2.2).

Table 2.2 Typical physical properties of different channel types and characteristic values of their flow resistance characteristics. From (Bathurst, 1993).

Stream Type	Approximate range of Channel Slope (%)	Bed Material D_{50}* (mm)	Manning's n
Sand bed	≤ 0.1	≤ 2	0.01 – 0.04
Gravel / Cobble bed	0.05 – 0.5	10 – 100	0.02 – 0.07
Boulder bed	0.05 – 5	≥ 100	0.05 – 5
Step pool / fall	≥ 5	variable	0.1 – 5

* D_{50} = bed material particle size for which 50% of the material is finer.

2.2.4 Roughness Handbook – Hicks and Mason

Fluvial researchers routinely measure the hydraulic properties of study reaches, sometimes as core data, in other cases simply to provide background or context. The majority of publications in this area focus on the streams in North America, although in the Australasian region Hicks and Mason (1991) authoritative guide for New Zealand streams is arguably the most relevant. An effort was made to replicate this work and to produce an Australian guide (Anderson et al., 2001; Ladson et al., 2003), however, to date information on only four reaches has been submitted.

The guide produced by Hicks and Mason (1991) for New Zealand streams is substantially more detailed than previous studies, covering a greater number of streams (78), and more importantly including measurements for a wide range of in-channel discharges. This seems to have set the standard for subsequent publications. Roughness is estimated using the guide by selecting a reference reach that is similar to the one being investigated. Reach similarity is established by matching, as far as possible, channel size and shape, bed material, channel slope, and bank vegetation characteristics. A first order match is obtained by matching the mean annual discharge (m^3/sec), water slope at the mean discharge (approximated herein by the mean bed slope), and bed surface material size (specifically, the median diameter statistic for the bed surface material, D_{50}).

2.2.5 Empirical and Theoretical Equations – Dingman and Sharma

There are tens of empirical equations in the scientific and engineering literature that can be used to estimate stream roughness coefficients such as Manning's n (Anderson et al., 2001; Duncan and Smart, 1999; Lang et al., 2004). Collections of these were compiled and their performance assessed against directly computed roughness measurements for four reaches in Victoria by Lang et al. (2004). This investigation demonstrated that the empirical equations suggested by Dingman and Sharma (1997) and by Riggs (1976) produced the best results, while also noting that overall one should be sceptical when using empirical equations to estimate Manning's n. The two empirical equations are defined in Table 2.3.

Table 2.3 Empirical equations for predicting Manning's n (after Lang et al., 2004), where A is flow cross-sectional area (m^2); R is hydraulic radius (m); S_w is water-surface slope (m/m); and S is the channel bed slope (m/m, assumed to equal S_w).

Author	Equation	Description / Conditions for use
Riggs (1976)	$n = 0.210\ A^{-0.33}\ R^{0.667}\ S_w^{0.095}$	Uniform cross-sectional area (preferably not converging); nearly full natural channel. Calibrated to 62 data points, comprising areas and slopes from Barnes (1967), and unpublished data from the USA; not thoroughly validated according to Dingman and Sharma (1997)
Dingman and Sharma (1997)	$n = 0.217\ A^{-0.173}\ R^{0.267}\ S^{0.156}$	Calibrated to 520 data points from Barnes (1967) and Hicks and Mason (1991); verified using 100 data points from Barnes (1967) and Hicks and Mason (1991).

2.3 Identification of morphologic features

Morphologic features of the stream channels were utilised in two respects that relate to the hydraulic analysis. First, a bankfull stage was required in order to compute the geometric parameters required to evaluate the empirical equations of Dingman and Sharma (1997) and Riggs (1976), and were also central to selecting an appropriate reach from Hicks and Mason's (1991) guide. Second, to construct an appropriate environmental flow regime it was important to establish (for ecological and geomorphological reasons) the discharge required to inundate particular channel features, in particular inset benches, high flow channels, and to simply wet the wetted perimeter of the low flow channel. These later surfaces were identified during the workshop at which the technical panel worked through the process of quantifying the environmental flow requirements, and discharges were determined from pre-computed hydraulic results (Section 2 of this report).

2.3.1 Defining Bankfull Discharge

The bankfull stage is an important hydraulic parameter. It's most obvious use is used to demarcate in-channel flows from overbank flows. However, the more important aspect of bankfull stage is that, in alluvial channels especially, it is a good indicator of the dominant discharge and the sediment regime in the stream. For the hydraulic analysis, bankfull channel properties were important as they are widely employed in the literature, and are required in order to draw comparisons with properties of other channels. For example, the relationships presented by Rigg's (1976) and Dingman and Sharma (1997) are applicable only to flows less than bankfull stage.

For many channels, bankfull stage is a difficult feature to identify with great accuracy. Gordon et al. (2004) list a range of criteria that can be applied to assist in the determination of bankfull stage. It is a property best estimated by a qualified Geomorphologist (Dr. Chris Gippel for this study) using a combination of field inspection and quantitative analysis of cross-section survey data.

A bankfull stage was identified for most, but not all, cross-sections. Bedrock confined sections for example do not develop a distinct bankfull stage. At other cross-sections multiple horizontal surfaces were present, in such cases the bankfull stage of upstream and downstream sections was used to guide the selection of the appropriate level, with the other surface representing features such as inset benches.

2.3.2 Computations involving parameters at bankfull stage

An average in-channel geometry was computed for each reach by averaging the in-channel (sub-bankfull) characteristics of each cross-section. The empirical relationships of Rigg's (1976) and Dingman and Sharma (1997) were then applied using the average geometric values at four values of stage: 25%, 50%, 75% and 100% of bankfull. The range of roughness values computed are reported in the summary tables of Manning's n values for each reach, with the average of the roughness at each stage used to estimate overall reach roughness.

2.4 Parameter uncertainty and model sensitivity

River channels are highly complex physical systems and the hydraulic models constructed in HEC-RAS represent an approximation of this system. Parameter values were defined with the greatest accuracy possible given the constraints of time, resources and available technology. The hydraulic analysis followed the FLOWS method (SKM et al., 2002), with models of the river reaches constructed around at least 5 survey cross-sections (6 – 10 for the Barwon River project) with best professional judgement used to establish Manning's n roughness coefficients. The two principal sources of uncertainty in the hydraulic model are associated with the value assigned to the roughness coefficient (Manning's n), and with the downstream boundary condition.

2.4.1 Manning's n uncertainty

It is generally accepted that the greatest parameter uncertainty in one-dimensional hydraulic modelling is associated with the value assigned to roughness coefficients (Aronica et al., 1998; Burnham and Davis, 1986; Coon, 1998; Western, 1994). There is no single 'best' tool, technique or equation, as numerous studies have demonstrated (Coon, 1998; Lang et al., 2004; Phillips and Ingersoll, 1998). The accuracy of the estimate hinges is thought to hinge on the experience of the practitioner, aided by the application of multiple methods of roughness estimation. Hence for this project six different tools were employed to estimate hydraulic roughness, giving six Manning's n values (n^1, n^2 ... n^6). The average of these estimates was selected as the 'best' estimate of reach roughness.

The standard deviation of the estimates also provided an indication of the uncertainty associated with the value selected. Uncertainty bounds for a sampled parameter are usually set at two standard deviations either side of the mean (where, for normally distributed, data 95% of values fall within these bounds). However, as well as sample error, the estimation of roughness may also be inaccurate simply due to the tool used. i.e. every technique is not expected to supply an accurate estimate for every reach. Therefore, it is more likely that the actual value of roughness lies closer to the mean than two standard deviations would suggest. The uncertainty associated with the roughness coefficient was therefore set to one standard deviation rather than two in recognition of these two error sources.

Floodplain roughness values suffer from similar uncertainty. Floodplain roughness values were perturbed in proportion to the perturbation of in-channel roughness.

2.4.2 Downstream boundary condition uncertainty

The flow scenarios examined during this analysis were restricted to sub-critical flows, hence only a downstream boundary condition was required (Chow, 1959). Given the information available, normal depth was specified as the downstream boundary condition, applying the so-called 'Slope-Area Method'. Under this condition the flow depth at the outlet is determined by the geometry of the outlet cross-section, the roughness coefficient, and the local water surface slope. The strengths and weaknesses of this method were examined in detail by Fenton and Keller (2001). As the outlet geometry is known with high accuracy from survey data, the fidelity of the boundary condition depends on the values given to the roughness coefficient and the water surface slope. Fenton and Keller's (2001) analysis demonstrates that the impact of errors in the water surface slope specified "is dwarfed by the inaccuracy of knowledge of the friction factor" (Fenton and Keller, 2001, p. 15).

Therefore, while the impact of uncertainty in Manning's n is reported explicitly, the impact of uncertainty associated with the downstream boundary condition is established by reference to the results of previous investigations. It is important to note that while the following paragraphs refer to an analysis conducted in a previous investigation, a short-cut has not been taken in the analysis for the Barwon River. Rather, the hydraulic analysis undertaken for the Barwon River study was more detailed than the previous work. In

fact, the author is confident to assert that the hydraulic analysis herein represents not only best practice, but is the most comprehensive hydraulic analysis ever undertaken in a FLOWS study in Victoria.

The impact of an error in the slope assigned to the normal depth boundary condition was investigated for a similar project to establish the environmental water needs of the Werribee River (Ecological Associates and Fluvial Systems Pty Ltd et al., 2005). In that project the sensitivity to slope was assessed by perturbing the mean slope assigned to the normal depth boundary condition by ±10% of the reach average slope. This perturbation impacts the water surface profile most in the vicinity of the outlet cross-section, and the magnitude of any error declines in an upstream direction. Flow profiles were computed for the 25 year ARI flow[1] for a steep upstream site (Werribee Site 1: Werribee River downstream of the Upper Diversion Weir having a bed slope of 0.0018) and at a lowland reach (Werribee Site 4: Werribee River downstream of Cobbledicks Ford having a bed slope of 0.00017).

The sensitivity of the water surface profiles at Werribee Site 1 to the assigned water surface slope was limited to the 80m of the reach immediately upstream of the outlet (Figure 2.1). Water surface profiles were much more sensitive to an error in slope at Werribee Site 4. Here the profiles remain divergent for the entire reach length (Figure 2.2). However, as predicted by Fenton and Keller (2001), the error due to uncertainty in the friction factor (Manning's n) has a significantly larger impact. It is important to bear in mind that error due to slope declines for smaller flows, whereas errors due to roughness remain significant across the entire flow range.

This analysis demonstrated two key points:

- reaches of low slope are more sensitive to errors in the downstream boundary condition than reaches of higher slope; and
- uncertainty in the value of the friction factor is the key determining factor in the accuracy of predicted water surface profiles.

Downstream cross-section extrapolation

In order to minimise the impact of an error in the specification of slope the modelled reach was extended by adding extra cross-sections beyond the most downstream cross-section surveyed ('the outlet'). These artificial cross-sections were copies of the outlet cross-section extrapolated downstream along a vector perpendicular to the plane of the outlet and depressed at an angle equal to the average reach slope. These additional cross-sections more than double the simulated reach length. This is sufficient to move divergent water surface profile beyond the surveyed cross-sections for slopes as steep or steeper than at Werribee Site 1 (S_{bed} = 0.0018). Of the representative reaches selected for the Barwon River, this includes Sites 1, 3, 7, 8, and 9. Of the remaining sites, the simulations for Site 2 (S_{bed} = 0.00087) and Site 6 (S_{bed} = 0.00084) will be improved. The remaining reach, the Barwon River through Geelong (Site 4), is a weir pool with the water surface elevation controlled by a weir at the end of the reach (at Breakwater Road). A separate sensitivity study was conducted for this reach (see Section 0).

[1] The 25 year flood was selected as being about the largest flow of interest to the FLOWS analysis, and adopted as a floodplain forming flow (e.g. Pickup and Marks, 2001).

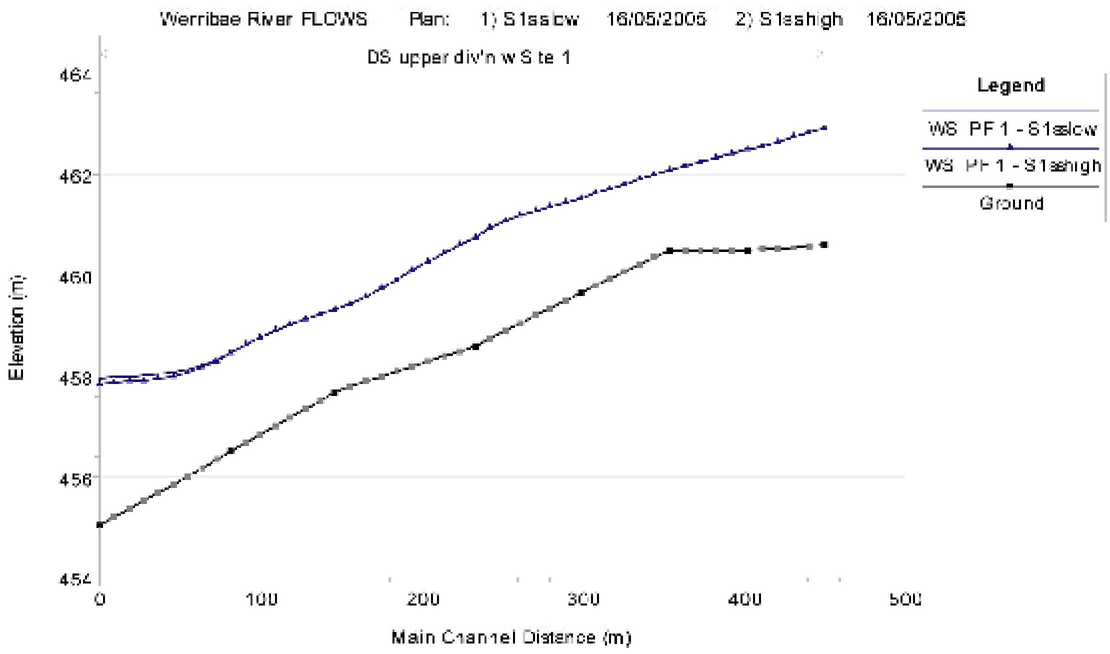

Figure 2.1 Water surface profiles resulting from slope sensitivity analysis at Site 1 reported as Elevation in metres relative to the Australian Height Datum (AHD). S1sslow and S1sshigh are for water surface slopes at the downstream boundary of 0.00159 and 0.00195 respectively. The convergence of the two profiles is complete at around 80m upstream of the outlet (i.e. Main Channel Distance).

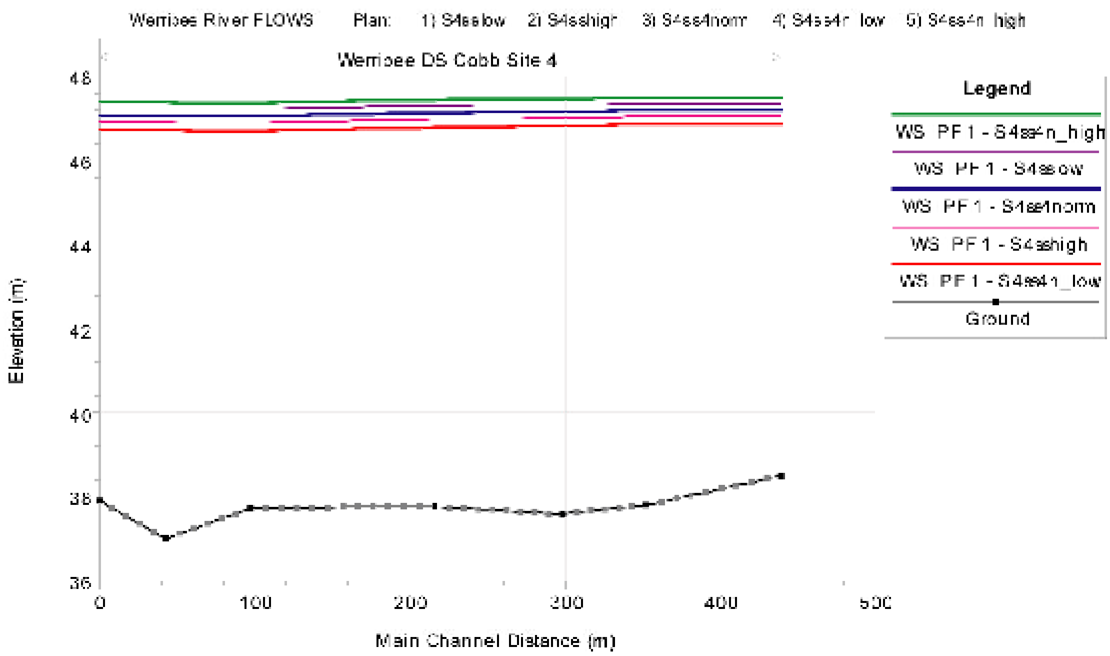

Figure 2.2 Flow profiles resulting from slope sensitivity analysis at Site 4. Profiles resulting from changing the water surface slope specified at the downstream boundary are denoted by S4sslow and S4sshigh. Profiles were also computed for the uncertainty in channel roughness, with three Manning's n cases reported: a best estimate (S4ss4norm); a low estimate (S4ss4n_low); and a high estimate (S4ss4n_high). (Refer to Site 4 in Section 2 for the values assigned for water surface slope and roughness coefficient).

3 Detailed Site Descriptions and Analysis

Detailed surveys were conducted at eight sites deemed to be representative of the Barwon River catchment (Table 3.1). The rationale for selecting these specific reaches is described in the companion to this report, the Site Paper (Lloyd Environmental 2005). Results of the hydraulic analysis are reported on a site-by-site basis. Note that no hydraulic analysis was conducted for site 5. The Lake Connewarre and Reedy Lake system are an estuarine systems and therefore not suitable for analysis by the FLOWS method.

Table 3.1 Site number and description

Site	Description
1	Barwon River @ Upper Barwon
2	Barwon River @ Kildean Road
3	Barwon River @ Murgheboluc Valley
4	Barwon River above Princes Bridge, Geelong
5	Lake Connewarre and Reedy Lake *(no hydraulic analysis)*
6	Birregurra Creek
7	Boundary Creek
8	Leigh River: Middle Reach
9	Leigh River: Lower Reach

3.1 Preparation of Surveyed Cross-Sections for Hydraulic Modelling

Cross-section surveys were completed by Reed & Reed Surveying. They supplied data in both text file format (comma separated values) and as ESRI format shape files (included on the data CD). The principal parameters provided were:

- Co-ordinates in Zone 54 AMG.66 (Easting and Northing to +-0.01 metres);
- Reduced levels to Australian Height Datum (AHD, +-0.02 metres);
- Lateral position (in East-North plane) measured from zero at the most extreme point on the left hand bank (left side facing downstream) and increasing toward the right bank.

The surveyors also surveyed the location of uniquely numbered pegs placed during the field survey conducted by scientific team to mark important physical features or vegetation assemblages. Water surface levels on the day of the survey were also noted, as were other features such as the elevation of gauging station boards.

The raw survey data was manipulated and translated into HEC-RAS geometry file format using custom written routines using the scripting language of **Matlab** (Release 14, The Math Works: http://www.mathworks.com/). The manipulations included:

- Identify longitudinal features including the thalweg and the left and right bank positions (for the main channel).
- Project points in the survey of the main channel (between the left and right banks) to a common plane so as to avoid exaggeration of the cross-section dimensions.
- Un-cross section lines (on floodplains) where the surveyed sections are overlapping[2] or need realignment with floodplain flow direction.
- Extrapolate most downstream cross-section (as described in Section 2.4.2).

Once this pre-processing is complete the cross-section data is written to a text file that can be read by HEC-RAS. Matlab routines were also written to:

- Compute the dimensional properties of each cross-section, including the variation with flow depth of wet perimeter, hydraulic radius, water surface top width and flow area.
- Estimate Manning's n roughness values using the empirical equations of Riggs (1976) and Dingman and Sharma (1997).
- Post-process flow results exported from HEC-RAS by evaluating quantitative discharge thresholds (see following section) with output written to a text file.

3.2 Tables of Discharge Thresholds

Some ecological and geomorphological processes can be expressed quantitatively. For example, the wetted perimeter is covered by sediments and, in some places, by vegetation. The movement or removal of these covers has been related to various hydraulic thresholds, as described in Section 5.3 of the Issues Paper. These thresholds are expressed in terms of shear stress, mean flow velocity and flow depth. Such quantitative criteria were evaluated using HEC-RAS flow output, thus defining a discharge required to satisfy each criterion at each cross-section. This section includes tables that report the indicative[3] discharge required to move sediment or remove vegetation. Complete tables include a larger range of criteria that were evaluated at each surveyed cross-section (rather than the reach average reported here).

The full tables of discharge thresholds are not published in this report for a number of reasons: 1) the discharge values are an intermediate step in setting the environmental flow; 2) the tables produced require expert interpretation; and 3) the values listed were developed specifically for use within the framework specified by the FLOWS Method, they are inappropriate for making decisions or predictions outside of this framework. It is important to recognise that these threshold values cannot be simply linked to an

[2] Section lines were un-crossed in two stages. First, a three dimensional surface was interpolated using the surveyed data point. Second, cross-section lines were moved so as to be parallel to the floodplain flow direction and to realign overlapping sections.

[3] The indicative discharge is an average over all the surveyed cross-sections at a given site.

environmental flow component (e.g. baseflow, high flow fresh). Some of the complicating factors include:

- some thresholds are only applicable at certain cross-sections (e.g. discharge to entrain riffle sediments is relevant only at riffles) and therefore require careful examination of the longitudinal profile and cross-section morphology;
- multiple threshold criteria must usually be satisfied by a given flow component; and
- many important ecological processes cannot be expressed as a quantitative criterion, hence qualitative considerations are an integral part of producing the final environmental flow recommendation.

To give the reader a feel for the type of information yielded by quantitative criteria the thresholds relating to sediment mobilisation and vegetation removal is reported. A brief description of these thresholds is given below. More detailed descriptions can be found in the referenced works or, alternatively, is documented fully in the report describing the environmental water needs of the Werribee River (Ecological Associates and Fluvial Systems Pty Ltd et al., 2005).

3.2.1 Thresholds for sediment mobilisation

For sediment mobilisation, shear stress thresholds were computed by applying Shields Critical Shear Stress Method (Gordon et al., 2004, p.194). Three generic sediment thresholds were computed, specifically the shear stress required to: a) flush fines (d = 0.01m) from a gravel surface ($\mathbf{t_c}$ = 0.34 d); b) entrain a normal, settled bed of sand; and c) to mobilise fine gravel. At each site an estimate of the median sediment calibre (*d50*) was defined. Shields method was used to estimate the shear stress and, from HEC-RAS simulation results, the discharge required to mobilise this sediment. At site 3 three thresholds were evaluated due to the relating to the riffle sediments measured. The shear stress required to mobilise the 16%, 50% and 84% of the riffle sediments were computed (i.e. sediment calibre equal to the median and two standard deviations either side of the median particle size).

3.2.2 Thresholds for vegetation removal

For vegetation, thresholds for the removal of grasses and rupture ('lodging') of macrophytes are computed. The minimum shear stress required to impact the least hardy of grasses (i.e. poorly established bunch grass) is 80 N/m^2. The discharge required to rupture macrophytes was computed by application of Groeneveld and French's (1995) relationship. The diameter of the macrophyte stems tested was set, as recommended by Groenveld and French (1995), to 0.0119m (11.9mm). Two thresholds were then evaluated to give a 95% and 99.9% chance of stem rupture respectively. The thresholds are reported as a discharge required for the product of flow depth and velocity to exceed either 0.152 ($Q_m^{95\%}$) or 1.52 ($Q_m^{99.9\%}$).

A summary of the thresholds that are computed for each site is listed in Table 3.2.

Table 3.2 Details of the thresholds computed to predict sediment entrainment or vegetation removal expressed in terms of either a critical shear stress (N/m^2) or a threshold discharge (ML/d)

Substrate	Conditions	Equation	Threshold
SEDIMENTS			
fines (d = 0.1 mm)	flushing from gravel	$t_c = 0.34\ d$	0.034 N/m^2
sand (d = 0.1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2
gravel (d = 0.1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	9.7 N/m^2
riffle material ($d_{16,50,84}$)	flat shape normal, settled bed	$t_c = 0.49\ d$	site specific N/m^2
VEGETATION			
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD = 0.152$ $uD = 1.52$	site and flow specific

The remaining sections provide details for of each site in turn.

3.3 Site 1: Barwon River @ Upper Barwon.

Plan View of Reach

Eight cross-sections were surveyed over a reach length of 585 metres at the Upper Barwon site. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.1, and indicative channel dimensions are listed in Table 3.3.

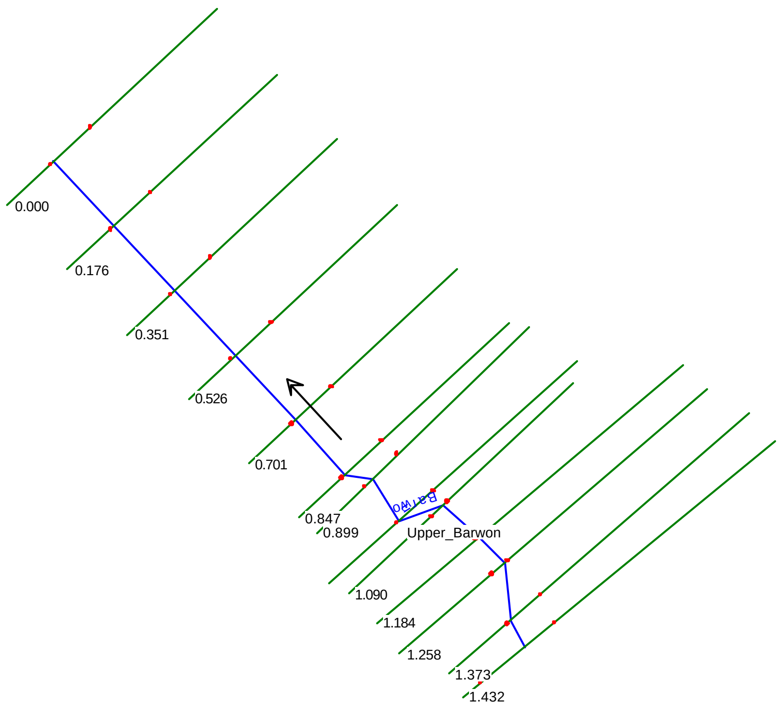

Figure 3.1 Plan view of Site 1 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.701) are extrapolated from cross-section 0.847.

Table 3.3 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions A (m^2)	B (m)	R (m)
1	1.431	121.2	14.8	15.7	0.9
2	1.373	121.3	14.2	14.3	0.9
3	1.257	120.9	8.2	10	0.8
4	1.184	120.7	14.9	17.2	0.8
5	1.089	120.3	8.4	10.7	0.7
6	0.997	120.1	8.4	12.8	0.6
7	0.899	120.1	5.3	8.6	0.6
8	0.846	119.7	3.5	5.3	0.6
		Reach average:	9.7	11.8	0.8
		Std. deviation:	4.1	3.7	0.1

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Natural	1 020	1725	2 865	8 250	13 215	22 230
	Current	405	735	1 140	2 325	2 325	6 735

Floodplain roughness

The floodplain zones at Site 1 are dissected by a number of small channels. These surfaces are in places covered with scattered brush (including macrophytes and some low trees (Chow's Table: D-2.c.1) and in the remainder it is pasture with high grass (Chow's Table: D-2.a.2). An intermediate roughness was assigned: n = 0.042.

Levees

This reach is dissected by a number of channels. The main functional channel is flanked by high levees, which hydraulic modelling suggests are capable of containing a large flood (5 - 15 year ARI; 6000 - 18000 ML/day). However, the field inspection revealed that some of the secondary channels were active, presumably supplied by breaches in the levee, under Winter baseflow conditions. Consequently, the levee was considered ineffective in the numerical model.

Site 1: Roughness coefficient estimation

Method	Manning's n	Selected values	Description
Cowan's Method	0.040	n_b = 0.020 n_1 = 0.000 n_2 = 0.005 n_3 = 0.000 n_4 = 0.015 m = 1.00	Silt-clay (earth) substrate with negligible irregularity (very flat profiles) with occasional cross-section shape change. Obstructions are negligible with vegetation (medium) important at lower flow stages. Meandering is considered minor in this context.
Chow's Table	0.040	Table Ref: D-1.a.5 (minimum)	Minor stream with some weeds (#4) but also at low stage (#5) - select low end of #5 (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.030 +veg = 0.015	Slope: 0.18% D_{50}: 0.008mm	Slope greater than threshold but finer bed material (than sand). Select intermediate roughness and add vegetation increment (n_4)
Hicks and Mason	0.054 – 0.073 0.051 – 0.061	id: 25902 (p.214) id: 45311 (p.234) Q = 0.48 m^3/sec S = 0.0018 silt/clay	Principal matched parameters: bed material (silt), slope and especially vegetation. Mean annual discharge is too high in both cases so have selected roughness range from bottom half of discharge measurements.
Empirical Equations	0.042 – 0.047 0.050 – 0.056	Rigg's (1976) Dingman and Sharma (1997)	
FINAL ESTIMATE:	0.050 ± 0.010	(mean ± 2 SD)	SD = standard deviation

Sediment entrainment and vegetation scour thresholds

Table 3.4 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.4 Site 1 thresholds for sediment entrainment and vegetation removal expressed in terms of either a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge*
SEDIMENTS				(ML/d)
fines (*d* = 0.1 mm)	flushing from gravel	$t_c = 0.34\,d$	0.034 N/m^2	0.1
sand (*d* = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\,d$	0.97 N/m^2	2.8
gravel (*d* = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\,d$	9.7 N/m^2	22 000
Riffle d_{50} = 0.008mm	flat shape normal, settled bed	$t_c = 0.49\,d$	0.004 N/m^2	< 0.1
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	> 22 230
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	uD/d_m = 12.8 uD/d_m = 128	(flow dependent)	97.7 > 22 230

* Median discharge (of all cross-sections excluding the outlet cross-section)

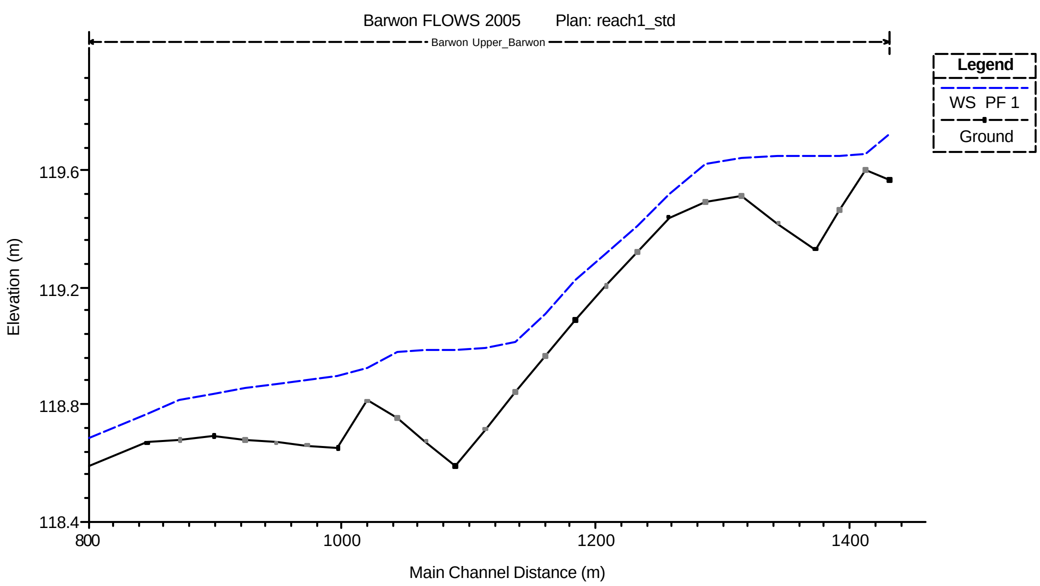

Figure 3.2 Longitudinal profile of Site 1 for very low flow (0.8 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.4 Site 2: Barwon River @ Kildean Road.

Plan View of Reach

Eight cross-sections were surveyed over a reach length of 179 metres at the Upper Barwon site. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.3, and indicative channel dimensions are listed in Table 3.5.

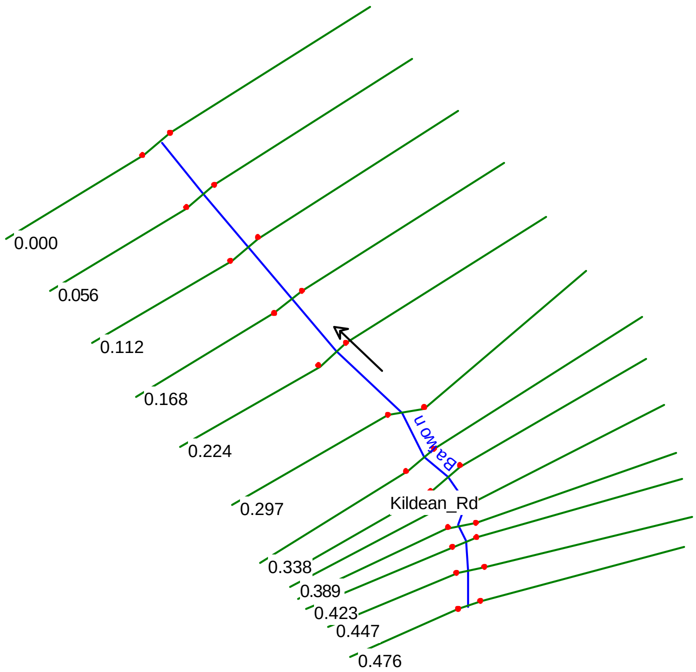

Figure 3.3 Plan view of Site 2 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.224) are extrapolated from cross-section 0.338.

Table 3.5 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions A (m^2)	B (m)	R (m)
1	0.476	91	58.4	20.4	2.5
2	0.447	91.4	77.8	25.1	2.7
3	0.423	91.2	68.3	21.3	2.8
4	0.408	91.5	74.3	24.7	2.7
5	0.389	91.7	107.2	32.3	3
6	0.363	91.6	118.9	32.8	3.3
7	0.338	91.7	96.4	29.7	2.9
8	0.297	91.5	91.7	30	2.8
		Reach average:	86.6	27	2.8
		Std. deviation:	19.2	4.5	0.2

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	5 400	10 900	21 690	53 170	83 750	141 960
	Natural	3 800	7 340	13 230	35 720	90 750	157 750

Floodplain roughness

The floodplains at this site are pasture with short grass. The Manning's n value suggested by Chow's table for such surfaces is 0.030 (D-2 a.1: normal).

Site 2: Roughness coefficient estimation

Method	Manning's n	Selected values	Description
Cowan's Method	0.035	n_b = 0.020; n_3 = 0.000; n_1 = 0.005; n_4 = 0.005; n_2 = 0.005; m = 1.15	Earth substrate with minor irregularity and a cross-section that alternates occasionally. Obstructions are negligible and vegetation is low.
Chow's Table	0.040	Table Ref: D-1.a.3	Minor plains stream, clean, winding, some pools and shoals (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.03 +veg = 0.010	Slope: 0.087%; D_{50}: 1 mm	Upper end of bed material calibre but mid-range slope.
Hicks and Mason	0.032 – 0.061	id: 45703 (p.174); Q = 5.7 m^3/sec; S = 0.00087; sand	Principal matched parameters: bed material (sand), slope, mean annual discharge, and photographs.
Empirical Equations	0.045 – 0.049 0.044– 0.046	Rigg's (1976) Dingman and Sharma (1997)	
FINAL ESTIMATE:	0.044 ± 0.008	(mean ± SD)	SD = standard deviation

Computed Thresholds: Sediments and Vegetation

Table 3.6 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.6 Site 2 thresholds for sediment entrainment and vegetation removal expressed in terms of either a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge*
SEDIMENTS				(ML/d)
fines (d = 0.1 mm)	flushing from gravel	$t_c = 0.34\ d$	0.034 N/m^2	0.6
sand (d = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2	25.8
gravel (d = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	9.7 N/m^2	1264
Riffle d_{50} = 1 mm	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2	25.8
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	92500
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	64 1218

* Median discharge (of all cross-sections excluding the outlet cross-section)

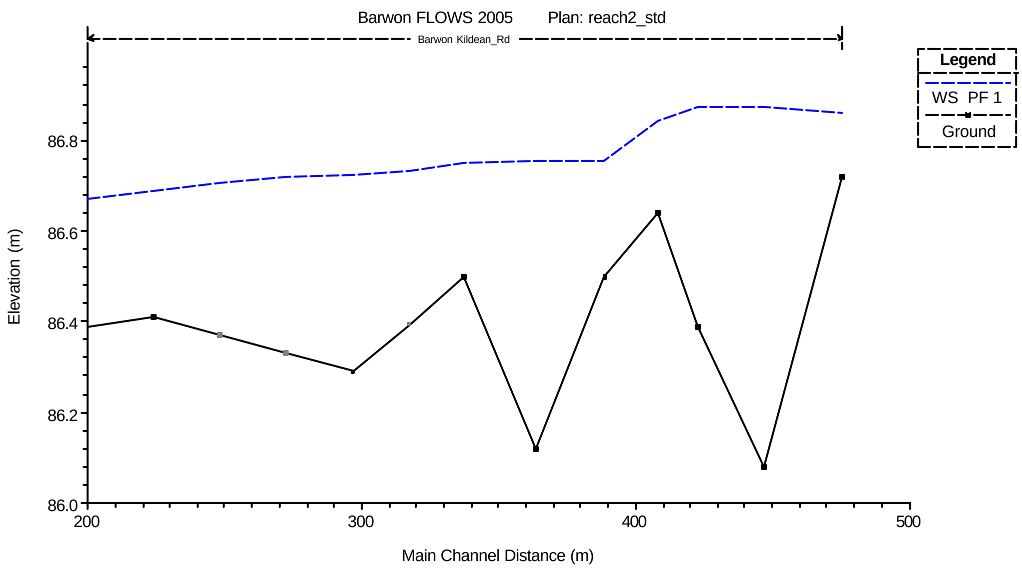

Figure 3.4 Longitudinal profile of Site 2 for very low flow (13 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.5 Site 3: Barwon River @ Murgheboluc Valley

Plan View of Reach

Seven cross-sections were surveyed over a reach length of 307 metres at the Murgheboluc Valley site. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.5, and indicative channel dimensions are listed in Table 3.7.

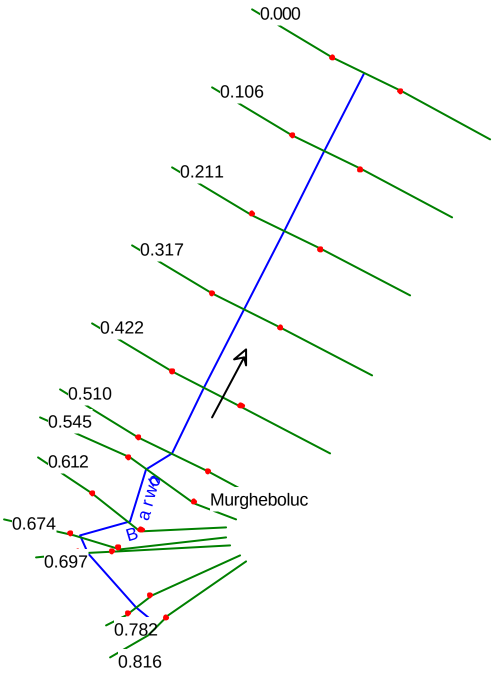

Figure 3.5 Plan view of Site 3 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.442) are extrapolated from cross-section 0.510.

Table 3.7 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions		
			A (m^2)	B (m)	R (m)
1	0.816	35.3	89.3	36.1	2.3
2	0.782	35.1	101.8	40.1	2.3
3	0.696	35.1	118.1	49	2.3
4	0.673	35.7	179	58.2	2.9
5	0.611	36.1	229.3	74.5	2.9
6	0.545	37.6	379.3	95	3.8
7	0.509	38.4	422	94.2	4.3
		Reach average:	217	63.9	3
		Std. deviation:	125	22.6	0.7

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	10 520	17 840	32 780	64 610	105 610	165 990
	Natural	6 670	11 800	19 700	40 860	102 480	159 450

Floodplain roughness:

Site 3 is flanked by floodplains hosting the equivalent of light brush and trees. A Manning's n of 0.060 was selected (Chow: D-2.c.3: normal).

Site 3: Roughness coefficient estimation

Method	Manning's n	Selected values		Description
Cowan's Method	0.063	n_b = 0.028 n_1 = 0.010 n_2 = 0.010	n_3 = 0.000 n_4 = 0.015 m = 1.00	Very coarse gravel to boulders with moderate irregularity and frequently alternating cross-sections (i.e. regular islands). The relative effect of obstructions is negligible. Meandering is minor. Vegetation has a medium effect on moderate to high flows.
Chow's Table	0.050 +veg = 0.015	Table Ref: D-1.b.1		Mountain stream with gravels, cobbles and a few boulders, with significant vegetation (= max) (Table 5-6 in Chow, 1959, p.112)
Bathurst's Table	0.06	Slope: 0.33%	D_{50}: 180 mm	Boulder bed (in riffles) but slope at low end of range
Hicks and Mason	0.039 – 0.048 0.045 - 0.062	id:23104 (p.126) id:29808 (p.218)	Q = 9.2 m^3/sec S = 0.0033 gravel/cobbles	Principal matched parameters: bed material, channel width (20-30m), photographs and slope.
Empirical Equations	0.036 - 0.045 0.046 - 0.050 +veg = 0.015	Rigg's (1976) Dingman and Sharma (1997)		
FINAL ESTIMATE:	0.056 ± 0.010	(mean ± SD)		SD = standard deviation

Computed Thresholds: Sediments and Vegetation

Table 3.8 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.8 Site 3 thresholds for sediment entrainment and vegetation removal expressed in terms of a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge
SEDIMENTS				(ML/d)
fines (*d* = 0.1 mm)	flushing from gravel	$t_c = 0.34\ d$	0.034 N/m^2	0.1
sand (*d* = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2	4.3
gravel (*d* = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	9.7 N/m^2	89
Riffle d_{16} 21.5mm d_{50} 60mm d_{84} 195mm	flat shape normal, settled bed	$t_c = 0.49\ d$	10.5 N/m^2 29.4 N/m^2 95.6 N/m^2	120 2950 24150
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	16950
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	56 1715

* Median discharge (of all cross-sections excluding the outlet cross-section)

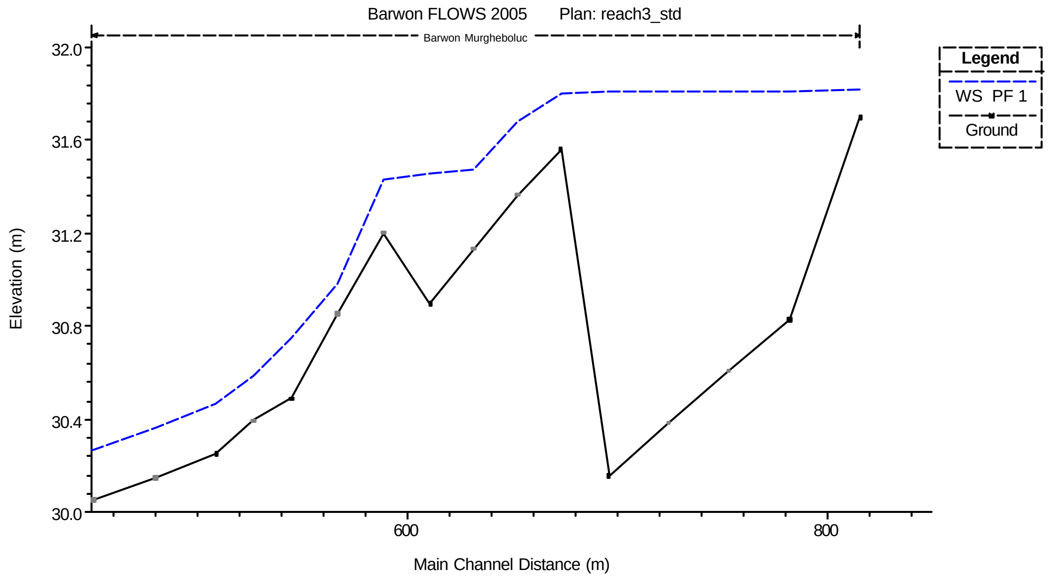

Figure 3.6 Longitudinal profile of Site 3 for very low flow (22 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.6 Site 4: Barwon River above Princes Bridge, Geelong

Plan View of Reach

Seven cross-sections were surveyed over a reach length of 1933 metres at the site in Geelong. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.7, and indicative channel dimensions are listed in Table 3.9.

Cross-section 0.663 is the breakwater at Breakwater Road as surveyed by GHD for the 1979 flood study (survey data courtesy of Tony Jones, Floodplain Manager, Corangamite Catchment Management Authority). The breakwater was constructed by a Captain Flinders in mid-1800s to provide fresh water upstream for the fledging settlement of Geelong. It continues to function as an hydraulic control, preventing saline intrusions from the estuarine region downstream. The breakwater cross-section ensures that the modelled reach acts as a weir pool.

Figure 3.7 Plan view of Site 4 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 2.650) are extrapolated from cross-section 3.404.

Table 3.9 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions A (m^2)	B (m)	R (m)
1	5.134	1.5	241.1	53.3	4.2
2	4.932	1.8	299.2	53.4	5.2
3	4.561	1.3	182.2	53.6	3.2
4	4.231	1.5	175.9	48.2	3.5
5	3.705	1.5	160.5	50.9	3
6	3.403	1.7	123	41.3	2.9
7	3.201	1.1	247.5	72.8	3.2
		Reach average:	204.2	53.4	3.6
		Std. deviation:	56.1	8.9	0.8

Hydrology

The following hydrologic properties (from the Issues Paper) were used to set the range for thirty flows simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	18 710	31 080	48 460	92 860	142 230	181 850
	Natural	10 580	17 990	30 900	46 280	106 510	159 450

Roughness Coefficients: In-channel and Floodplain

Roughness coefficients for both the in-channel and floodplain section were determined by reference to the values associated with an existing flood study completed for this reach (Wellington, 1982). More detail is provided at the end of this section.

Site 4: Roughness coefficients

The State Rivers and Water Supply Commission in September 1979 commissioned Gutteridge Haskins & Davey Pty. Ltd. (GHD) to study flooding of the Barwon River through Geelong (Wellington, 1982). Channel surveys were completed at this time and a HEC-2 hydraulic model[4] constructed for the reach and calibrated to observed flood levels. The GHD report details the energy loss parameters derived from the calibration study. These parameters include: main-channel roughness coefficient; depth-varying floodplain roughness coefficients; and expansion/contraction coefficients (where they differ from the default values of 0.1/0.3). Cross-sections from the GHD study that are relevant to the site chosen for the current FLOWS assessment are: xs16, xs17 and xs18 (Wellington, 1982). The calibrated parameter values for these cross-sections are reproduced in Table 3.10. These values were used to specify the energy loss parameters for the HEC-RAS model constructed as part of the current FLOWS investigation.

Table 3.10 Relevant energy loss parameters for hydraulic model from Wellington (1982)

[4] HEC-2 was a precursor to the HEC-RAS software that applied in this FLOWS assessment.

Cross-section	Channel Manning's n	Floodplain: Flow Depth	Manning's n	Contraction Coeff.	Expansion Coeff.
16. Princes Bridge				0.6	0.9
17. Balcombe Rd.	0.045	1.0 m 1.8 m 2.5 m	0.095 0.075 0.060	0.1	0.3
18. Jackman Rd.				0.1	0.3

In adopting these parameter values we assume that the character of the Barwon River through Geelong has not changed substantially in the 26 years since the flood study was completed. The 1979 cross-section surveys were obtained and compared to the surveys commissioned for the current work. The principal hydraulic dimensions of the river (bankfull width and depth, floodplain geometry, etc) remain essentially unchanged. Comparison of photographs included in Wellington's (1982) report suggest that the vegetation present on the lower floodplain surfaces (AHD ~ 2m) may be denser now than it was in 1979. Hence, the uncertainty bounds associated with Manning's n coefficients for this reach were: -0%, +10%.

Computed Thresholds: Sediments and Vegetation

Table 3.11 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.11 Site 4 thresholds for sediment entrainment and vegetation removal expressed in terms of a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge
SEDIMENTS				(ML/d)
fines (d = 0.1 mm)	flushing from gravel	$t_c = 0.34\ d$	0.034 N/m^2	261
sand (d = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2	1970
gravel (d = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	9.7 N/m^2	43200
Riffle d_{50} = 0.008mm	flat shape normal, settled bed	$t_c = 0.49\ d$	0.004 N/m^2	98
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	> 181 850
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	494 5450

* Median discharge (of all cross-sections excluding the outlet cross-section)

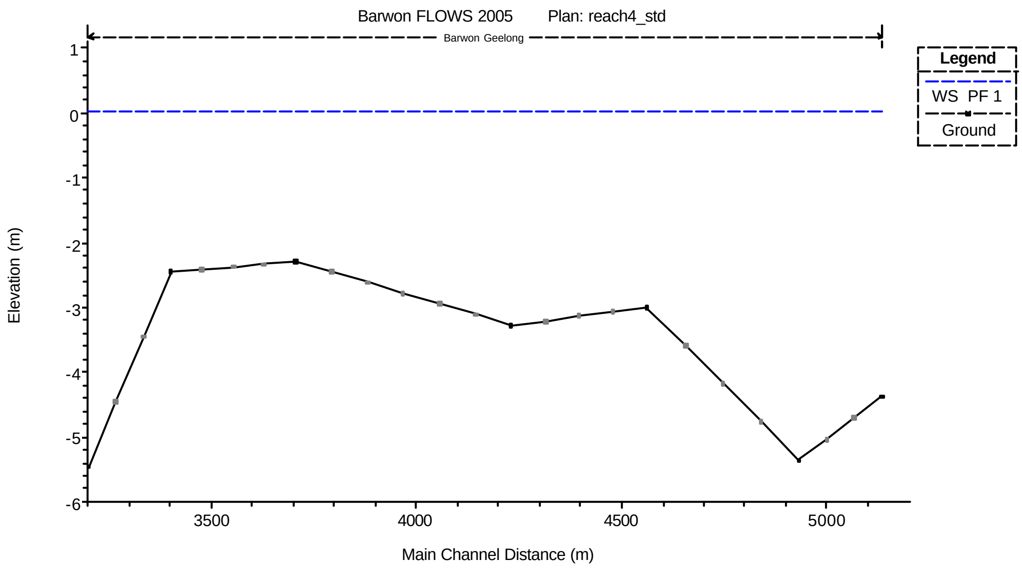

Figure 3.8 Longitudinal profile of Site 4 for very low flow (35 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.7 Site 6: Birregurra Creek

Plan View of Reach

Seven cross-sections were surveyed over a reach length of 506 metres at Birregurra Creek. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.9, and indicative channel dimensions are listed in Table 3.12. Separate roughness coefficient values were estimated for the top three cross-sections (1.130-1.483) which are bare earthen channels, while the bottom two cross-sections (1.040 - 0.978) are larger and host significant vegetation communities.

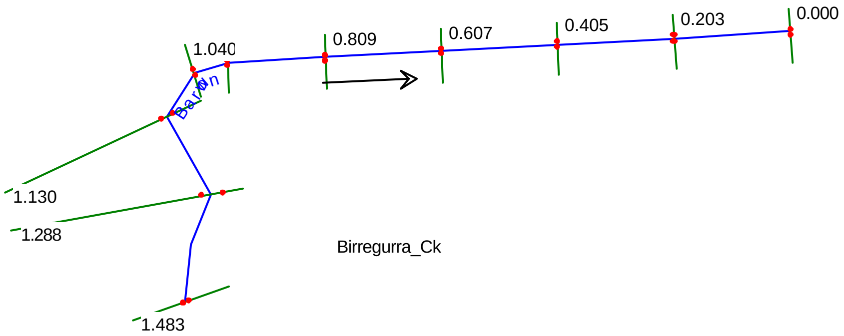

Figure 3.9 Plan view of Site 6 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.809) are extrapolated from cross-section 0.978.

Table 3.12 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions		
			A (m^2)	B (m)	R (m)
1	1.483	105.2	1.1	6.9	0.2
2*	1.380	105.1	2.6	10.8	0.2
3	1.287	105.1	4.2	20.8	0.2
4	1.130	105.1	3.3	10.3	0.3
5	1.039	105.1	4.6	9.5	0.5
6	0.977	105.1	4.5	8.5	0.5
		Reach average:	3.4	11.1	0.3
		Std. deviation:	1.2	4.5	0.1

* interpolated cross-section replaced surveyed section in model as the surveyed section was inappropriate for hydraulic modelling.

Hydrology

The following hydrologic properties (from the Issues Paper) were used to set the range for thirty flows simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	100	190	300	430	670	710
	Natural	360	490	610	930	1 070	1 220

Floodplain roughness:

The floodplains at Site 6 were mostly bare earth with some short grasses. These surfaces offer minimal resistance so Manning's n was set to 0.025 (Chow: D-2 a.1 minimum).

Site 6: Roughness coefficient estimation (upstream cross-sections)

Method	Manning's n	Selected values	Description
Cowan's Method	0.025	n_b = 0.020; n_3 = 0.000; n_1 = 0.000; n_4 = 0.000; n_2 = 0.005; m = 1.00	Earth substrate (silt) with no appreciable irregularity and occasionally alternating cross-section shape. Obstructions are negligible and there is no vegetation. Meandering is minor.
Chow's Table	0.025	Table Ref: D-1.a.1	Minor plains stream, clean and straight. (Table 5-6 in Chow, 1959, p.112)
Bathurst's Table	0.020	Slope: 0.084%; D_{50}:0.008 mm	Silt substrate and low slope, selected bottom end sand bed range
Hicks and Mason	0.028 - 0.034	id:9140 (p.70); Q = 0.61 m^3/sec, S = 0.00084, silt	Principal matched parameters: bed material (silt over smooth cobbles) and slope. Mean annual discharge larger but this is the best available match.
Empirical Equations	0.027 – 0.035 (0.042 – 0.046)	Rigg's (1976) Dingman and Sharma (1997)	Roughness predictions by Dingman and Sharma's equation were excluded on the basis that they were inconsistent with other estimates. This relationship is known to be a poor predictor of roughness in low discharge channels.
FINAL ESTIMATE:	0.028 ± 0.005	(mean ± SD)	SD = standard deviation

Site 6: Roughness coefficient estimation (downstream cross-sections)

Method	Manning's n	Selected values		Description
Cowan's Method	0.035	n_b = 0.020 n_1 = 0.000 n_2 = 0.005	n_3 = 0.000 n_4 = 0.010 m = 1.00	Earth substrate (silt) with no appreciable irregularity and occasionally alternating cross-section shape. Obstructions are negligible but vegetation is moderate. Meandering is minor.
Chow's Table	0.040	Table Ref: D-1.a.3		Minor plains stream, with some weeds and winding. (Table 5-6 in Chow, 1959, p.112)
Bathurst's Table	0.020 +veg = 0.010	Slope: 0.084%	D_{50}:0.008 mm	Silt substrate and low slope, selected bottom end sand bed range
Hicks and Mason	0.028 - 0.034 +veg = 0.010	id:9140 (p.70)	Q = 0.61 m^3/sec S = 0.00084 silt	Principal matched parameters: bed material (silt over smooth cobbles) and slope. Mean annual discharge larger but this is the best available match.
Empirical Equations	0.027 – 0.035 0.042 – 0.046	Rigg's (1976) Dingman and Sharma (1997)		
FINAL ESTIMATE:	0.038 ± 0.007	(mean ± SD)		SD = standard deviation

Computed Thresholds: Sediments and Vegetation

Table 3.13 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.13 Site 6 thresholds for sediment entrainment and vegetation removal expressed in terms of a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge
SEDIMENTS				(ML/d)
fines (d = 0.1 mm)	flushing from gravel	$t_c = 0.34\,d$	0.034 N/m^2	< 0.1
sand (d = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\,d$	0.97 N/m^2	18
gravel (d = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\,d$	9.7 N/m^2	> 1220
Riffle d_{50} = 0.008mm	spherical shape normal, settled bed	$t_c = 0.97\,d$	0.002 N/m^2	< 0.1
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	> 1220
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	212 > 1220

* Median discharge (of all cross-sections excluding the outlet cross-section)

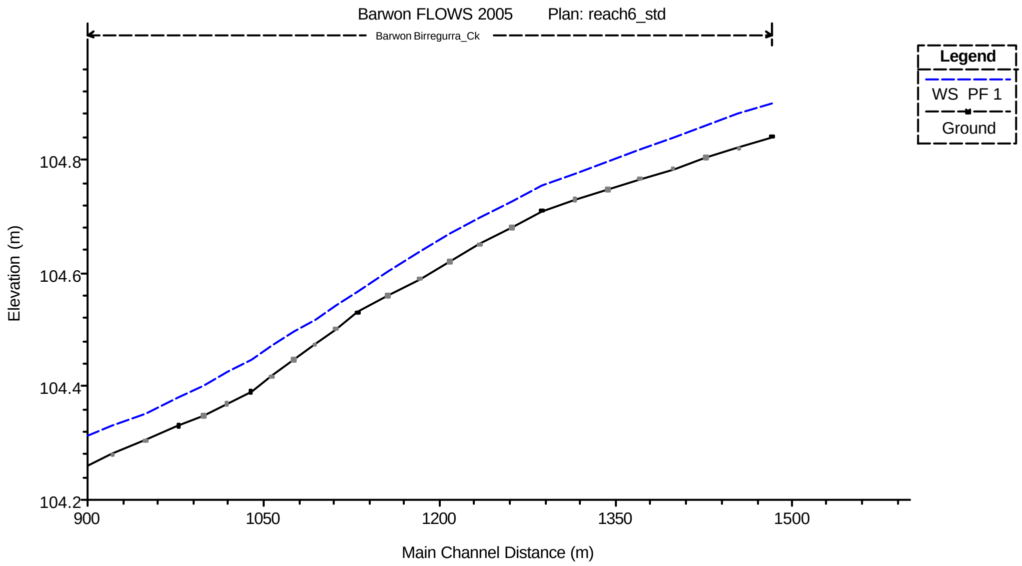

Figure 3.10 Longitudinal profile of Site 6 for very low flow (0.33 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.8 Site 7: Boundary Creek

Plan View of Reach

Ten cross-sections were surveyed over a reach length of 172 metres at the Boundary Creek site. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.11, and indicative channel dimensions are listed in Table 3.14.

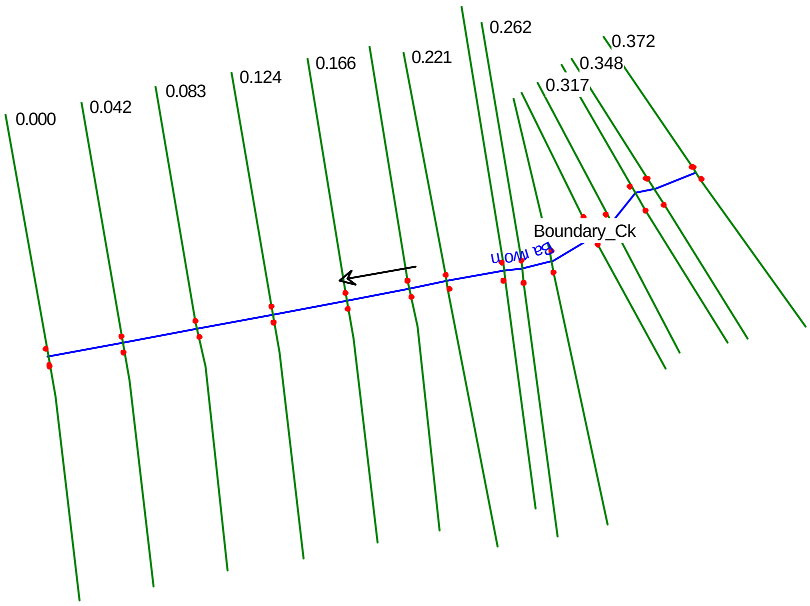

Figure 3.11 Plan view of Site 7 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.166) are extrapolated from cross-section 0.200.

Table 3.14 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions A (m^2)	B (m)	R (m)
1	0.371	128.1	7.4	7.4	0.8
2	0.347	128.1	15.5	17.8	0.8
3	0.337	127.8	10.7	17.9	0.6
4	0.316	127.6	5.4	7.6	0.7
5	0.304	127.6	12.1	14.7	0.7
6	0.278	127.6	10.3	11.7	0.8
7	0.261	127.4	12.9	11.9	1
8	0.251	127.6	10.2	10.5	0.9
9	0.220	127.4	9	7.9	0.9
10	0.199	126.9	11.2	25	0.4
		Reach average:	10.5	13.2	0.8
		Std. deviation:	2.7	5.4	0.2

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	107	133	151	196	278	447
	Natural	89	123	166	211	246	250

Floodplain roughness:

Flood plains comprise pasture with short grass. Chow's roughness table (D-2 a.1: normal) recommends Manning's n = 0.030.

Site 7: Roughness coefficient estimation

Method	Manning's n	Selected values		Description
Cowan's Method	0.045	n_b = 0.020 n_1 = 0.005 n_2 = 0.005	n_3 = 0.000 n_4 = 0.015 m = 1.00	Fine silt substrate (earth) with minor irregularity and cross-section alternating occasionally. Obstructions are negligible, but in-channel vegetation is medium. Meandering is minor.
Chow's Table	0.045	Table Ref: D-1.a.4 (normal)		Minor plains stream, with significant in-channel vegetation (tall grass and spiny rush). (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.025 +veg = 0.015	Slope: 0.88%	D_{50}: 0.015 mm	Red silt substrate with low slope (mid range value chosen). Dense in-channel vegetation included via Cowan's increment (n_4)
Hicks and Mason	0.023 - 0.032 +veg = 0.015	id:8604 (p.54)	Q = 0.13 m^3/sec S = 0.0088 Substrate: silt	Reference lacks channels with fine substrates at low slope and discharge. Selected reach represents closest approximation. Vegetation is not dense enough in 8604 (add n_4 from Cowan)
Empirical Equations	0.047 - 0.059 (0.064 - 0.073)	Rigg's (1976) Dingman and Sharma (1997)		Roughness predictions by Dingman and Sharma's equation were excluded on the basis that they were inconsistent with other estimates. This relationship is known to be a poor predictor of roughness in low discharge channels.
FINAL ESTIMATE:	0.046 ± 0.007	(mean ± SD)		SD = standard deviation

Computed Thresholds: Sediments and Vegetation

Table 3.15 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.15 Site 6 thresholds for sediment entrainment and vegetation removal expressed in terms of either a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge
SEDIMENTS				(ML/d)
fines (d = 0.1 mm)	flushing from gravel	$t_c = 0.34\ d$	0.034 N/m^2	0.5
sand (d = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2	5
gravel (d = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	9.7 N/m^2	72
Riffle d_{50} = 0.015 mm	flat shape normal, settled bed	$t_c = 0.49\ d$	0.0074 N/m^2	< 0.1
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	> 447
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	22 > 447

* Median discharge (of all cross-sections excluding the outlet cross-section)

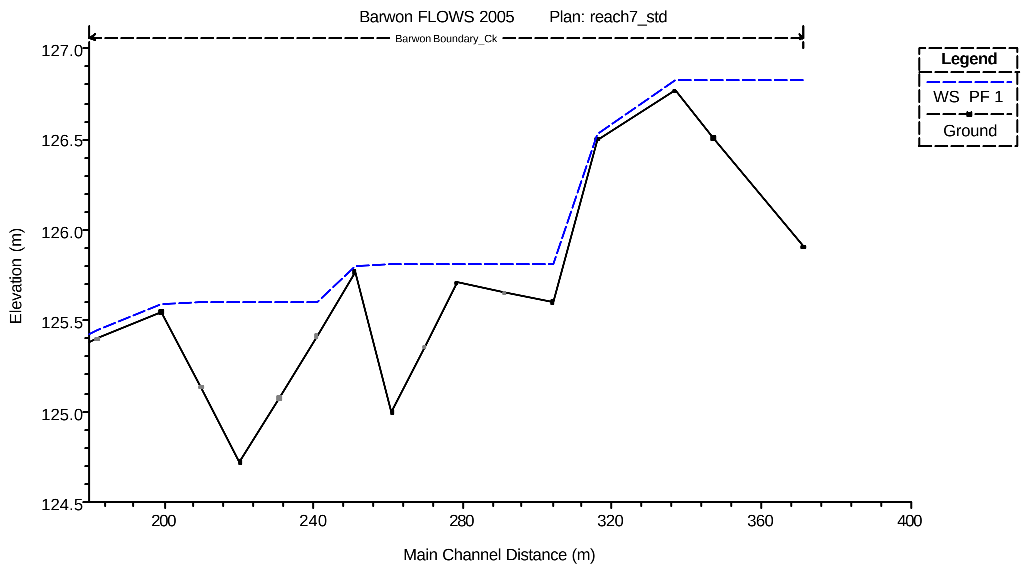

Figure 3.12 Longitudinal profile of Site 7 for very low flow (0.3 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.9 Site 8: Leigh River: Middle Reach

Plan View of Reach

Ten cross-sections were surveyed over a reach length of 324 metres at the Middle reach on the Leigh River. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.13, and indicative channel dimensions are listed in Table 3.16.

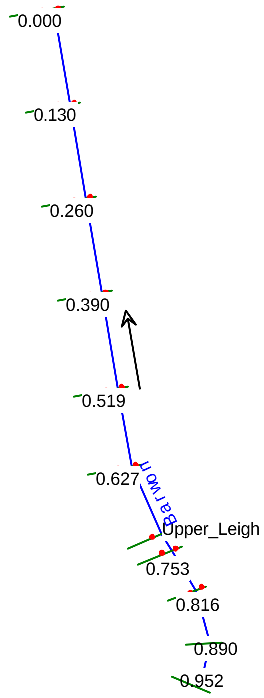

Figure 3.13 Plan view of Site 8 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.166) are extrapolated from cross-section 0.200.

Table 3.16 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions A (m^2)	B (m)	R (m)
1	0.951	193.1	31.3	18.6	1.6
2	0.89	194.4	59.2	29.3	1.7
3	0.816	192.9	28.1	17.9	1.4
4	0.753	193	51.6	21.7	2.1
5	0.727	193	33.8	24.7	1.2
6	0.627	192.2	79.3	25.2	2.9
		Reach average:	47.2	22.9	1.8
		Std. deviation:	18.2	4	0.6

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	1 660	3 000	4 450	6 830	8 150	9 670
	Natural	1 950	3 180	5 150	7 270	8 080	13 230

Floodplain roughness:

Floodplain surfaces at Site 7 are rough, covered by moderate to dense scrub and trees. Manning's n was set to 0.070, following the recommendations of Chow's table (D-2 c.4: normal).

Site 8: Roughness coefficient estimation

Method	Manning's n	Selected values		Description
Cowan's Method	0.058	n_b = 0.028 n_1 = 0.010 n_2 = 0.010	n_3 = 0.000 n_4 = 0.010 m = 1.00	Substrate material coarse gravel with moderate irregularity and channel cross-section shape alternating occasionally. Obstructions can be neglected while vegetation is medium (especially at control sections – riffle XS5) and meandering is minor.
Chow's Table	0.050	Table Ref: D-1.b.2 (normal)		Coarse gravel to small boulders with vegetation on horizontal surfaces (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.050 +veg = 0.010	Slope: 0.71%	D_{50}: 170 mm	Coarse gravels to small boulders. Selected low end of boulder bed roughness (slope is at low end of spectrum) and added vegetation.
Hicks and Mason	0.052 – 0.061 0.048 – 0.057	id:75259 (p.242) id: 29250 (p.250)	Q =1.8 m^3/sec S = 0.0071 gravel/boulders	Principal matched parameters: similar slope, bed material, downstream channel slope and vegetation (esp. id: 29250). Ignored low flow roughness at 29250 (Q < 0.4 m^3/s)
Empirical Equations	0.042 – 0.054 0.056 – 0.062	Rigg's (1976) Dingman and Sharma (1997)		While a vegetation increment would normally be added, it does not seem to be required given the relatively high values predicted by both equations.
FINAL ESTIMATE:	0.055 ± 0.006	(mean ± SD)		SD = standard deviation

Computed Thresholds: Sediments and Vegetation

Table 3.17 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.17 Site 8 thresholds for sediment entrainment and vegetation removal expressed in terms of a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge
SEDIMENTS				(ML/d)
fines (*d* = 0.1 mm)	flushing from gravel	$t_c = 0.34\ d$	0.034 N/m^2	3
sand (*d* = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	0.97 N/m^2	40
gravel (*d* = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\ d$	9.7 N/m^2	280
Riffle d_{50} 170mm	flat shape normal, settled bed	$t_c = 0.49\ d$	83.3 N/m^2	4600
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	4300
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	82 1540

* Median discharge (of all cross-sections excluding the outlet cross-section)

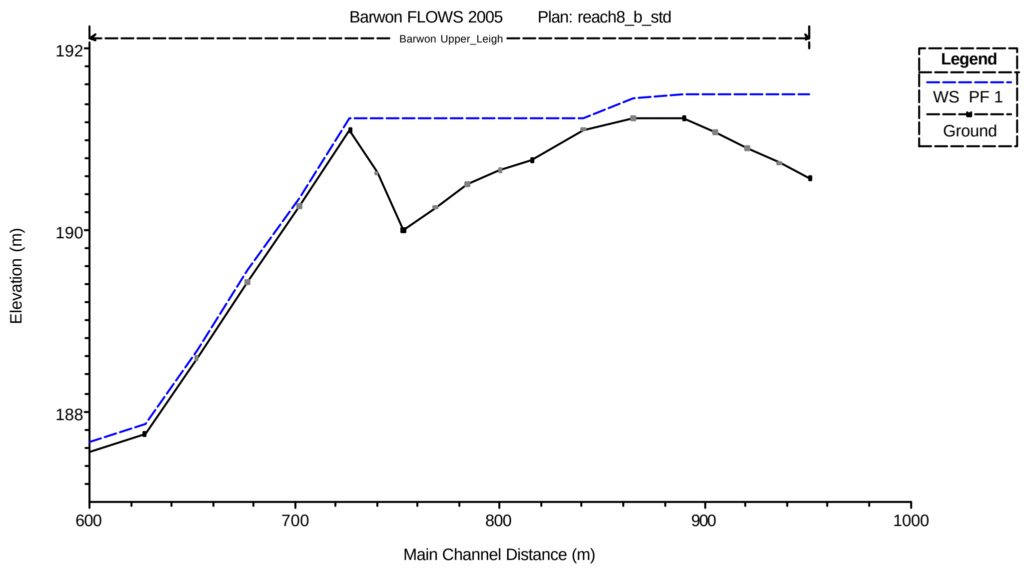

Figure 3.14 Longitudinal profile of Site 8 for very low flow (5.5 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

3.10 Site 9: Leigh River: Lower Reach

Plan View of Reach

Ten cross-sections were surveyed over a reach length of 243 metres at the Lower reach on the Leigh River. The HEC-RAS model of these cross-sections is shown in plan view in Figure 3.15, and indicative channel dimensions are listed in Table 3.18.

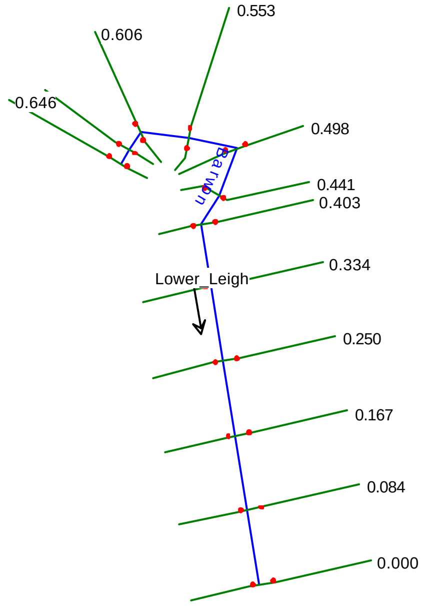

Figure 3.15 Plan view of Site 9 (labels give distance (km) upstream of reach outlet). The five lower cross-sections (0.000 - 0.334) are extrapolated from cross-section 0.403.

Table 3.18 Summary of Channel Dimensions

XS	Distance (km)	Elevation (m)	Dimensions A (m^2)	B (m)	R (m)
1	0.646	74	50.4	21.2	2
2	0.628	72.9	36.3	13.4	2.1
3	0.605	73.2	40.4	14.7	2.2
4	0.553	73.7	52.3	21.6	2
5	0.497	73.7	64	21.8	2.5
6	0.441	73.4	60.1	21.8	2.4
7	0.403	73.5	63.8	23.3	2.4
		Reach average:	52.5	19.7	2.2
		Std. deviation:	10.2	3.6	0.2

Hydrology

The following hydrologic properties were extracted from the issues paper. Thirty flows were simulated in the HEC-RAS model. The minimum flow simulated was set at 50 times lower than the smallest flow listed. The maximum flow simulated was set equal to the highest discharge.

ARI (yr)		0.5	1	2	5	11	31
Discharge (ML/day)	Current	2 380	3 830	6 390	9 370	11 120	13 840
	Natural	2 420	4 060	6 670	8 930	10 310	17 230

Floodplain roughness:

Flood plains comprise pasture with short grass. Chow's roughness table (D-2 a.1: normal) recommends Manning's n = 0.030.

Site 9: Roughness coefficient estimation

Method	Manning's n	Selected values	Description
Cowan's Method	0.046	n_b = 0.020; n_3 = 0.000; n_1 = 0.005; n_4 = 0.010; n_2 = 0.005; m = 1.15	Earth substrate (sand) with minor irregularity but the cross-section shape alternates occasionally. Considering obstructions negligible vegetation has a low-medium effect. Meandering is appreciable.
Chow's Table	0.045	Table Ref: D-1.a.4 (normal)	Weeds on banks and trees instead of stones (pt 4). A windy reach (+pt 3) with pools and shoals. (Table 5-6 in Chow, 1959, p.113)
Bathurst's Table	0.035 +veg = 0.010	Slope: 0.29%; D_{50}: 1 mm	Sand substrate with slope three times top end of range. Vegetation needs to be accounted for (add Cowan's increment).
Hicks and Mason	0.044 – 0.065	id:1014641 (p.154); Q < 1.90 m^3/sec, S = 0.0029, sand	Principal matched parameters: bed material, mean annual flow, and vegetation (neglected high flow roughness as an outlier).
Empirical Equations	0.055 – 0.059 0.055 – 0.058	Rigg's (1976) Dingman and Sharma (1997)	While a vegetation increment would normally be added, it does not seem to be required given the relatively high values predicted by both equations.
FINAL ESTIMATE:	0.052 ± 0.008	(mean ± SD)	SD = standard deviation

Computed Thresholds: Sediments and Vegetation

Table 3.19 lists the thresholds for sediment entrainment and vegetation removal.

Table 3.19 Site 9 thresholds for sediment entrainment and vegetation removal expressed in terms of either a critical shear stress (N/m^2) or a threshold discharge (ML/d).

Substrate	Conditions	Equation	Threshold	Discharge
SEDIMENTS				(ML/d)
fines (*d* = 0.1 mm)	flushing from gravel	$t_c = 0.34\, d$	0.034 N/m^2	< 0.1
sand (*d* = 1 mm)	spherical shape normal, settled bed	$t_c = 0.97\, d$	0.97 N/m^2	1.4
gravel (*d* = 10 mm)	spherical shape normal, settled bed	$t_c = 0.97\, d$	9.7 N/m^2	41
Riffle d_{50} = 1 mm	spherical shape normal, settled bed	$t_c = 0.97\, d$	0.97 N/m^2	1.4
VEGETATION				(ML/d)
bunch grass	Bunch grass (minimum)	erosion study	80 N/m^2	18000
macrophytes	d_m = 0.0119 m u = velocity (m/s) D = flow depth (m)	$uD/d_m = 12.8$ $uD/d_m = 128$	(flow dependent)	44 730

* Median discharge (of all cross-sections excluding the outlet cross-section)

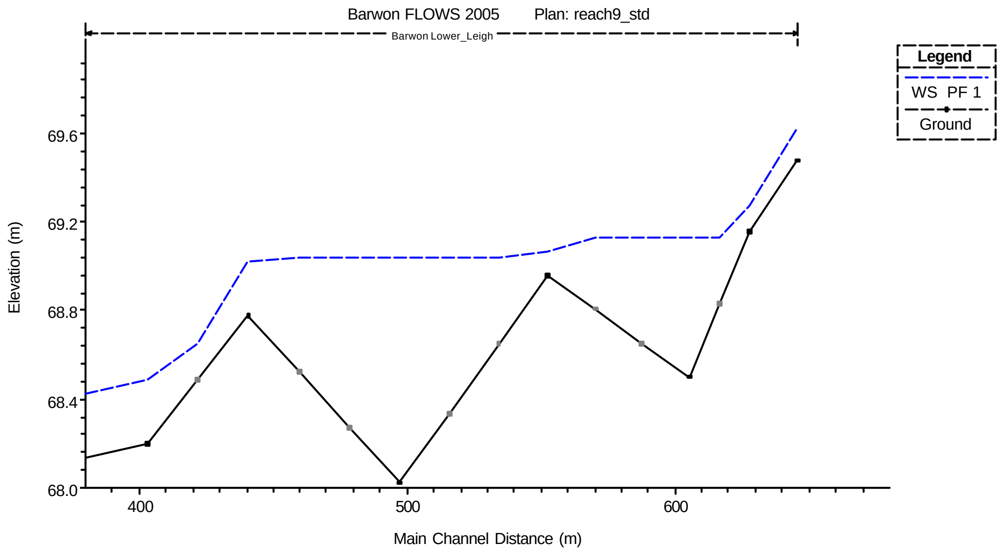

Figure 3.16 Longitudinal profile of Site 9 for very low flow (7.9 ML/d) with normal roughness specified (i.e. best estimate Manning's n). Water surface elevation (m) is the broken line (WS), and the ground represents the thalweg profile (deepest point at each section). Channel distance is measured increasing upstream from zero at the outlet.

4 References

Anderson, B.G., Rutherfurd, I.D. and Ladson, A.R., 2001. Towards an Australian handbook for the estimation of stream roughness coefficients, SAGES, University of Melbourne, Melbourne, Australia.

Arcement, G.J. and Schneider, V.R., 1989. Guide for selecting Manning 's roughness coefficients for natural channels and flood plains. Water-Supply Paper 2339, US Geological Survey.

Aronica, G., Hankin, B. and Beven, K., 1998. Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. Advances in Water Resources, 22(4): 349-365.

Barnes, H.H., 1967. Roughness characteristics of natural channels. Water Supply Paper 1849, United States Geological Survey.

Bathurst, J.C., 1993. Flow Resistance Through the Channel Network. In: K. Beven and M.J. Kirkby (Editors), Channel Network Hydrology. John Wiley & Sons Ltd., pp. 69 - 98.

Burnham, M. and Davis, D., 1986. Accuracy of computed water surface profiles. Research Document 26, The Hydrologic Engineering Centre, U.S. Army Corps of Engineers, Davis, California.

Chow, V.T., 1959. Open channel hydraulics. McGraw Hill, New York.

Coon, W.F., 1998. Estimation of roughness coefficients for natural stream channels with vegetated banks. 2441, U.S. Geological Survey, Denver, CO, U.S.A.

Cowan, W.L., 1956. Estimating Hydraulic Roughness Coefficients. Agricultural Engineering, 37(7): 473-475.

Dingman, S.L. and Sharma, K.P., 1997. Statistical development and validation of discharge equations for natural channels. Journal of Hydrology, 199: 13-35.

Duncan, M. and Smart, G., 1999. Flow Resistance: An overview of formulae for alluvial channel flow estimation, National Institute of Water and Atmospheric Research Institute Ltd, Napier, New Zealand.

Ecological Associates and Fluvial Systems Pty Ltd et al., 2005. The Environmental Water Needs of the Werribee River - Issues Paper (Incorporating Site Paper), Melbourne Water.

Fenton, J.D. and Keller, R.J., 2001. The calculation of streamflow from measurements of stage. Project FL3, Cooperative Research Centre for Catchment Hydrology, Monash University, Victoria, Australia 3800, Melbourne, Australia.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. and Nathan, R.J., 2004. Stream Hydrology: An Introduction for Ecologists, 2nd Edition. John Wiley & Sons, Chichester.

Hicks, D.M. and Mason, P.D., 1991. Roughness Characteristics of New Zealand Rivers. Water Resources Survey, Wellington, NZ.

Ladson, A.R., Lang, S., Anderson, B.G. and Rutherfurd, I.D., 2003. An Australian Guide to Stream Roughness Coefficients, 28th Hydrology and Water Resources Symposium. The Institution of Engineers, Australia, Wollongong, NSW, Australia.

Lang, S., Ladson, A. and Anderson, B., 2004. A review of empirical equations for estimating stream roughness and their application to four streams in Victoria. Australian Journal of Water Resources, 8(1).

Phillips, J.V. and Ingersoll, T.L., 1998. Verification of roughness coefficients for selected natural and constructed stream channels in Arizona. 1584, U.S. Geological Survey, Denver, CO, U.S.A.

Pickup, G. and Marks, A., 2001. Identification of floodplains and estimation of floodplian flow velocities for sediment transport modelling. CLW 12.

Riggs, H.C., 1976. A simplified slope-area method for estimating flood discharges in natural channels. U.S. Geological Survey Journal of Research, 4(3): 285-291.

Rooseboom, A., Basson, M.S., Loots, C.H., Wiggett, J.H. and Bosman, J. (Editors), 1986. Manual on Road Drainage. National Transport Commission, Pretoria, South Africa.

SKM, CRCFE, Freshwater Ecology (DSE) and Lloyd Environmental Consultants. 2002. The FLOWS Method –– a method for determining environmental water requirements in Victoria, Report prepared by Sinclair Knight Merz, the Cooperative Research Centre for Freshwater Ecology, Freshwater Ecology (NRE) and Lloyd Environmental Consultants. Department of Natural Resources and Environment, Melbourne.

Wellington, N.B., 1982. Energy loss parameters for the Barwon River at Geelong, The Association for Computer Aided Design, Ltd (ACADS) Forum/Workshop on energy loss parameters for flow profile computation programs. ACADS, October 6, 1982. Melbourne.

Western, A.W., 1994. The Behaviour of Salinity and Density Stratified Flows in the Wimmera River, Australia. PhD Thesis, The University of Melbourne, Melbourne, Australia.

Yen, B.C., 1991. Hydraulic resistance in open channels. In: B.C. Yen (Editor), Channel Flow Resistance: Centennial of Manning's Formula. Water Resources Publications, Littleton, Colorado, U.S.A., pp. 1-135.

Environmental Flow Needs of the Barwon Estuary Complex

Associate Professor John Sherwood, Deakin University, October 2005

1. Nature of the Present Estuary (adapted from Sherwood et al. 1987)

The Barwon River estuary is that part of the river system noticeably affected by tidal influence, or with a salinity gradient attributable to dilution of seawater. Prior to European settlement salt water penetrated above Geelong. A breakwater was built three kilometres southeast of Geelong in 1844 to prevent this. Around 1898 a second breakwater (the "Lower Breakwater") was built at the southeast end of Reedy Lake to further limit the upstream migration of saline water (Coulson, 1933; Figure 1). A system of floating gates was installed at the lower Breakwater in the late 1950's to limit inundation of low-lying areas during floods (Webster, 1959). The design of these gates was subsequently altered to prevent river levels upstream of the breakwater falling too low in summer.

For this study the Barwon estuary "complex" is defined as comprising the following four spatial components (See Figure 1):

1. A river channel from the Upper Breakwater to Lake Connewarre (10.25 km). The Lower Breakwater is 1.9 km upstream of Lake Connewarre;

2. Reedy Lake;

3. Lake Connewarre;

4. A river channel (the Lower Barwon) downstream from Lake Connewarre to the mouth at Barwon Heads (9.8 km).

The river mouth is 24.5 km below the Upper Breakwater. These components include most of the "pre-European" and all of the present estuary.

Reedy Lake, Salt and Hospital Swamps are not included in this estuarine environmental flows section. Reedy Lake is now a freshwater system and it and Hospital Swamp have water regimes manipulated at present by a system of channels and gates. Salt and Hospital Swamp vegetation communities are discussed elsewhere in this report.

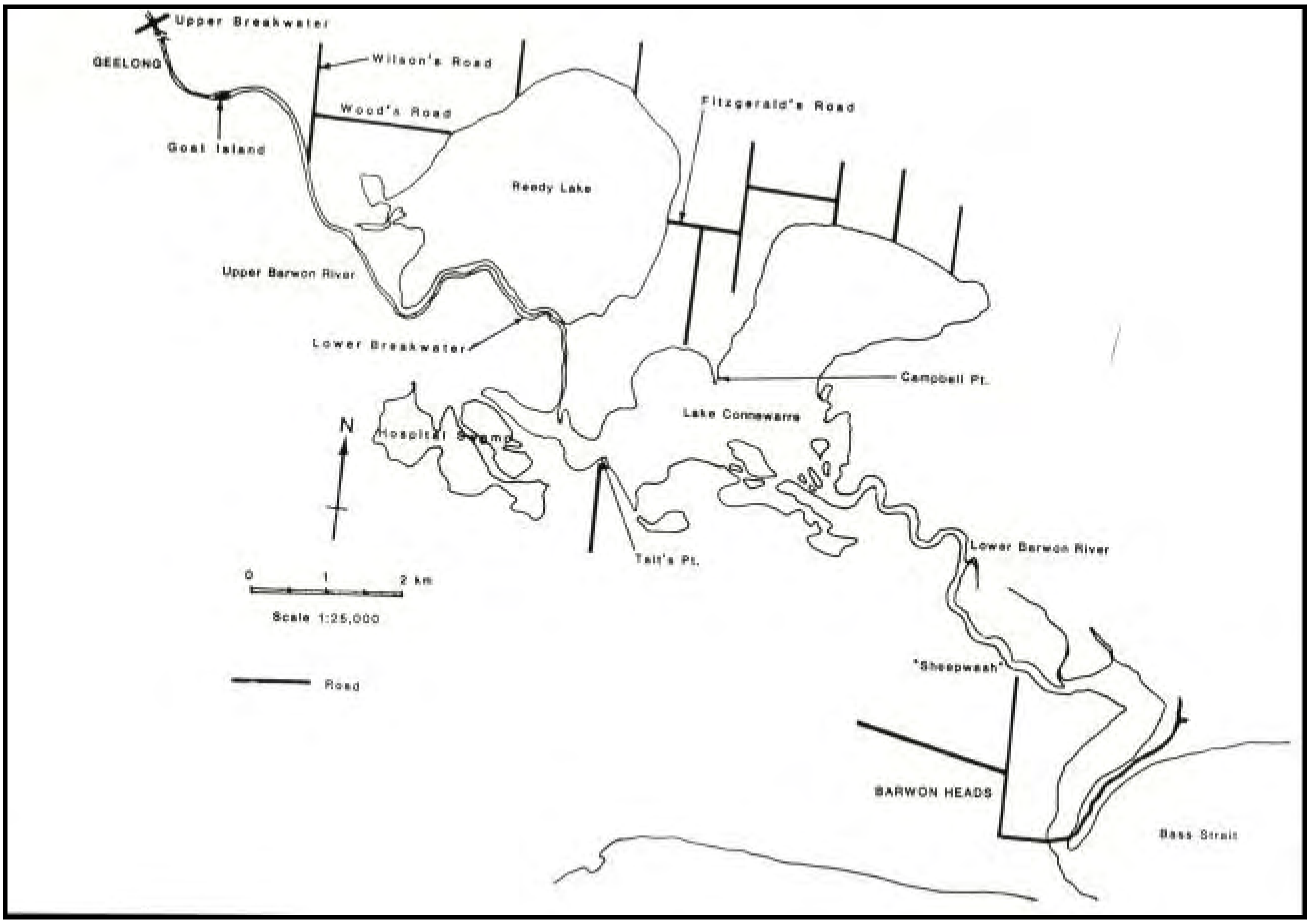

Figure 1: The Barwon estuary complex (Source: Sherwood et al. 1987).

1.1 Characteristics of the Estuary Components

Sherwood et al. (1987) reported that the Barwon estuary complex exhibits physical, chemical and biological characteristics representative of other Australian estuaries. None of the physico-chemical, parameters they studied exhibited extreme or abnormal values when compared to other estuaries. No previously undescribed or endangered species of plankton or macroinvertebrates were found in the complex.

Despite this overall picture of "normality" the Barwon estuary complex is not a "typical" estuary. In contrast to other Australian estuaries it combines several clearly identifiable components which are very different in their physico-chemical properties and hence support very different biological communities. This is partly due to the geological processes which have shaped the present estuary complex but it is also partly due to man's interference in the natural system.

(a) The Upper Barwon

This component of the complex is a river channel approximately 50m wide, 3 to 4m deep and about 10 km long. The river bottom is about 3m below mean sea-level. Prior to the construction of both breakwaters a salt-wedge would have penetrated upstream past Geelong from Lake Connewarre.

Little change in the concentration of chemicals monitored by Sherwood et al. (1987) occurred between the Upper Breakwater and the entrance to Lake Connewarre. This indicates that inputs from Reedy Lake or changes due to in-stream biological processes do not have any appreciable effect on water quality, in particular for nutrients or salinity. Total oxidised nitrogen concentrations were generally higher here than elsewhere in the estuary for most of the study period. This form of nitrogen is rapidly utilised in estuarine food chains.

An essentially normal freshwater riverine fauna occurred in this component.

(b) Reedy Lake

Reedy Lake is shallow (mean depth ~0.6m) with a large surface area ($5.5 \times 10^6 m^2$). It is connected to the Upper Barwon by two small channels above the Lower Breakwater. It's level changes in response to river discharge. Salinity in Reedy Lake decreases as lake level rises and is always slightly greater (by about 1 to 2 ppt) than that in the river. This is attributed to the lake's restricted circulation in conjunction with evaporation from its surface. During major floods, water flows directly through the lake when the river overtops its banks.

Nutrient limitation in Reedy Lake is different to all other components. The ratio of total N to total P is (18.1 ± 4.3) in Reedy Lake whereas for all components it is (9.2 ± 4.9). Thus, in Reedy Lake, productivity is limited by phosphorous while that of the rest of the complex appears to be nitrogen limited.

It is a highly productive ecosystem with relatively high concentrations of Kjeldahl nitrogen and total organic carbon reflecting this. Nutrient concentrations are high enough to classify the lake as eutrophic (as is Lake Connewarre).

The fauna is typical of a shallow macrophyte dominated freshwater lake. As such, it is unlikely to be affected by salinities up to 5ppt. Salinity above this level would drastically alter the nature of the lake's plant and animal communities.

(c) Lake Connewarre

Approximately 42% of the water in the estuary complex occurs in Lake Connewarre. It is about 50% larger than Reedy Lake in both volume and surface area. About half of the lake has a depth less than 50cm and its maximum depth is about 1m.

Lake Connewarre is a truly estuarine environment. Salinity varies from "fresh" (~1ppt) to values close to that of sea water(35ppt)during a typical year (Figure 2). During drought conditions, Lake Connewarre may become hypersaline (ie >35ppt).In the autumn of 1983 salinities reached 60ppt - presumably as the result of reduced tidal exchange and an increase in the significance of evaporation. Rosengren (1973) also refers to observations of hypersalinity in the Lake prior to 1983.

In order to predict the effect of river discharge on Lake Connewarre several approaches were used. Analysis of data from this, and an earlier study (Rooney, 1984) showed there was a linear logarithmic relationship between the salinity of Lake Connewarre (S) and monthly discharge of the Barwon River at Geelong (Q Ml/month):

$$\log_{10}Q = (4.86 \pm 0.19) - (1.08 \pm 0.16)\log_{10}S$$

The uncertainties associated with the constants in the equation limit its usefulness for predictive purposes. A computer "box" model for Lake Connewarre successfully predicted salinity changes in the lake during 1986 and offers more promise as a predictive tool.

Wind-induced turbulence exerts a major influence on Lake Connewarre. The lake is exposed to the prevailing SW winds. Its shallow depth means that wind-generated waves remobilise bottom sediments and efficiently mix lake water. Thus the water is always well oxygenated and frequently has very high suspended solids concentrations (up to 300 mg/l.). Total phosphorous and particulate organic matter concentrations are also high when suspended solids levels are high as a result of windy conditions.

Tides in Lake Connewarre are delayed by several hours compared to the mouth, with a mean spring tide range of about 15cm. The tidal prism of Lake Connewarre is about 1 x $10^6 m^3$, 15% of the lake volume. Tidal flushing of the lake is thus efficient. Residence time of water in the lake is probably less than 1 to 2 weeks.

The lake's phytoplankton appears to be sparse, probably due to turbulence, turbidity and nitrogen limitation. Phytoplankton would probably only increase in abundance if the lake depth was increased, reducing the effects of wind. The zooplankton and macroinvertebrate fauna is truly estuarine. Species number is less than elsewhere in the complex - indicating that the lake is an extreme environment. Elevated salinities (>35ppt) would not affect the estuarine organisms which can cope physiologically with a wide salinity range (up to ~60ppt).

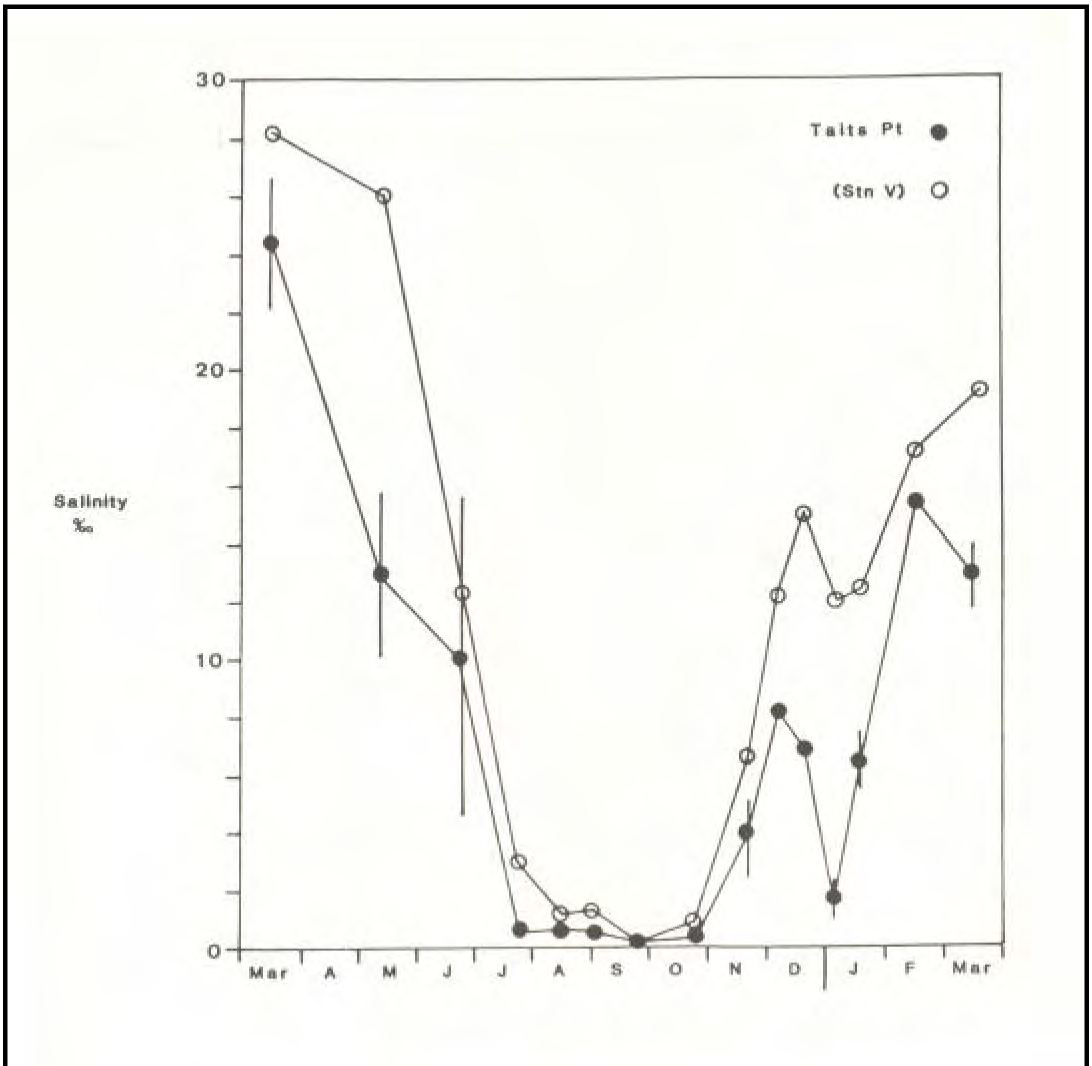

Figure 2: Temporal variation of salinity at two sites in Lake Connewarre during 1986-87. Station V is in the north arm of the Lake, Taits Point is on the southern shore (Source: Sherwood et al. 1987).

However, if salinity remained at or near 35ppt for long periods of time marine predators and competitors could become established in the lake, displacing estuarine organisms. This group is less euryhaline and would disappear when salinities fell below 25ppt. If salinity greatly exceeded 35ppt for long periods Of time both the true estuarine and marine forms would disappear. Overall, production in the lake might decrease as a result as the more salt tolerant forms in other highly saline coastal lagoons are not present in the Barwon complex.

(d) Lower Barwon

The Lower Barwon is another narrow, relatively deep (3 to 4m) riverine type component, about 10 km long. Near Barwon Heads the Lower Barwon widens substantially, and becomes shallower (1 to 2m). It is an extremely energetic component of the estuary complex. Large amplitude tides (mean spring range is 1.6 m at the mouth) propagate along the Lower Barwon and its waters are rarely still. The tidal prism of the Lower Barwon is equal to its volume($2.7 \times 10^6 m^3$) and so the residence time of water in this component is only a few tidal cycles.

Low salinities (<5ppt)are frequently encountered above Sheepwash in the Lower Barwon but the estuary was never totally "flushed" during the study period (1986/87) because of the large flood tides. The Lower Barwon is generally a well –mixed estuary with relatively small vertical gradients in salinity. Salinities rise during flood tides as seawater enters the estuary and fall on the ebb tide as less saline water from Lake Connewarre flows downstream (Figure 3).

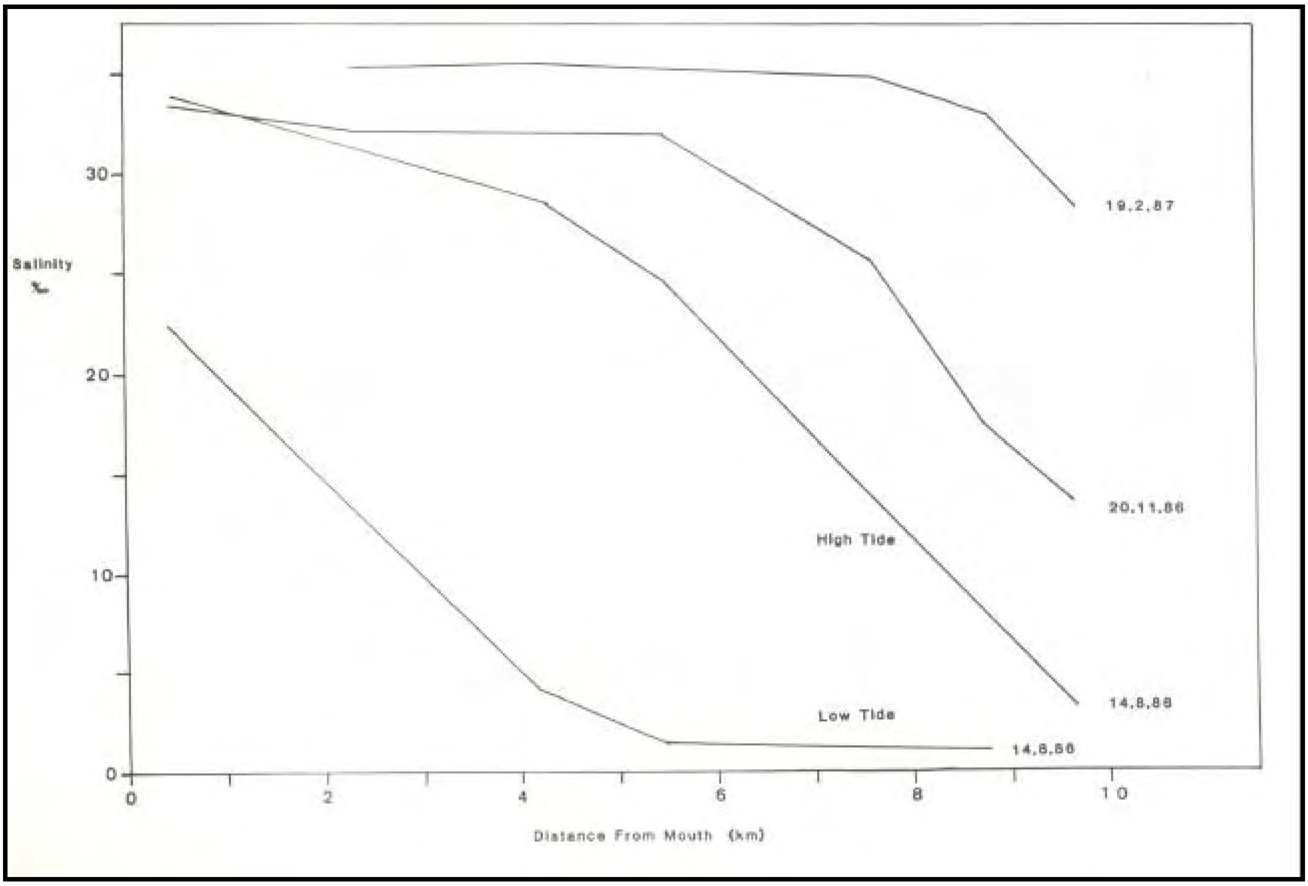

Figure 3: Longitudinal variation in salinity in the Lower Barwon estuary at times close to high water (19/2/87; 20/11/86/; 14/8/86) and low water (14/8/86). Note the increasing salinity at high tide as discharge decreased from August 1986 to February 1987.

Concentrations of nutrients and other chemicals monitored generally had their lowest concentrations in the Lower Barwon. This is because of their low concentration in seawater and the frequently high salinities encountered in this component.

The organisms characteristic of this section of the complex are essentially marine forms which can tolerate slightly lowered salinities. These organisms may move upstream into Lake Connewarre during periods of minimum flow and maximum salinity. Mangrove mud flats occur along the Lower Barwon but with reduced frequency above Sheepwash.

1.2 Evolution of the Present Estuary Complex

Coulson (1933, 1935) carried out the first detailed investigation of the estuary's geology. As well as identifying the major stratigraphic units of the region he drew attention to two other features:

1. the presence of fossil molluscan beds in the estuary indicating invasion by the sea at some time(s) in the past;

2. an apparent increase in siltation of Lake Connewarre since European settlement.

Evolution of the estuary complex has been affected by changes in sea level as outlined by various authors (Gill and Collins 1983; Gill and Lane, 1985). During the Last Interglacial Period, approximately 100,000 years ago, sea level peaked at +7m. Fossil shell beds between 4m and 7m on the Moolap Lowland have been linked to this time (Gill and Collins, 1983). During the Last Glacial Period sea level dropped until it was over 100m below present 20,000 years ago. At this time the Barwon River greatly deepened its channel and the "estuary" of the Barwon would have been many kilometres seaward of the present coast. Sea level rose subsequently peaking at a level 1-2m higher than now about 6000 years ago (Gill and Lane, 1985). Sand, silt and molluscan shell beds, some of which occur above present sea level, gradually filled up the ancestral Barwon River valley. Since then the sea has gradually receded resulting in the emergence of the flat lowlands characteristic of the study region.

1.3 Sedimentation in the estuary

In a letter published in the Geelong Advertiser (Tuesday 8 May 1855) the Assistant Surveyor, John Hamlet Taylor, reported on his survey of the lower Barwon in preparation for construction of a second breakwater downstream of that constructed at Geelong in 1841. The report, dated April 12 1855, states that the average depth of water from the Geelong breakwater to the “entrance into lakes is 15 feet”[4.6m] and that the “depth of water in lakes varies from 3 inches to 8 feet”[2.4m]. The present depth in the upper Barwon reach is still 3-4m however neither Lake Connewarre or Reedy Lake have depths close to 2.4m.

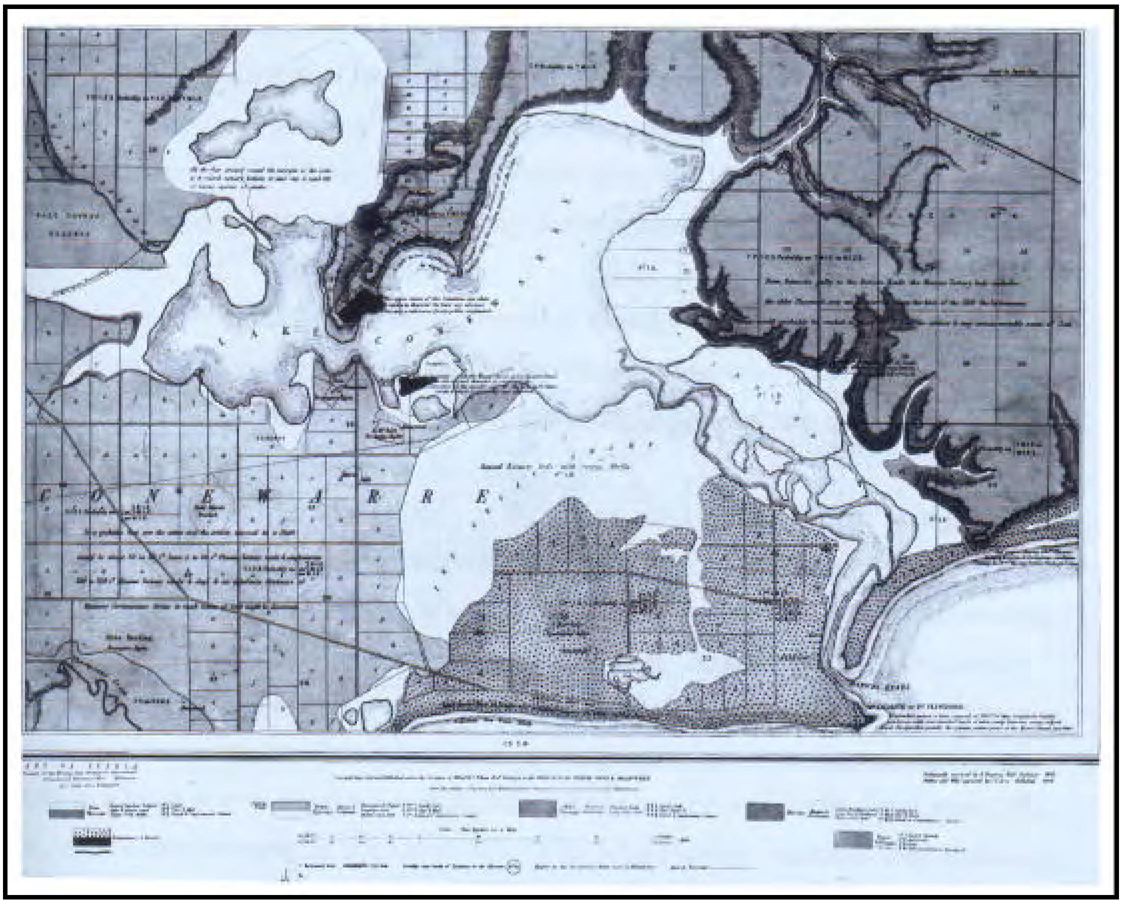

Figure 4: Map of Lake Connewarre in 1863 – note open water at the western end (Daintree, 1863; Source: Stokes 2002).

Comparison of maps of the estuary complex in 1863 (Figure 4; Daintree, 1863) and today (Figure 1) shows there has been a reduction in the area of open water in Lake Connewarre. Infilling has occurred in the western arm and along the southern shore of the lake. Coulson (1934) estimated that the southern shore had advanced "10 chains"[201m] and that there had been a reduction in depth:

> …"*the present depth of water in the middle of the lake is 4 feet, where formerly it was 7 feet. New mud and sand bars have appeared and others are forming.*"

A survey in 1987 (Sherwood et al., 1987) found a maximum depth in the northern arm of Lake Connewarre of 0.9m.

It seems clear that Lake Connewarre has shallowed substantially over the last 150 years. In evidence presented to a Parliamentary Public Works Committee in 1954 (Strom and Forbes, 1954) the State Rivers and Water Supply Commission identified 3 sources of the sediment:

- natural erosion
    - landslips, principally in the Otways.
- man-made erosion
    - large scoured gullies have formed in the country south of Winchelsea as a result of land clearing (eg on Wormbete Creek, near Wurdale).
- mining
    - large quantities of crushed rock, a waste product of gold mining, were dumped into the Yarrowee Creek (a tributary of the Leigh River) until 1912.

In its conclusions the Commission stated:

> ..."*but much of the silt released by the former uncontrolled minings has not yet reached its final resting place. Manmade or soil erosion can, and should, be lessened by soil conservation practices. About natural erosion little if anything can be done. Fortunately, it is not so rapid in its effects as the other two.*" (SRWSC,1954, p29)

Stokes (2002) has examined aerial photographs of the flood tide delta at the exit of Lake Connewarre into the Lower Barwon. She found relatively small changes in the islands and sand flats of the delta between 1947 and 2001 (Figure 5).

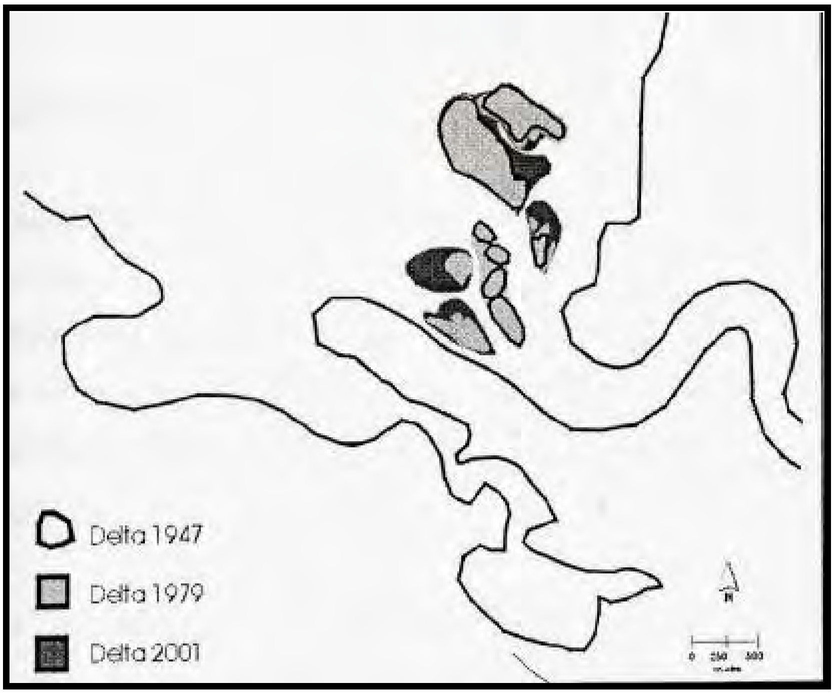

Figure 5: Changes to islands and shoals at the exit of Lake Connewarre to the Lower Barwon based on aerial photographs taken in 1947, 1979 and 2001 (Source: Stokes, 2002).

Sherwood et al. (1988) obtained radiocarbon dates for fossil beds of the oyster *Ostrea angasi* which form a surface pavement in shallow water (< 0.5m) off Campbell Point in Lake Connewarre. These ages (4,410 ± 60 yBP [SUA2766]; 5770 ± 70 yBP [SUA2767]) are similar to that found for a Koorie midden on Campbell Point by Gill and Lane ((5,270 ± 80 yBP [SUA2153]; 3620 ± 80 yBP [SUA2152]; 1985). It is most probable that Koories harvested oysters from these offshore beds. The presence of this ancient surface still exposed in Lake Connewarre is surprising given its recent history of sedimentation. The reason appears to be linked to wind re-suspension of sediments. Winds from the southwest quadrant constitute 40-50% of all winds and those from the northeast 20-25%. Strong winds in excess of 10 knots comprise 30-45% of monthly records. Southwest and northeast winds have the longest fetch in Lake Connewarre (~ 5 km; Sherwood et al, 1988). Re-suspension of sediment by wind-generated waves has constantly swept this fossil surface clean and moved sediments to the deeper parts of the lake or to the shoreline.

Taken together the evidence suggests that sedimentation in Lake Connewarre was greatly accelerated after European settlement through a combination of mining and agricultural practices. This sedimentation has resulted in significant changes to the western and southern shorelines of the lake and to a shallowing of the deeper sections in the northern arm. Shallow areas associated with the flood–tide delta may have been relatively stable for thousands of years. The Lake has operated as a sediment trap for the Barwon River over all this time but wind generated remobilisation of sediment has shifted it constantly to lower energy parts of the lake.

1.4 Primary Production in the Barwon Estuary System

The estuary complex is a macrophyte dominated system. Reedy Lake and fringing wetlands of the estuary (Hospital and Salt Swamps) are densely covered by stands of macrophytes (including *Typha*, *Phragmites*, *Distichlis* and *Sarcocornia* species). These ecosystems are sites of high productivity.

Within Lake Connewarre Sherwood et al. (1987) found a depauperate phytoplankton community (20 taxa) dominated by diatoms. Although algal blooms were observed these were localised and short-lived. Generally low cell densities suggested the contribution of phytoplankton to total primary production in the estuary was small (Sherwood et al., 1987).

Isolated colonies of sea grass (eel grass - *Zostera* or *Heterozostera* sp.) were observed in the northern arm of Lake Connewarre and at its exit to the Lower Barwon during 1986/87 (Sherwood et al, 1987). In August 2005 Mr Ron Scotland photographed a much more extensive stand of sea grass extending almost completely along the northern shore of the Lake and about 50m wide. Constant remobilisation of sediment in the shallow areas (<0.5m) of Lake Connewarre mitigates against establishment of seagrass beds there. Sedimentation in the northern arm of the Lake, however, may have created more favourable conditions for eel grass by improving the benthic light climate while maintaining a depth where sediment resuspension is still low. Expansion of the eel grass beds since 1987 may also reflect reduced freshwater inflows during the present long drought (at least 6 years). Elevated salinities in Lake Connewarre may have created conditions more favourable to these plants.

An increase in the distribution of seagrass would be expected to raise the biodiversity values of Lake Connewarre. The high productivity of seagrass meadows supports other components of an estuary ecosystem by providing a significant food source for herbivores - which are themselves food for organisms such as fish and birds higher in the food chain. They also act as a refuge for larvae and juveniles of many species such as commercially and recreationally important fish. Finally, they act to stabilise sediments (Howard and Edgar, 1994). Loss or decline of seagrass beds has been a cause for concern in areas such as Westernport (Vic.) and Botany Bay (NSW) because of their important roles in estuarine ecosystems (Keogh & Jenkins, 2000).

One disadvantage of these seagrass meadows is that detached leaves of eel grass accumulate on the Lake's northern shore. Their decomposition has generated strong unpleasant odours particularly in summer 2004/5 (R. Scotland, personal communication). Decomposition of the leaves is an important recycling step however – returning nutrients and carbon to the lake ecosystem (Keogh and Jenkins, 2000).

Salt marsh and mangrove communities of the Lower Barwon are also highly productive. Both types of plant community make a major contribution to an estuarine ecosystem through their supply of plant litter. This material, like that of the sea grass, is either consumed directly or in various degraded forms by many animals (McLuskey and Elliott, 2004). Stokes (2002) has mapped the distribution of salt marsh and mangroves in the Lower Barwon and concluded that both have increased over the last 150 years – with the mangrove population increasing substantially since 1947. These changes would also be expected to have improved the productivity and biodiversity of the estuary.

2. The Estuarine Hydrodynamic Cycle

A marked seasonal inequality in discharge results in an annual hydrodynamic cycle for western Victoria's estuaries. During winter and spring, high flows may flush all salt water from the estuary, which becomes an extension of the freshwater section of the river for periods up to several weeks (Figure 6). As flows recede through spring and summer, salt water reinvades the estuary. As flow decreases the length of the salt water intrusion increases. Re-entry of well-oxygenated saline water into the estuary appears to be a trigger for breeding in many estuarine organisms, from zooplankton to fish (Newton 1996; Nicholson *et al*, 2004). During summer and autumn, salt water penetrates to its maximum extent and estuarine circulation is reduced. This can lead to extended periods of anoxia or hypoxia in deeper water of the estuary. The aerobic community is then confined to the surface water layer under these conditions – a layer found to be less than 1m thick in some estuaries (Sherwood and Rouse, 1997, Rouse, 1988). Spawning success in some species with floating eggs and/or larval life stages may be compromised by the presence of anoxic saline waters containing high concentrations of toxic substances such as hydrogen sulphide (H_2S) and ammonia (NH_3). The black bream (*Acanthopagrus butcherii*) for example has eggs which float in the halocline as they are neutrally buoyant in water of salinity 16-20 (Nicholson *et al* 2004, Sherwood and Backhouse 1982).

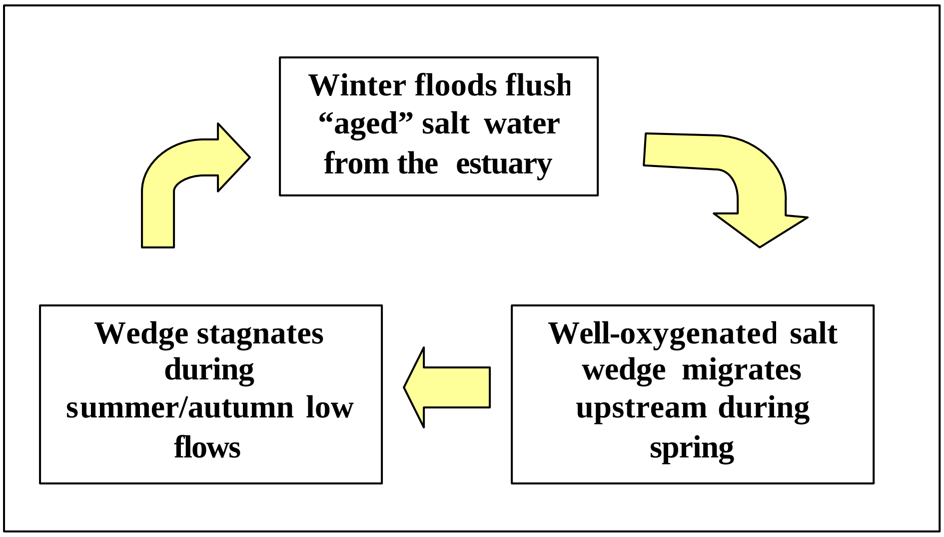

Figure 6: Annual hydrodynamic cycle of west Victorian estuaries (Sherwood, 1985).

Two important features of the annual hydrodynamic cycle are relevant to the consideration of environmental flows:

(a) Winter flows sufficient to flush salt water from the estuary.
The biological communities of the Barwon estuary have adapted to seasonal pulses in river discharge and salt water incursion. These pulses alter salinity spatially and temporally within the estuary. Any alteration to normal patterns of river discharge will affect seasonal salinity cycles within the estuary and may subject estuarine communities to salinity extremes beyond their tolerances or provide suitable conditions for competing organisms. Also, bottom water may be anoxic or hypoxic and this reduces the availability of water having both adequate dissolved oxygen for respiration and optimal salinity for breeding of estuarine organisms.

(b) Summer/autumn low flows sufficient to maintain estuarine circulation. Turbulent entertainment of bottom salt water (either generated by wind, river flow or tidal forcing) into surface waters, and the subsequent transport of this from the estuary, allows replacement of bottom water. This reduces the incidence and longitudinal extent of hypoxic/anoxic conditions. In the Lower Barwon estuary, tidal exchange is an efficient mechanism for water replacement. Upstream it has reduced effectiveness in the absence of freshwater surface flow.

3. Summary of Flow-related Environmental Risks

Pierson *et al* (2002) have identified 16 major flow-related processes which impact on estuarine environments (Table 1). The impacts have been categorised according to the relative flow magnitude for which their effects are most noticeable. Not all of these will be significant for all estuaries. The likelihood of each of the flow-related processes being significant for the Barwon estuary is summarised - below as is an assessment of the severity of consequences should the adverse effects manifest themselves.

Table 1: Major ecological processes by which reduced estuary flows can impact on estuarine ecosystems (Pierson *et al.*, 2002)

Relative River Inflow	Process	
	No.	Nature
Low	1	Increased incidence of hostile water quality conditions at depth
	2	Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna
	3	Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora
	4	Extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota
	5	Extended periods when flow-induced currents cannot suspend eggs or larvae
	6	Extended periods when flow-induced currents cannot transport eggs or larvae
	7	Aggravation of pollution problems
	8	Reduced longitudinal connectivity with upstream river systems
Middle-High	9	Diminished frequency of flushing of the estuary bed of fine sediments and organic matter – reducing the quality of physical habitat
	10	Diminished frequency of flushing of organic matter from deep sections of the estuary – reducing water quality
	11	Reduced channel maintenance processes
	12	Reduced inputs of nutrients and organic material
	13	Reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to the estuary
All	14	Altered variability in salinity structure
	15	Dissipated salinity/chemical gradients used for animal navigation and transport
	16	Decreases in the availability of critical physical habitat features, particularly those components associated with higher velocities

3.1 Low Flow Conditions.

Process 1. Increased incidence of hostile water conditions at depth.

Likelihood – High

Anoxic bottom waters occur during low flows in the uppermost estuarine reach between Lake Connewarre and the Lower Breakwater. A reduction in freshwater flows will reduce the thickness of the surface oxygenated water in this reach – reducing available habitat for fish and other aerobic organisms.

Consequence – Severe

Anoxic water close to the surface in the upper Barwon could impede migration of organisms between Lake Connewarre and the upstream reaches of the river. The viability of eggs and larvae in contact with anoxic water will be greatly reduced (eg at the halocline).

Process 2 and 3. Extended durations of elevated salinity in the upper – middle estuary adversely affecting sensitive flora and fauna.

Likelihood – High

Lake Connewarre is the largest component of the present estuary. During high flows its salinity is lowered – and it may be fresh for several weeks during floods. Reduction in flows will increase salinity in the lake – favouring less euryhaline species. Strongly marine or hypersaline conditions may persist for longer.

Data from an EPA survey of Lake Connewarre shows that under very low flow conditions (as in 1982-83) the Lake can become hypersaline (Rooney, person comm., 1984). A 1987 survey of the estuary showed the macroinvertebrate fauna of Lake Connewarre included species with very wide salinity tolerances. This may reflect the influence of conditions ranging from fresh to hypersaline. (Sherwood, et al, 1987)

Consequence – Severe

Stenohaline species may compete successfully against estuarine organisms if marine conditions persist for longer periods. This will alter the estuary's community structure. Hypersalinity could reduce the diversity of Lake Connewarre.

Process 4. Extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota.

Likelihood – Medium to Low

Mangroves may increase their range upstream in the Lower Barwon if freshwater influence in this reach is reduced. The well-mixed nature of this reach, due to the large tidal exchange, means this reach is marine dominated under all but the highest flows.

Consequence – Minor

Extension of saline conditions in the Lower Barwon should have little impact on the species present.

Process 5 and 6. Extended periods when flow-induced currents cannot suspend or transport eggs and larvae.

Likelihood – Low

In Lake Connewarre wind-generated turbulence generates water currents. The lake is relatively well-mixed and nearly constant re-suspension of bottom sediments has prevented establishment of macrophytes and maintained high turbidity. A fossil oyster bed (*Ostrea angasi*; Gill and Lane, 1985) is still exposed on the lake floor to the east and south of Campbell Point because sediment is continually being swept from it.

Tidal circulation is effective in the Lower Barwon and low river flow is unlikely to substantially increase water currents. In the Lower Barwon the major energy comes from tides – the tidal prism is approximately the same as the volume of this reach. Residence time of water in this reach is probably less than a few days and not much influenced by freshwater flows except in higher floods.

Freshwater flow does however establish a marked halocline important for buoyancy control mechanism for eggs and larvae of some species in the upper Barwon reach.

Consequence – Severe

The absence of transporting mechanisms could compromise breeding success of susceptible species – altering species composition in the estuary as well as the river – where freshwater species enter the estuary to breed.

Process 7. Aggravation of pollution problems.

Likelihood – Medium to Low

The major water quality threat to the estuary would be expected to come from eutrophication. Algal blooms are most likely in the reach above Lake Connewarre – anoxic bottom waters are nutrient enriched adding to nutrient inputs from freshwater. Reduction in freshwater flows will increase the residence time of water in this section favouring phytoplankton communities.

Turbidity in Lake Connewarre and tidal exchange in the Lower Barwon mitigate against algal blooms in these components. However, in April and May 2005 a bloom of two salt –tolerant blue-green algae (*Nodularia* and *Anaebaenopsis*) persisted in Lake Connewarre and the Lower Barwon for several weeks. Calm conditions, sunny days, neap tides and low river flow favour algal growth during autumn.

River flow may improve flushing of algae and pollutants from the estuary, but river water quality is not high. For example it may not constitute a diluting flow for nutrients.

Consequence – Severe

Any increase in the incidence of algal blooms threatens other species and reduces the recreational amenity of the estuary.

Process 8. Reduced longitudinal connectivity with upstream river systems.

Likelihood – Medium to Low

Under low flow conditions barriers to fish migration at the upper and lower breakwaters would have maximum impact on fish migration. The significance of this on fish migration is not known. Tunbridge (1988) summarised the seasonal movement of fish in the Barwon River and estuary (Table 2). He concluded that the distribution of highly mobile species (such as short-headed lamprey, short-finned eels, broad-finned galaxias, common galaxias, spotted galaxias, tupong and grayling) would be influenced by the upper and lower barrages and Buckley's Falls.

Period	Fish Activity
Dec-Feb	Adult short-finned eels leave the estuary to spawn at sea.
March- Nov	Juvenile common galaxias and broad-finned galaxias run upstream from the estuary.
May-July	Grayling spawn. There is a possible downstream movement of larvae. Adult tupong and common galaxias run downstream into the estuary to spawn. Glass eels enter the estuary from the sea.
Oct-Nov	Brown elvers run upstream from the estuary. Adult lamprey run upstream to spawn in fresh water. Carp, redfin and blackfish move to spawning sites in the river. Adult short-finned eels move from freshwater into the estuary.

Table 2: Seasonal movement of fish in the Barwon River and estuary (Tunbridge, 1988)

Construction of fish passages may improve fish migration at the barrages. This may have greater impact than flow regulation.

Consequence – Severe

Migration is essential for some fish species to complete their life cycles. If this is not possible species may be lost from the river system.

3.2 Middle-High Flow Conditions.

Process 9, 10. Diminished frequency of flushing of the estuary bed and deep sections of fine sediments and organic matter – reducing the quality of physical habitat.

Likelihood – High

Lake Connewarre has received large volumes of sediment since European sediment. Large winter floods are probably important to remove fine sediments from the upper Barwon estuary (above Lake Connewarre) and from Lake Connewarre. Large floods generate currents in the NE arm of Lake Connewarre and at the Lake exit which can transport fine organic sediments downstream.

Consequence – Severe

The wide expanse of Lake Connewarre means it acts as a natural sediment trap as river flows decrease on entry to the lake. Without high flows to erode deposited sediment the lake will shallow with consequent habitat loss..

Process 11. Reduced channel maintenance processes.

Likelihood – High

Higher water currents associated with large floods serve as important function by eroding sediment at the upstream and downstream entrances to Lake Connewarre.

Consequence – Severe

The efficient exchange of water requires good connectivity between the lake and riverine sections above and below it. Reduction in the cross-sectional area of the Lake exit to the Lower Barwon will increase residence time of water in the lake and so increase the frequency of hypersalinity.

Process 12. Reduced inputs of nutrients and organic material.

Likelihood – Low

The estuary is eutrophic – there is no evidence for a shortage of nutrients or organic material. River flows are probably a minor source of nutrients compared to the sediments of Lake Connewarre.

Consequence – Minor

Remineralisation of organic matter in the sediments of the estuary can provide necessary nutrients for the ecosystem.

Process 13. Reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to the estuary.

Likelihood – Unknown

Flooding frequency of the wetlands adjacent to the open waters of the estuary would be expected to be an important determinant of their vegetation communities. An extensive system of drains and locks currently allows this to be manipulated by management agencies.

In the lower Barwon flooding of fringing salt marsh may be more dependent on tidal range – although winter floods may increase the frequency of inundation.

Consequence – Severe

Vegetation communities in the fringing wetlands require periodic inundation by either fresh (upper estuary) or marine waters (lower estuary). A reduction in flooding events will lead to deterioration of the ecosystem as species of plant are lost.

3.3 All Flow Conditions.

Process 14. Altered variability in salinity structure.

Likelihood – High

The organisms of the estuary have adapted to the annual hydrological cycle of the Barwon River. This is characterised by winter/spring floods and summer/autumn low flows. Long periods of constant flow do not naturally occur. In low flow conditions small increases in flow ("freshes") change salinities in the upper Barwon and Lake Connewarre, with smaller impacts on the lower Barwon.

As previously discussed, the impacts of altered flow regimes on the hydrodynamic cycle have important implications for the distribution of organisms and the breeding success of some species

Consequence – Severe

Truly estuarine species may be out-competed by more stenohaline species (either marine or freshwater) if constant salinity conditions are maintained for long periods.

Process 15. Dissipated salinity/chemical gradients used for animal navigation and transport.

Likelihood – High(?)

The impacts of flow on factors such as this are not well understood. Freshwater outflows from the estuary are important in attracting the juvenile stages of diadromous species (eg. eels, galaxiids) into the river. Freshwater outflows are also important for transporting eggs and larvae of some diadromous species into the marine environment, and act as adult migration triggers for diadromous species that migrate from freshwater to the estuary or sea to spawn. Reductions in freshwater outflow, therefore, are likely to reduce recruitment of diadromous fish in the catchment.

Consequence – Severe

Interference with animal migration or transport threatens the viability of species populations in the river and estuary. Localised extinctions could result.

Process 16. Decreases in the availability of critical physical habitat features, particularly those components associated with higher velocities.

Likelihood – Unknown (low?)

High velocities are associated with tidal exchange in the lower Barwon. In the Upper Barwon freshwater flows have maximum velocities because of the riverine morphology nature of this reach. The significance of this for the provision of habitat is not known.

Consequence – Severe

Loss of habitat may see reduced populations of dependent species in the estuary.

4. Draft Management Recommendations.

4.1 Key Characteristics of Environmental Flows.

Given uncertainties over the ecological effects of changes in flow to estuaries these recommendations for environmental flows are based on the principle that:

> *diversion of water from river systems should not disturb the major features of the estuarine hydrodynamic cycle.*

In the case of estuaries in Western Victoria, this means that the following key characteristics should be maintained.

(i) Late winter to early spring flows sufficient to flush "aged" salt water from the estuary and allow migration of a well-oxygenated salt water upstream as the flows reduce.

(ii) Flows sufficient to maintain a salinity gradient both vertically and horizontally. The gradients should ensure that water over the range of salinities from fresh to strongly marine is present in the estuary most of the time.

(iii) Avoidance of long periods of constant flow. The inherent variability of stream flow (including periods of cease-to-flow conditions if naturally occurring) should be maintained. This will require short periods when higher flows ("spates" or "freshes") enter the estuary. These serve also to improve the flushing characteristics of the estuary.

4.2 Late winter to early spring flushing flows

Recommendation 1.

A flow of at least 600 ± 200 ML/day measured at McIntyres Bridge (Geelong) should be maintained for at least 3 months in late winter/early spring (between July and October) as a flushing flow to maintain freshwater conditions. This flow should occur at least once annually.

This estimate is based on a logarithmic relationship found between disxcharge and salinity in Lake Connewarre and on a hydrodynamic model developed for the lake (Sherwood *et al*. 1987)

4.3 Summer/Autumn Low Flows

Recommendation 2.

Salinity in Lake Connewarre should not exceed 35ppt during summer and autumn low flow conditions and this maximum level should not be maintained for more than 2 months. The miinimum environmental flow needed to achieve this is 30 ± 10 ML/day at McIntyres Bridge

4.4 Flow variability

Temporal variability in the input of freshwater flow is an inherent component of a functioning estuarine environment. Such variability, for example, results in variations in salinity that advantage euryhaline species adapted to highly variable salinity regimes. Loss of this variability has the potential to drastically alter community structure, with euryhaline estuary species replaced by stenohaline species adapted to either truly marine or freshwater environments. A minimum flow (Recommendation 2) will provide flows to ensure that a salinity gradient is maintained in the upper estuary. However, a minimum flow will not provide the variability required to maintain the estuarine ecological community. It is recommended, therefore, that the managed flow regime include periods of low flow (or cease to flow conditions) and freshes to mimic natural levels of flow variability. The frequency and timing of the recommended flows, and any independence rules related to meeting the recommendations, have not been specified here and will need to be formulated via further analysis of modelled flow data.

Recommendation 3.

Flows less than the minimum flow established in Recommendation 2 (including cease to flow conditions) should be allowed to occur at their natural frequency and timing. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

Recommendation 4.

Periods of higher flow should occur during summer and autumn at their natural frequency and timing to mimic natural freshes. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

4.5 Maintenance of Connectivity

The Upper and Lower Breakwaters (or Barrages) present barriers to fish migration in the Barwon River. Such barriers break the connectivity between the sea, estuary and river essential for the lifecycles of diadromous fish including galaxids, tupong , eels and, potentially, the threatened Australian grayling.

Recommendation 5.

Fish passage should be provided to allow migration of diadromous species between freshwater and the estuary/sea.

References

Coulson A. (1933) *Astudy of Lake Connewarre*. Victorian Naturalist, L, 12 –17.

Coulson A. (1935) Geological Notes on Lake Connewarre near Geelong, Proceedings of the Royal Society of Victoria, 48, Part 1, 1 –12.

Daintree R. (1863) *Geological Map of Lake Connewarre and Surrounds,* Victorian Geological Survey, Melbourne, Victoria, Australia.

Gill E.D. and Collins A.C. (1983) *Ancient seaway between Geelong Harbour and Bass Strait Victoria.* Victorian Naturalist, 100(5), 200 – 203.

Gill E.D. and Lane L.N. (1985) *Sea level and aboriginal oyster midden at Lake Connewarre, Victoria, Australia*. Proceedings of the Royal Society of Victoria, 97(2), 95 –100.

Howard R. K. and Edgar g. J. (1994) "Seagrss Meadows" in L. S. Hammond and R. N. Synnot (eds) Marine Biology, Longman Cheshire, Melbourne, pp 257-271.

Keogh M. J. and Jenkins G. P. (2000) "Seagrass Meadows and their inhabitants: In A. J Underwood and M. G. Chapman, Coastal Marine Ecology of Temperate Australia, UNSW press, Sydney, pp. 221-239.

McLusky D.S. and Elliott M. (2004) "The Estuarine Ecosystem : Ecology, Threats and Management", Oxford University Press, UK, (3rd edn)

Newton G.N. (1996) *Estuarine ichthyoplankton ecology in relation to hydrology and zooplankton dynamics in a salt-wedge estuary,* Marine and Freshwater Research, 47:99-111.

Nicholson G, Sherwood J, Jenkins G and Longmore A (2004) *Effects of Environmental flows on the spawning success of resident black bream in estuarine environments.* Primary Industries Research, Queenscliff, Victoria. Report No.23, June 2004 (68pp)

Pierson W.T., Bishop K., Van Senden D., Horton P.R. and Adamantidis C.A. (2002) *Environmental Water Requirements to Maintain Estuarine Processes*, Environment Australia, Environmental Flows Initiative Technical report No. 3 (147pp).

Rosengren N.J. ((1973) *Lake Connewarre and the Barwon Estuary*, Victoria's Resources, Sep-Nov., 19-22.

Sherwood J.E., (1985). *Hydrodynamics of South West Victorian Estuaries*. Faculty of Applied Science and Technology, WIAE, Research Report 85-1 (27pp).

Sherwood J.E. and Backhouse, G. (1982*). Hydrodynamics of Salt Wedge Estuaries - Implication for Successful Spawning in Black Bream (Acanthopagrus butcheri)*. Faculty of Applied Science and Technology, WIAE, Research Report 82-3, September, 1982 (16pp).

Sherwood, J.E., Mitchell, B.D., Magilton, C.J., Walsh,C.J., and Newton, G.M. (1987). *A Study of the Barwon Estuary Complex.* Report 87-2, Centre for Aquatic Science, WIAE. Prepared for the South-West Regional Water Resources Task Force (147pp).

Sherwood J.E., Mitchell B.D., Magilton C.J., Walsh C.J. and Newton G.M. (1988) "Victoria's Barwon Estuary - a test of adaptability" In D. Wilkinson (ed) Silver Jubilee Conference Commemorative Volume, Australian Marine Sciences Association, Sydney University, Sydney, 125-130.

Sherwood J. and Rouse A. (1997) *"Estuarine chemistry - primordial soup Down Under!"* Chemistry in Australia. August 1997 ,19-22.

Strom H.G. and Forbes I.G.(1954) *The Barwon river and its Catchment: Evidence prepared for submission to the Parliamentary Public Works Committee,* State Rivers and Water Supply Commission, Victoria, October 1954.

Stokes D. (2002) *Tidal Dynamics and Geomorphology of the Lower Barwon Tidal Inlet*, Honours Thesis, School of Arts and Education, LaTrobe University, Bendigo.

Tunbridge B.R. (1988) *Environmental Flows and Fish Populations of Waters in the South-western Region of Victoria.* Arthur Rylah Institute for Environmental Research, Dept of Conservation, Forests and Lands, Melbourne, Victoria (140pp)

Webster A.G. (1959) *Floating gates on Barwon River.* Aqua, 10(7), 142 –3.