Environmental Water Requirements of the Werribee River Estuary

Final Estuary FLOWs Report

by:

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for **Corangamite Catchment Management Authority**

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1 INTRODUCTION

Environmental flows determinations for estuaries are important to support their intrinsic, ecological, social and economic values. Until recently there was no accepted method for the determination of the required input of freshwater flows into estuaries in Victoria. A draft method for estuaries was developed by Hardie et al. (2006) based on an extension of the FLOWS methodology (NRE, 2002). FLOWS is the accepted state-wide method for the determination of environmental water requirements for rivers. It is an objective-based, multi-disciplinary, rigorous approach that can be broadly extended to estuaries. The draft methodology proposed by Hardie et al. (2006) required pilot testing. This current project on the Werribee River is a pilot test of this method and also includes considerable upgrading of the modelling approach and refinement of the ecological conceptual models and knowledge requirements.

This report presents the results of the pilot application in the form of the Final Estuary FLOWS Report, which documents the refined biodiversity and hydrological objectives for the Werribee estuary and recommends environmental flows to achieve the defined objectives.

1.1 The Werribee River Estuary FLOWS Project

The Werribee River catchment is over 1,424 km^2 in area and flows through Werribee into northern Port Phillip Bay (Figure 1-1). Werribee is located approximately 30 km south west of Melbourne. The river system is highly flow-stressed and regulated with diversions for irrigation at Pykes Creek, Merrimu and Melton Reservoirs and at the Lower Werribee Diversion Weir (Figure 1-1). The Victorian Government has committed to improving the river's ecological health by funding three projects designed to enhance the health of the Werribee River. These projects include 'Habitat works and willow removal', 'Environmental flow needs of the river', and 'Environmental flow needs of the estuary'. In turn these projects are part of larger project titled the *Vision for the Werribee Plains: the Next Step. Action Plan 2004* and includes a plan to enhance the environmental water reserve for the Werribee River by greater use of recycled water in the Werribee Irrigation District (Victorian Government, 2004).

The Werribee estuary is 8.25 km long with an upstream limit defined by a ford located about 3.5 km downstream of central Werribee (Figure 1-2). The ford was constructed in the 1860s and is situated close to the earliest crossing of the Werribee River (which was part of the first road to Geelong in the 1840s). Upstream of the ford fresh water forms a deeper long pool. The water level drops about 0.5 m after flowing over the ford. About 100 m downstream of the ford the estuary narrows to a shallow riffle area preventing boat access upstream.

Land on the western side of the estuary is managed by Melbourne Water and is primarily used for dryland grazing of stock as part of the Werribee Farm, containing the sewerage treatment plant. On the eastern bank of the estuary the dominant land uses are a golf course (upper estuary) and market gardens (lower estuary). The water for irrigation is supplied from the Werribee River via the Lower Werribee Diversion Weir, located about 9 km upstream of central Werribee. A public boat launching ramp is located within a few hundred metres of the entrance of the estuary from Port Phillip Bay at the town of Werribee South (Figure 1-2).

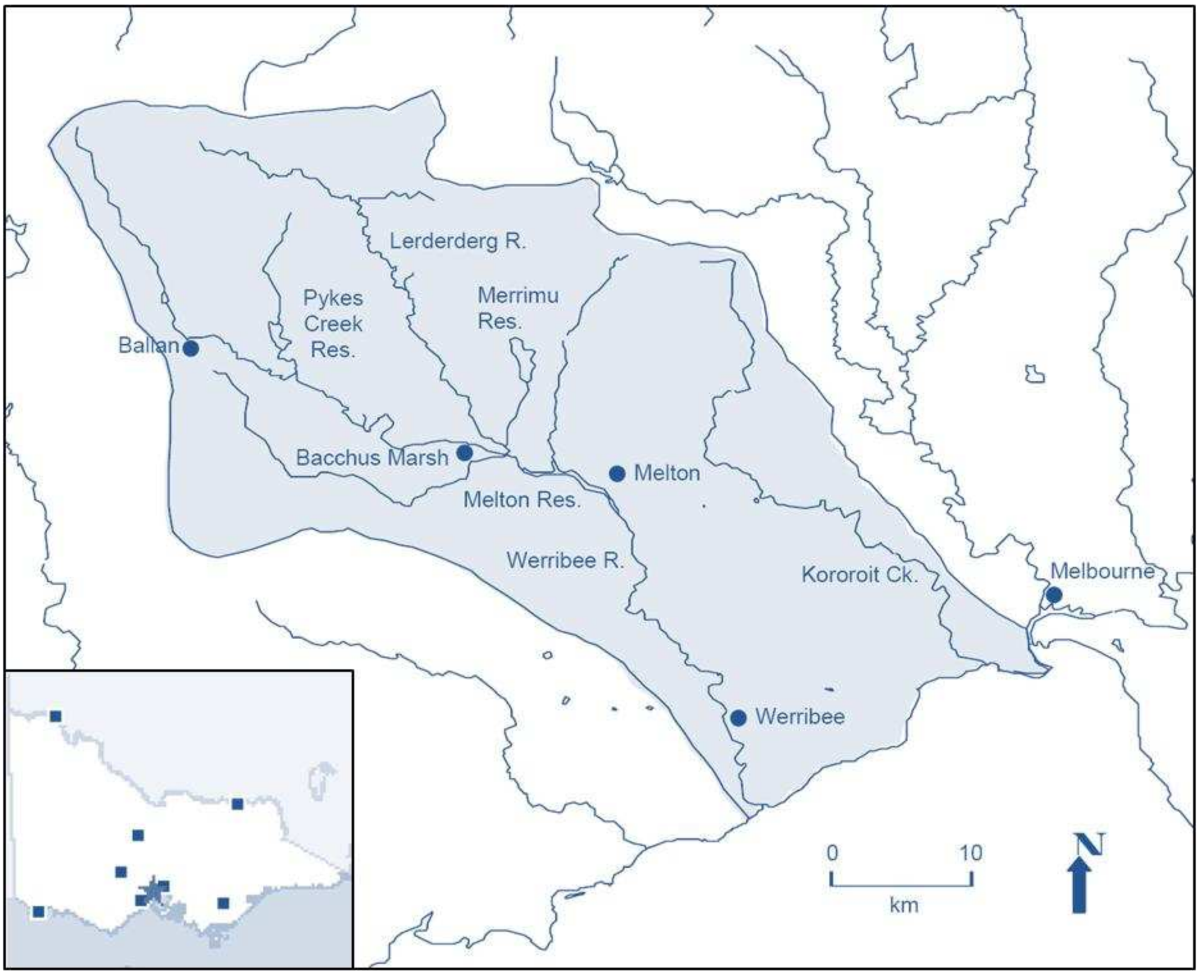


Figure 1-1. Werribee River catchment. Source: Sherwood et al. (2005).

1.2 Project Objectives

The major objectives of this project are to:

- identify freshwater-inflow dependant environmental and social values within the estuary;
- gauge the current health of the estuary values;
- identify the flow regimes that will maintain or enhance the environmental values;
- develop Environmental Flow Objectives that take into account current social, economic and environmental values of the river; and,
- recommend an environmental flow regime to meet the objectives.

In addition, the Panel should also test the effectiveness of the methods and techniques as described in the draft method.

Figure 1-2. Location of the Werribee River estuary, from downstream of the ford. Shading indicates the 1 in 100 year floodplain.

1.3 The Pilot Methodology

The methodology used in this study of the flow needs of the Werribee River estuary was based on that developed by developed by Hardie et al. (2006) for the Corangamite CMA and DSE, and intended for application to Victorian estuaries. The methodology has three stages (first 3 stages in Figure 1-3). It is a framework, with some recommended steps and some common tools and approaches applied to systematically review the information available for the target estuary. Stage 1 seeks to review the available information on the estuary and gain input from community and agency stakeholders and an initial inspection of the site by the Scientific Panel co-ordinator and agency project manager. The stage results in a **Scoping Report** (Lloyd et al. 2007a) and, separately, a brief for Stages 2 and 3.

Stage 2 consists of specialist investigations required to fill knowledge gaps identified in Stage 1, without which a flow determination could not be undertaken. This is likely to include information on the bathymetry of the estuary to allow hydraulic modelling to take place, but in estuaries with little biological information, it may also include flora and fauna investigations.

Stage 3 begins with a Scientific Panel Site assessment in which the scientists with both physical and biological expertise inspect the reaches to understand the values and components of the estuary. This allows the group to develop the ecological and flow objectives for the estuary, which are documented in the **Issues Paper** (Lloyd et al. 2007b). Modelling and application of various analysis tools allows the Scientific Panel to fully understand the dynamics and the links between flow and ecological requirements of the estuary. A Scientific Panel Workshop reviews the modelling results and determines the preliminary Environmental Water Requirements (EWR) recommendations for the system. These recommendations are reviewed and subject to a “reality check” by stakeholders before being finalised as a **Final Estuary FLOWS Report** (this report).

This project will also contribute to an additional Stage 4 (Figure 1-3), which is the review and updating of the **Estuary FLOWS Method**.

1.4 The Scientific Panel

The Scientific Panel for this project was made up by:

- Lance Lloyd (Lloyd Environmental), Estuary FLOWS Project Co-ordinator; fish and aquatic fauna ecologist;
- Dr Marcus Cooling (Ecological Associates), aquatic and floodplain vegetation ecologist;
- Dr Chris Gippel (Fluvial Systems), hydrology and geomorphology specialist;
- Dr Brett Anderson (Water Technology), hydraulic modeller;
- Associate Professor John Sherwood (Deakin University), estuarine environmental flow scientist (water quality and estuarine processes);
- Dr Adam Pope, (Deakin University), estuarine ecologist (environmental processes);
- Dr Jeremy Hindell, (Freshwater Ecology, ARI, DSE), estuarine fish ecologist;
- John Leonard (John Leonard Consulting Services), hydrogeologist and environmental scientist;
- Dr Phillip Macumber (Phillip Macumber Consulting Services), hydrogeologist, geomorphologist and archaeogeologist; and
- Dr Danny Rogers, waterbird specialist.

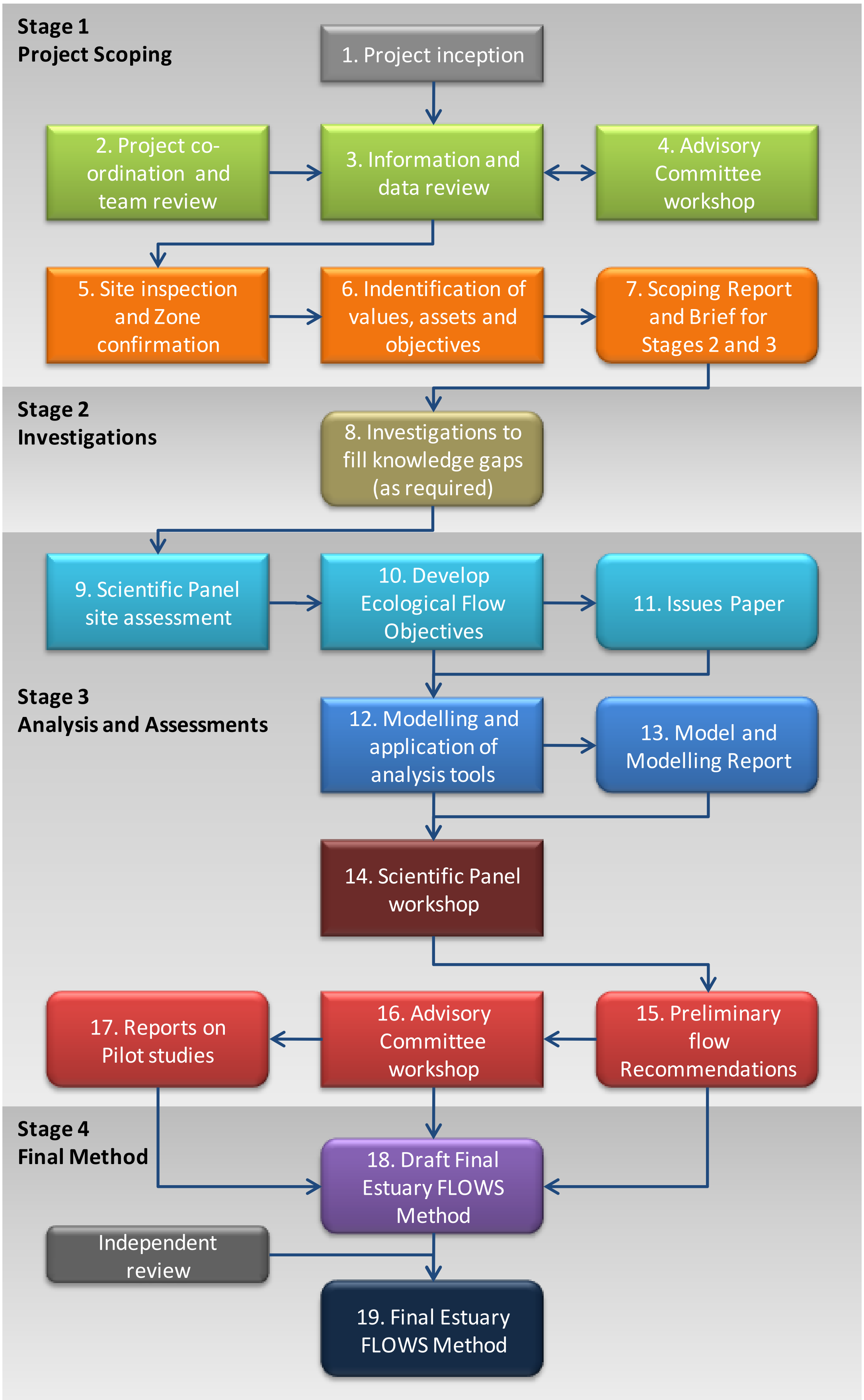


Figure 1-3. Steps of the estuary FLOWS method used for the Werribee River estuary.

1.5 Objectives of Final Estuary Flows Report

The Final Estuary FLOWS Report (this report) has a number of objectives:

- present refined biodiversity and hydrological objectives for the Werribee River estuary;
- provide a clear link between important estuarine processes and assets and the key flow components;
- document flow-ecology, geomorphology and other physical science relationships for the estuary;
- identify the opportunities and limitations of the system to deliver hydrological objectives through modelling results; and,
- recommend environmental flows to achieve the defined objectives.

2 METHODOLOGY

In determining estuary flow requirements, the method of Hardie et al. (2006) first seeks to define broad classes of flow components and objectives that relate to the maintenance of identified assets. Detailed hydraulic modelling and hydrological analysis is then undertaken to develop numerical relationships between flow and ecological, salinity and geomorphological processes that are associated with the objectives. Armed with this information, a scientific panel workshop is held to determine the details of the specifications of the flow components required to mutually satisfy all of the ecological and geomorphological objectives. This section details the methodology as applied to the Werribee River Estuary. Flow – ecology relationships were developed for fish and vegetation assemblages. General flow – geomorphology relationships were also developed. It was not possible to develop quantitative flow – ecology relationships for wetland bird species given the currently available scientific information (Dr Danny Rogers, pers. comm.).

2.1 Flow Components

The freshwater FLOWS method (NRE, 2002) requires recommendations to be made for a number of different flow components (Table 2-1). Each flow component has a known or assumed important environmental function for the river reach of interest. The FLOWS method is generic for Victoria, so all components are not necessarily important or critical in all reaches of all rivers. In developing the Estuary FLOWS method, these same flow components were adopted as a generic description of the desirable flow regime. However, as generally applies to the FLOWS method, the Scientific Panel may determine that one or more of the generic components are not applicable, or new ones need to be added. In this study, the required flow components were identified as the hydraulic and hydrological needs of the assets were described.

One important estuary-specific flow component describes the river discharge necessary to maintain the estuary entrance in an open/closed state for the required duration and timing. Connectivity with the marine environment is critical to maintain estuarine circulation and water quality. The estuary entrance is also an essential conduit for particular life stages of fish and other organisms. This is particularly relevant to intermittently opening/closing estuaries, but even permanently open estuaries may require flood events and/or baseflows to maintain that state.

The Werribee River estuary is permanently open to Port Phillip Bay. The entrance is reasonably wide (around 60 – 100 m) and deep (1 – 3 m), providing permanent access to the estuary for marine species. Being located within Port Phillip Bay, the wave energy is relatively low, and the marine sourced sediment is of a relatively low supply. Estuary mouth closing is normally associated with high marine sediment supply and high wave energy. Tidal energy (although muted in Port Phillip Bay) and periodic fluvial flushing would help maintain open entrance conditions in the Werribee estuary. Despite these factors, the estuary entrance is regularly dredged to maintain a channel that is deep enough for boats to pass unhindered.

Table 2-1.
Hydrological description of the generic FLOWS flow components

FLOWS flow component	Hydrological description	Relevant season
Cease-to-Flow (also called "zero flows")	Cease-to-flow is defined as periods where no flows are recorded in the channel.	Not present in some streams, nearly always occurs in summer, but can occur in winter
Low Flows	Low flows are the natural summer/autumn baseflows that maintain water flowing through the channel, keeping in-stream habitats wet and pools full.	Summer
Low Flow Freshes	Low flow freshes are frequent, small, and short duration flow events that last for one to several days as a result of localised rainfall during the low flow period.	Summer
High Baseflows	High baseflows refer to the persistent increase in baseflow that occurs with the onset of the wet season.	Winter
High Flow Freshes	High flow freshes refer to sustained increases in flow during the high flow period as a result of sustained or heavy rainfall events.	Winter
Bankfull Flows	Bankfull flows fill the channel, but do not spill onto the floodplain.	More common in winter, but occurs in summer
Overbank Flows	Overbank flows are higher and less frequent than bankfull flows, and spill out of the channel onto the floodplain.	More common in winter, but occurs in summer

2.1 Workshop and final flow recommendations

A workshop was convened at Werribee on 18 – 19 September 2007. Present were the Scientific Panel and several representatives of the steering committee. The process involved consideration of the flow magnitudes determined by hydraulic analysis to meet the flow objectives previously identified in the Issues Paper. These magnitudes were shaped into detailed flow recommendations covering duration, frequency and timing by considering the hydrology of both the inflowing river and estuary, and the specific requirements of the biota.

2.2 Hydraulic Analysis Method

To develop a sufficient understanding of the hydrodynamics of the estuary, it was necessary to jointly focus on field measurements and the use of appropriate numerical models. Field measurements were taken to provide sufficient data for the construction and calibration of the numerical models. For this pilot study a coupled topographic-hydrographic survey was commissioned that included 21 cross-sections (see Section 8 for more survey details). At each cross-section a hydrographic survey of the river bed was completed, with topographic surveys of the left and right banks and extending onto the floodplains. In addition, water level variations at four sites along the estuary were measured with automatic logging tide gauges. Design of the field data collection program was informed by:

- an initial field inspection (12 April 2007);
- data collected by Sherwood et al. (2005) for the initial estuary environmental flow assessment (including an unpublished depth profile); and
- LIDAR data prepared for the Western Treatment Plant Flood Mapping Project (flown on 31 October 2002, with data provided by Melbourne Water).

The field data were used to define and calibrate two numerical models:

- **Tide Model:** A two-dimensional vertical (2DV) simulation was developed using RMA-10 software. The model was used to predict the interaction of freshwater inflows and tidal fluctuations on water levels, velocity profiles and the salinity structure of the estuary.
- **Flood Model:** A two-dimensional model was developed using MIKE-21. This model was used to provide a preliminary estimate of the relationship between flood discharge magnitude and the water depths and inundation extents they produce over the floodplains and wetlands adjacent to the estuary channel.

2.2.1 Investigations with the Tide Model

A series of standard scenarios were run with the calibrated Tide model. The scenarios examined the sensitivity to inflow discharge of water level fluctuations and the salinity structure. The model was run for four different freshwater inflow discharges: 1, 20, 50 and 100 ML/day. The estuary entrance is maintained in an open state by regular dredging, therefore a constant entrance cross-sectional area was defined (based on survey data). The downstream tidal boundary was defined by a repeating spring-neap tidal cycle (based on constituents for Williamstown from: Australian Hydrographic Service, 2004).

These simulation runs produced data on variations in water depth along the estuary as well as the variation in salinity and velocity through the water column. A series of output plots and animations were prepared to provide the Scientific Expert Panel with an overview of the sensitivity of the Werribee River Estuary to inflow discharge. The primary output comprised:

- Longitudinal salinity profile: animation and snapshots at particular times.
- Time series variation of vertical salinity profiles (top, middle and bottom parts of the water column) at discrete locations along the estuary.
- Variation of velocity (top, middle and bottom parts of the water column) at discrete locations along the estuary. These data may also be used to estimate shear stresses for preliminary sediment transport estimates.
- Residence time measured by the ‘e-folding time’. This gives a practical measure of the time interval required for a certain volume/parcel of water in the estuary to be exchanged with new water (Abdelrhman, 2005; Monsen et al., 2002). E-folding time is defined as the time interval in which an initial quantity decays to 1/e or 36 percent of its initial value. The e-folding time was reported at key locations along the estuary to indicate the variability of residence time with location and inflow discharge.
- Saline recovery rates were qualitatively observed via animations of the salinity profile. The time taken to develop an equilibrium salinity profile was estimated based on the initial 4 weeks of simulation, which started with the estuary completely fresh.

A series of more specific evaluations were undertaken to support the development of the final flow recommendations by the Scientific Panel. These evaluations involved extracting salinity/velocity/water depth time series at particular locations of interest and providing key statistics of the series (e.g. maximum, minimum, mean). More detail on the hydraulic model results and the analysis of them is presented in Section 3.4 and Section 9.

2.2.2 Investigations with the Flood Model

The objective of simulation with the Flood Model was to estimate the inflow discharge required to cause various overbank water levels at different points along the estuary. A two-dimensional model was developed using the LiDAR data (0.25 m contour surface). The level of detail offered by LiDAR was necessary given the complexity of the overland flow paths across the golf course and around the bend downstream of the golf course (Figure 2-1).

A simple calibration of the Flood Model was undertaken using the February 2005 flood event which peaked at just over 16,500 ML/d. Anecdotal evidence and photographs taken near the point of maximum inundation allowed a preliminary model calibration to be completed. The calibrated model was then run to make a preliminary estimate of the inundation that might be caused by a freshwater flood arriving at the estuary from the upstream catchment. The flood was simulated by a ramped freshwater inflow hydrograph starting at 100 ML/day and finishing at a maximum discharge of 60,000 ML/day. A mean high tide was assumed for the downstream boundary condition. Results from the ramp flood simulation were also used to estimate flows required to scour sediments from the estuary lagoon and the entrance (see Section 9.3 for a full description).

It is important to emphasize that the flood modelling completed for this project are to be strictly regarded as only a first approximation. There was no scope for considering the complex interaction of catchment hydrology, tides, atmospheric pressure and wind generated storm surge, let alone the potential for sea level changes likely to occur due to climate changes or shifts. Consequently, flood levels were established under the following simplifying assumptions:

- no storm surge, no wind effects and standard atmospheric pressure; and
- a constant downstream water surface elevation equal to Mean High Water (MHW[1]) of 0.276 mAHD.

[1] Mean High Water is defined as the average of all high waters observed over a sufficiently long period (definition from the Australia Hydrographic Office Tidal Glossary adopted by the Permanent Committee on Tides and Mean Sea Level: http://www.icsm.gov.au/icsm/tides/tidal_interface.html)

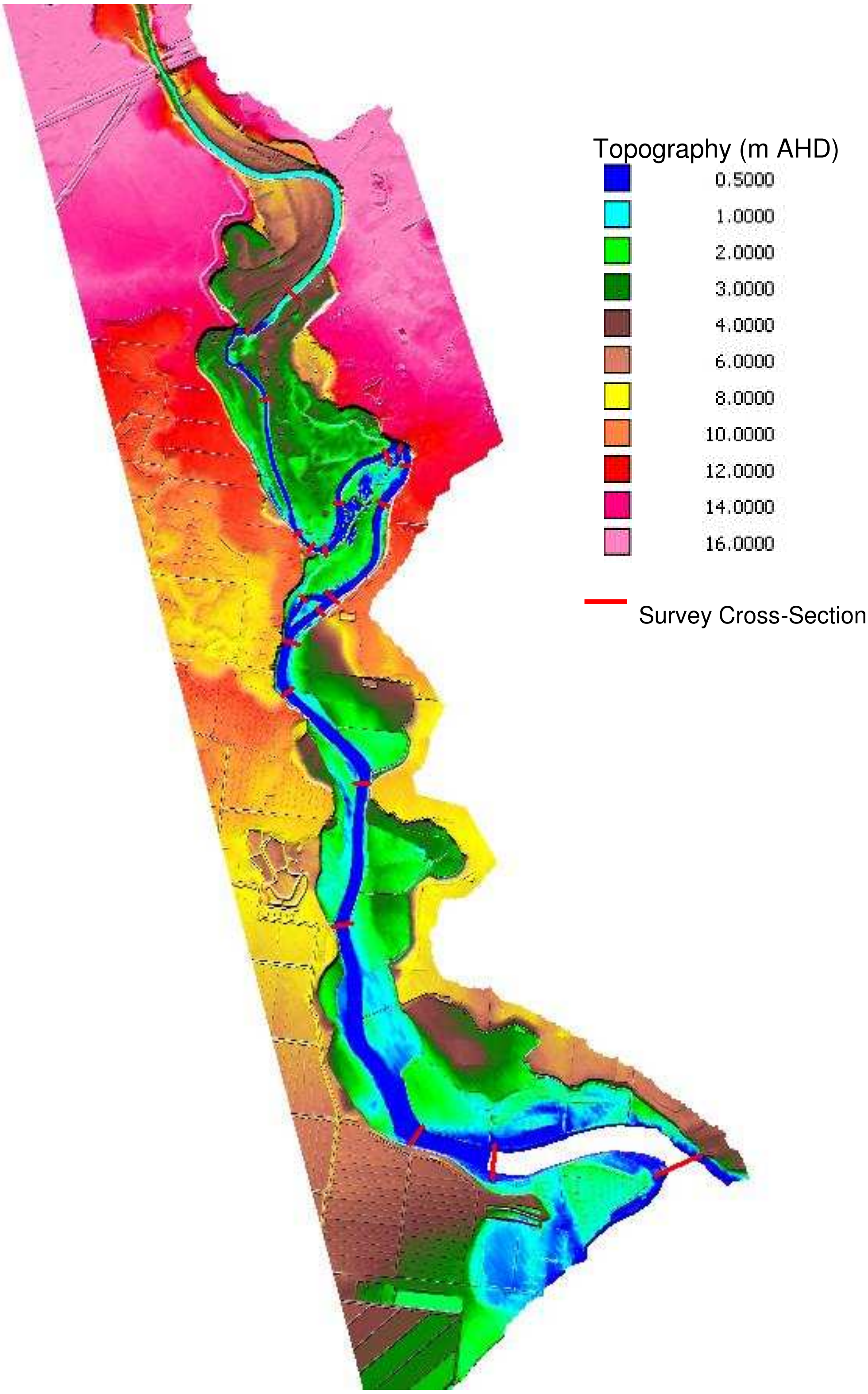


Figure 2-1. Image of Werribee estuary generated from digital elevation model. Colour variation indicates elevation. Photogrammetry undertaken by QASCO for the Western Treatment Plant Flood Mapping project. Data suppled by VicRoads.

2.3 Hydrological Analysis

2.3.1 Statistical description

The Panel considered ecological and geomorphological objectives which led to the definition of a number of flow components in terms of magnitude (upper or lower threshold), frequency (average number per year or defined seasonal period), duration of the component (days above or below threshold), and defined seasonal period. The flow magnitude thresholds were derived from the hydraulic model, which converted objectives expressed as elevations, velocity or shear stress thresholds into equivalent discharge. The timing, frequency and duration of components were specified using a combination of (i) known or suspected requirements taken from the ecological and geomorphological literature (if available, these were offered as a first estimate) and (ii) hydrological statistics calculated from the REALM natural flow series. These statistics related to the timing, frequency and duration of the identified magnitude of the components. In practice this was an interactive process, with the Panel members having the opportunity to re-consider their first estimates of required timing, frequency and duration. The time series analysis also allowed the Panel to consider the requirements for inter-annual variability of the flow components.

In most environmental flows studies, it is normal practice for the Panel hydrologist to prepare separate flood frequency curves, flow duration curves and monthly or seasonal flow distribution plots. Examination of these as separate entities invariably leads to over-estimation of the frequency of event components (freshes, bankfull and overbank) in the flow series, because for events to be counted as valid components they have to simultaneously satisfy the magnitude, timing, duration and frequency requirements. The frequency of events that satisfy all requirements is usually considerably less than that of events that only satisfy one of the requirements. For example, the occurrences of events that exceed a certain magnitude in a time series can be relatively easily calculated, but of these, a lesser number will have a certain timing and duration. Also, event components are specified as requiring a certain annual frequency. If this is greater than one per season, then years with one instance of the event will not qualify as having satisfied the environmental flow requirements for that year.

The frequency of the specified event flow components was calculated using spells analysis that took account of event duration and annual frequency. An independence criterion of 7 days was assumed. The spells analysis was undertaken for the two available REALM flow scenarios: natural and current. The input data were the magnitude threshold, if the spell (event) was for flows above or below the threshold, the months over which the component was relevant, and the minimum duration required. In considering statistics calculated of annual periods, the water year started in December. The spells program calculated a wide range of statistics, including:

- An annual time series of event occurrence
- Average recurrence interval (ARI) of events calculated using the Cunnane plotting formula
- Percentage of years on record with at least one event
- Percentage of years on record with the required number of events

- Central tendency and dispersion of the duration of individual events in the daily time series of events [25th (Q1). 50th (Q2 or median) and 75th (Q3) percentile] – for events where event duration was critical
- Central tendency and dispersion of the annual time series of percent of time that the event was active in the specified season [25th (Q1). 50th (Q2 or median) and 75th (Q3) percentile] – for events where total time above threshold in the season was more important than individual event durations

In undertaking hydrological analysis, baseflow components (Low flow and High flow) had to be treated differently to event components, because baseflow components do not have a frequency specification. The baseflow components were separated from the record on the basis of magnitude and seasonality requirements. The percentage of the season (i.e. duration) occupied by the baseflow components was then calculated for each year.

2.3.2 Compliance

Compliance is the degree to which the specified flow components occur in the flow series. A compliance statistic is a way of comparing the relative performance of flow scenarios, and it allows the Panel to reality check their expectations regarding required frequency and duration of their defined flow components. To comply with the requirements of a component, an event-type component (i.e. fresh, bankfull or overbank) had to mutually satisfy the specifications for frequency, duration and magnitude. Thus, the event was deemed to have occurred only when the magnitude was exceeded for the required duration. The frequency of occurrence of the events was then summed for each year of record. Each year was then assessed for the minimum number of times the component was required to occur. If there were too few events then that year was non-compliant. Having more than the minimum recommended number of events in a particular year did not result in ‘over-compliance’ that could somehow compensate for other years when the event did not occur frequently enough.

One potential measure of compliance is the percentage of years in the record that satisfied all of the annual requirements of the component. The closer is that value to 100 percent, the higher the level of compliance. A value of zero would mean that the component did not occur in the time series. Not all components were expected to have a compliance of 100 percent with the preferred environmental flow regime in the natural scenario. There are two main reasons for this:

- The time series contained drought years when the flow components would not necessarily be expected to occur, and
- The hydraulic models contained uncertainties that could have led to inaccuracies in the specification of flow magnitudes required to achieve the given ecological and geomorphological objectives.

Given these factors, for event-type components, the flow series could be said to ‘comply’ if the event was satisfied in more than a certain percentage of years. This could be done by setting an arbitrary threshold, or the compliance of the current serries could be expressed relative to the occurrence of events in the natural series (effectively giving the natural series perfect compliance). A weakness of this approach is that it takes no account of the temporal distribution of the non-complying years. For example, a long sequence of non-complying years for a fish spawning component could be catastrophic for the species in question. Thus, a long-term frequency requirement was specified for each component. This was an expression of the expected inter-annual variability.

The long-term frequency was stated as the number of years in every 10 years that the component had to comply. In this sense, ‘every 10 years’ means every sequence of rolling 10-year long periods in the record, not simply the record divided into discrete periods, each of 10 years length (Figure 2-2). The period length does not have to be 10 years – the Panel relies on their collective expertise to establish a meaningful period length and required frequency, so this might vary between studies. A frequency of 5 in every 10 year sequence was adopted by the Panel for many of the Werribee River components. For example, if a fresh component appeared in at least 5 years in every one of the 31 sequences of 10 years in the 40 year modelled period (1960 to 1999 inclusive), then the compliance was 100%, while compliance of 48% would mean that in 15 of the 31 rolling 10-year periods the component appeared in at least 5 of those 10 years (Figure 2-2). For the less frequent bankfull and overbank components (with required frequency less than annual) there was no requirement to meet a particular frequency within sequences of years. For these components, the compliance of the event in the current series was expressed as the ratio of the component’s ARI in the natural series over its ARI in the current series, with values limited to a ratio of 1 (100%). By default, the natural series has perfect compliance for these components.

Compliance for baseflow components (Low flow and High flow) had to be calculated using a slightly different approach, because baseflows are not specified with a frequency. For baseflows, duration above the threshold is the important characteristic. A required duration of a certain percent of the time over the relevant season was set by the Panel for each baseflow component as the lower limit of annual compliance (this percentage was based on expert opinion, and would vary between components and river systems). Due to the high degree of variability of flow from year to year, it was only expected that the threshold baseflow duration requirement would be met in 5 years of every rolling 10-year period (i.e. the other years were too dry to meet this requirement). In rivers with low inter-annual hydrological variability, a higher expectation can be placed on the long-term frequency of flow components.

2.1 Flow-ecology relationships

2.1.1 Vegetation

Estuarine vegetation exists in a complex network of environmental gradients. Physical conditions such as flooding depth, salinity regime, groundwater moisture and salinity and scour all influence plant distribution and all vary in relation to elevation, proximity to the estuarine channel and distance from the river mouth.

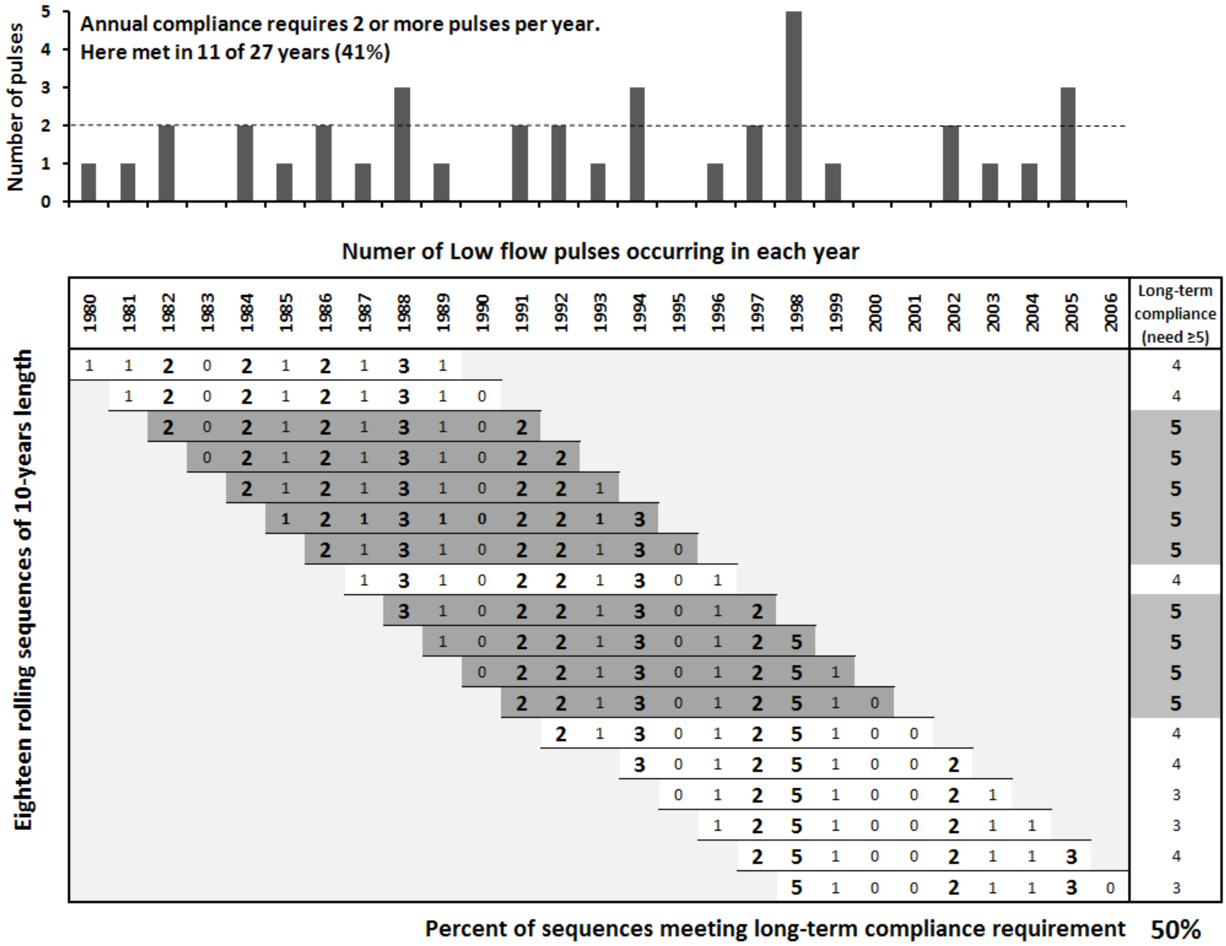


Figure 2-2. Illustration of the method of calculation of long-term compliance, where annual even frequency is 2 per year and long-term requirement is 5 complying years in every rolling 10 year sequence. This example is from a river in China (Gippel and Cosier, in review), not from the Werribee River. Here the term pulse is used instead of fresh.

Despite these complexities, estuaries tend to exhibit considerable uniformity in vegetation, and feature zones with consistent vegetation structure and composition. Vegetation communities are comprised of plants which tolerate a specific range of conditions and occur in the areas of the estuary where these conditions are provided. Within these zones, the plant species and vegetation structure is remarkably uniform. There is an ecotone at the edge of these zones where vegetation communities blur, but generally the boundaries are distinct.

The uniformity in vegetation communities provides the basis for the adopted approach to define environmental water requirements in the Werribee estuary. The water requirements of the estuary as a whole could be defined in terms of the water requirements of each of the component communities.

The overall objectives of the vegetation assessment were therefore to:

- identify plant communities which were internally homogeneous and had distinct boundaries with adjacent plant communities;

- define these communities at a scale which could be related to likely estuarine and riverine water management scenarios;
- identify the role of flow in the physical habitat requirements of each community and specify these as conceptual models; and
- quantify the optimum and tolerable range of flow-dependent habitat requirements as far as possible.

It was then necessary to explore the mechanisms by which flow (including river discharge, estuary level and estuary salinity) control or influence physical habitat requirements. These linkages provided a basis to specify the frequency, duration and timing with which particular flow events should be provided in order to maintain the distribution, composition and condition of the plant communities which make up the estuary vegetation.

The vegetation assessment was undertaken in the following stages.

1. Site inspection

The estuary was inspected to identify the composition and distribution of plant associations in the landscape. This involved a walk-over of the entire estuary to describe the plant associations present and their distribution in relation to landforms, tidal levels, flood levels, drainage features and likely groundwater conditions.

Consideration was given to how these conditions change seasonally. It was important to appreciate the interaction between flow variables, as the depth and salinity achieved by a particular flow would be affected by tidal levels and closure of the estuary entrance. For the Werribee this assessment was assisted by Dr John Sherwood who has a detailed familiarity with the estuary and could describe the spread of water under various hydrological conditions. His experience also provided an important introduction to the scale of particular events, such as the likely duration and frequency of flow events.

2. Existing data

Existing data were collated and reviewed to describe the composition and structure of the vegetation and provide information on the physical conditions in which vegetation communities exist.

Existing flora records for the estuary and local vicinity were reviewed. This included data lodged in the Flora Information System, specific surveys of the area and data provided by local naturalists. Information was sought on the species which appear under specific circumstances which were not visible at the time of the visit, such as during winter flooding or in floodplain wetlands during summer.

Plant associations were related to previously defined Ecological Vegetation Classes. The EVC descriptions provided additional information on likely species present within each vegetation zone and provided a consistent approach for future studies to assess water requirements in estuaries. EVCs were defined from the site inspection and a review of EVC mapping.

Physical data were sought to define the habitat of each vegetation type. Physical data included:

- topographic survey which described thresholds for the spread of water and the depth and extent of floodplain depressions;

- data which described the salinity of water on the floodplain or in the main estuary channel;
- estuary water level data which described the normal tidal range and elevations of other events;
- groundwater data which described groundwater levels, salinity and flow;
- data which described the depth of water on the floodplain or channel, particularly in relation to particular flow events.

Information describing the habitat requirements of EVCs was sought to supplement and help interpret local physical habitat data. Important sources included:

- previous conceptual models, such as set out in the Estuary Entrance Management Decision Support System (EEMS); (Arundel 2006), which identify the tolerance of estuarine EVCs to various physical conditions; and
- quantitative information on the habitat requirements of dependent species such as *Leptospermum lanigerum* (Ecological Associates 2005).

3. Conceptual models

Conceptual models were developed to assign a set of physical habitat components to the major vegetation types present in the estuary. Ecological Vegetation Classes were selected as the basis for conceptual models because:

- existing EVC mapping described estuary vegetation at a scale which corresponded to expected zonation in physical habitat components such as salinity regime, water regime, groundwater conditions and topography;
- existing frameworks, particularly EEMS, provide a source of information on the tolerance and requirements of EVCs to various physical conditions; and
- EVCs are the universal framework for classifying vegetation in Victoria, so an approach using EVCs in the Werribee estuary could be applied to other estuaries in future studies.

The conceptual models comprised a diagram and description. The diagram presented a cross-section of the estuary bed illustrating the role of estuary levels, salinity or flow in the distribution of plant species in each EVC. The description identified the main plant species present and defined the physical conditions within that EVC.

The components of EVC habitat which depend on, or are influenced by, flow were identified. The optimum or tolerable range of conditions was described as quantitatively as possible. The descriptions were based on:

- the known habitat requirements of component species or plant assemblages from the literature or other surveys;
- the experience of the author (Marcus Cooling); or
- local monitoring data.

In some cases, important environmental variables could only be explained in terms of gradients without specific values. For example it was expected that gradients in groundwater level and salinity would influence the distribution of plant associations, but no local data were available. In these cases, salinity values could only be specified as 'brackish" or "fresh" or varying from "high salinity" to "low salinity". Data from other sites where habitat preferences, such as for groundwater salinity, were known was used to fill these gaps.

Even when data were not available to support the conceptual models, the models served an important purpose in identifying data gaps and important areas for further data collection.

4. Flow recommendations

In order to identify the flow events required to maintain vegetation communities, it was necessary to determine the mechanisms which link flow to flow-dependent habitat components in the EVCs.

The simplest relationships were for water depth. Hydraulic modelling of the estuary predicted water depths for various river flows under a range of tide level and estuary closure scenarios. These could be related to floodplain depth using physical survey cross sections through the EVCs of interest.

Surface water salinity was more complex because the salinity of the water which inundates the floodplain is subject to complex interactions between river flow and marine water ingress. Furthermore, water which is retained on the floodplain in wetland depressions is subject to evaporative concentration and possibly saline groundwater discharge.

Groundwater relationships were also complex but there were no data available to relate specific groundwater levels, fluctuations or salinities to estuary levels. A purely conceptual approach was used to describe groundwater.

The mechanisms linking flow to habitat components were identified principally in a workshop involving ecologists, hydrogeologists, the hydrologist and the hydraulic modeller. The linkages were used to specify quantitative recommendations for flow provisions. Due to the uncertainties in the linkages, the process was documented in tables in a step-by-step process so that assumptions were identified and uncertainties could be refined. The process involved:

- specifying the ecological outcome of a particular flow-dependent habitat component;
- specifying, as quantitatively as possible, the optimum or permissible variation in the habitat component;
- identifying the aspects of estuary level, salinity or flow (for which quantitative models were available) which influence the habitat component and describing the mechanism of influence;
- estimating possible values for estuary level, salinity, flow or closure which might provide the required habitat conditions.

These estimates were provided to the modelling team to develop appropriate queries and provide model outputs.

2.1.2 Fish

The fish fauna is important to estuary health as a vector for mineral nutrients and energy. Fish interact with a wide variety of habitats in the estuary and respond to a wide variety of flow-related cues such as river discharge, velocity, temperature, salinity and water level. Analysis of fish habitat requirements therefore provides an extensive and comprehensive set of ecologically-meaningful physical criteria to assess ecosystem health.

Furthermore, the fish fauna of the Werribee estuary also includes several species of conservation and economic significance. By specifying fish requirements for flow, it is possible to identify management measures with a high conservation return.

1. Define estuary fauna

The fish fauna of the estuary was characterised by a review of available records of fish from the estuary. This included data from the Atlas of Victorian Wildlife, records from local naturalists and scientific research.

Literature on the habitat requirements of fish was reviewed in order to identify the behaviours and habitat requirements of the particular fish found in the estuary. Three main groups of fish were identified:

- estuarine residents;
- estuarine dependent; and
- estuarine opportunists.

It was recognised that within these groups there are fish which exhibit some of the characteristics of other groups. However, this classification was helpful in identifying the key habitat components of the estuary and their importance to fish life-stages. These included seasonal and other requirements for passage through the estuary entrance and access to seagrass meadows, floodplain vegetation and freshwater reaches of the catchment. They also included specific flow events such as freshes, tide levels and halocline dynamics.

2. Select representative species and collate autecological data

A subset of fish species was selected to define flow requirements for fish. The species were selected to:

- represent a wide variety of habitat requirements which were sensitive to flow and water management in the estuary;
- represent each of the three groups;
- include species for which there was a significant autecological knowledge-base; and
- include species of conservation or management significance.

For the selected species ecological information was collated on all aspects of life history which interact with flow. This included requirements for breeding, spawning, juvenile development, dispersal, migration, predation, shelter and resting. Information was sought on the physical habitat conditions at each stage. Physical habitat conditions included simple water quality parameters such as temperature, dissolved oxygen and salinity and complex water quality parameters such as halocline development and stratification. Habitat requirements also included access to specific habitats within the estuary, such as passage through the estuary entrance, access to the floodplain and access to upstream riverine reaches.

3. Develop conceptual models for key species

The existing autecology data for the fish was applied specifically to the Werribee estuary to provide conceptual models from which flow recommendations could be derived.

A site inspection enabled the habitat requirements identified from the literature to be located and described specifically for the Werribee estuary. Physical survey data was used to specify the elevation, extent and position of recognised floodplain and channel habitats. Existing local monitoring data, particularly for water level and water quality, was used to refine estimates of habitat requirements for the Werribee estuary.

The conceptual models were arranged to present the main life-stages of the fish, specifically identifying the role of flow in sustaining critical habitat components. The conceptual models were presented as description and a diagram which illustrated the behaviours of fish in various estuarine, marine and riverine habitats.

The optimum and tolerable habitat conditions were specified as far as possible. The descriptions were based on:

- the known habitat and ecological requirements of selected species from the literature or other projects;
- the experience of the authors (Lance Lloyd and Jeremy Hindell); or
- local monitoring data.

4. Flow recommendations

A workshop was held to identify the role of flow in the habitat requirements of fish. The workshop brought together expertise in fish ecology, hydrology and hydraulics to describe the processes which link river discharge, tide and estuary opening to the range of water level and water quality parameters on which fish habitat is based.

Following the workshop these linkages were specified in a step-by-step process which summarised evidence and stated assumptions, so that flow recommendations could be queried, modified or refined as data becomes available. Tables were prepared which presented:

- the key flow-dependent habitat components on which the fish depend;
- quantitative estimates of the optimal or tolerable range of physical conditions (water level, discharge or quality); and
- the parameters and thresholds to be tested in the hydrological or hydraulic models to meet ecological requirements.

The models were then examined by the hydrologist and hydraulic modeller to provide estimates of flows and flow events required to address the ecological objectives.

3 FLOW RELATIONSHIPS AND CONCEPTUAL MODELS

Fundamental to the Estuary FLOWS method is the development of detailed flow relationships between physical and ecological objectives through documenting conceptual models of key species and processes.

3.1 Geomorphic flow objectives

While general empirical relationships have been proposed for explaining the basic dimensions of estuaries in terms of flow indices (Prandle, 2006), it is not a simple matter to specify the characteristics of the flows required to maintain the particular features and dimensions of individual estuaries. There is still much debate in the literature over the relative merits of low flows of long duration versus high flows of short duration in their efficiency in maintaining estuary mouths in an open state. For example, there is an unresolved debate over the relative merits of an annual flush or a regular baseflow in maintaining the Murray Mouth in an open state (MDBC, 2005). Powell et al. (2002) were unable to find any relationships between sediment deposition and river flows in Texas Bays and estuaries, and therefore did not include any geomorphology-related flow objectives.

Smakhtin (2004) proposed a model that predicted a continuous time series of estuary mouth openings/closures on the basis of river inflow data. Inflows were routed through a reservoir model, and the estuary mouth was considered open on days when the spillage from an estuarine ‘‘reservoir’’ occurs. This model has potential, but it does not include a description of the processes associated with the marine system. These processes (wave over-wash in the mouth region, marine currents, longshore sand movement, and tides) may, however, have a profound impact on mouth dynamics (Smakhtin, 2004). For example, bar closure events could build bars of a variable height, as determined by the wave and tidal conditions when the bar closed. This would mean that the capacity of the estuary “reservoir” would be different after each closure, confounding the model. The other implication of this is that different bar heights means different estuary hydraulics for the same freshwater inflows.

Cooper (2002) concluded that the flood flows necessary to produce morphological change in river-dominated estuaries are likely to be much greater than those required in tide-dominated estuaries. The velocities necessary for erosion of mud-rich or vegetation-bound river-dominated sediments will exceed those for unconsolidated sands in tidal deltas. The frequency of occurrence of morphologically significant floods in tide-dominated estuaries will, therefore, exceed that of river-dominated estuaries.

The application of shear stress methodologies can be complicated in estuaries, where biotic factors significantly affect sediment erosion potential. While physical forces undoubtedly overwhelm most biological influence during storms and floods, during quiescent periods a spectrum of biotic effects rises in importance. Black et al. (2002) broadly classified these effects as either contributing to sediment stability (termed bio-stabilization) or factoring against it (termed bio-destabilization). Bio-stabilization of sediments is effected by several variables. These include the density of microphytobenthos, algal mats, higher plants (such as sea grass and salt marsh vegetation), tube-building polychaetes (spionid worms) and biogenic reefs, such as mussel beds (Uncles, 2002). Bio-destabilization mainly results from the bioturbation caused by burrowing and deposit-feeding animals, such as bivalves, polychaetes and crustaceans

(Uncles, 2002). Also, there is a body of literature on the relative roles of mineral sediment deposition and vegetative growth in raising the levels of marsh surfaces through time (e.g. Nyman, et al., 1993; Neubauer et al., 2002; de Deckere, 2003; Silvestri and Marani, 2004; Kirwan and Murray, 2005; D'Alpaos et al., 2006; Nyman et al., 2006).

A review by EMPHASYS (2000) concluded that no individual model or approach could provide an adequate hindcast of the recorded morphological evolution of the estuaries studied. Part of the reason for this may have been the poor resolution and accuracy of the available data, and the other part due to the fact that no single model represented all of the relevant processes, especially those involving biology or waves (Uncles, 2002). However, even for sandy systems where biological processes are likely to be less important, substantial differences between observed and predicted patterns of sediment movement were apparent (Uncles, 2002).

Although there are difficulties in modelling the geomorphology of estuaries on the basis of freshwater inflows, there is evidence that a reduction in inflows can have a dramatic impact on estuary morphology. On the macro-tidal Cambridge Gulf, the bed of the East Arm, fed by the Ord River, has aggraded by 3 m since the river was regulated in 1970, while the West Arm, fed by unregulated rivers has not changed for the last 100 years. The West Arm sediment is now being imported into the East Arm and does not reach Cambridge Gulf (Wolanski et l., 2004).

Given the difficulty in predicting estuary geomorphology on the basis of river flows, for this FLOWS project only general geomorphological objectives could be proposed. These general objectives relate to maintaining sediment processes (Figure 3-1). The objectives are based on maintaining baseflows and high flows, as both of these have been implicated in maintenance of estuaries in an open state. Baseflows maintain the position of the salt wedge. If the mean position of the salt wedge migrates upstream due to reduced flows, then salt intolerant bank vegetation can become salt affected and bank erosion is likely to follow. Summer baseflows are important for maintaining the mouth in an open state.

Sherwood et al. (2005) conducted an investigation of salt wedge flushing in the Werribee estuary. The magnitude of flows required to remove all salt water from the estuary was estimated using a mathematical model proposed by Kuelegan (1966), who studied the relationship between salt wedge length and discharge in laboratory tank systems. The model suggests that in the upper estuary erosion of the salt wedge would occur at flows above 300 ML/day. A salt wedge in mid-estuary (say 5 km chainage) would retreat at flows greater than 800 ML/day. In both cases the wedge length is significantly reduced for flows greater than 1,000 ML/day. On this basis, Sherwood et al. (2005) recommended that "*A flow of at least 1,000 ML/day measured at the Lower Werribee Diversion Weir should be maintained for at least 3 days in late winter/early spring (September or October) as a flushing flow to significantly reduce the salt wedge length. This flow should occur at least once annually unless natural flows have a lower frequency.*" The three-day period of flood flow was recommended because it was observed to be the common duration of such flows in the historical records.

A rational analysis of sediment transport potential undertaken with one of the hydraulic models developed for this project (the 'Flood Model' – see Section 2.2) indicated that the minimum magnitude of the flushing flow suggested by Sherwood et al. (2005) (i.e. 1,000 ML/d) would not mobilise sands or silts within the Werribee estuary. The discharge required to entrain coarse to medium sands was found to be around 2,000 ML/day at Red Cliffs, and around 8,000 ML/d at the entrance. Thus, it cannot be assumed that the salt wedge flushing flow (as defined) will achieve bed sediment scour.

High (morphological bankfull) flows are recommended to maintain channel morphology (as is often assumed for the freshwater sections of rivers). The recommended frequency is the natural frequency for bankfull flows. Magnitude of bankfull flows was defined by morphology; the magnitudes of the summer and winter baseflow component were based on flow required to maintain the salinity profile of the estuary in a position that satisfied ecological requirements (i.e. the geomorphologic requirement would not override the ecological requirement unless such a requirement was lacking). The objectives are given in Table 3-1.

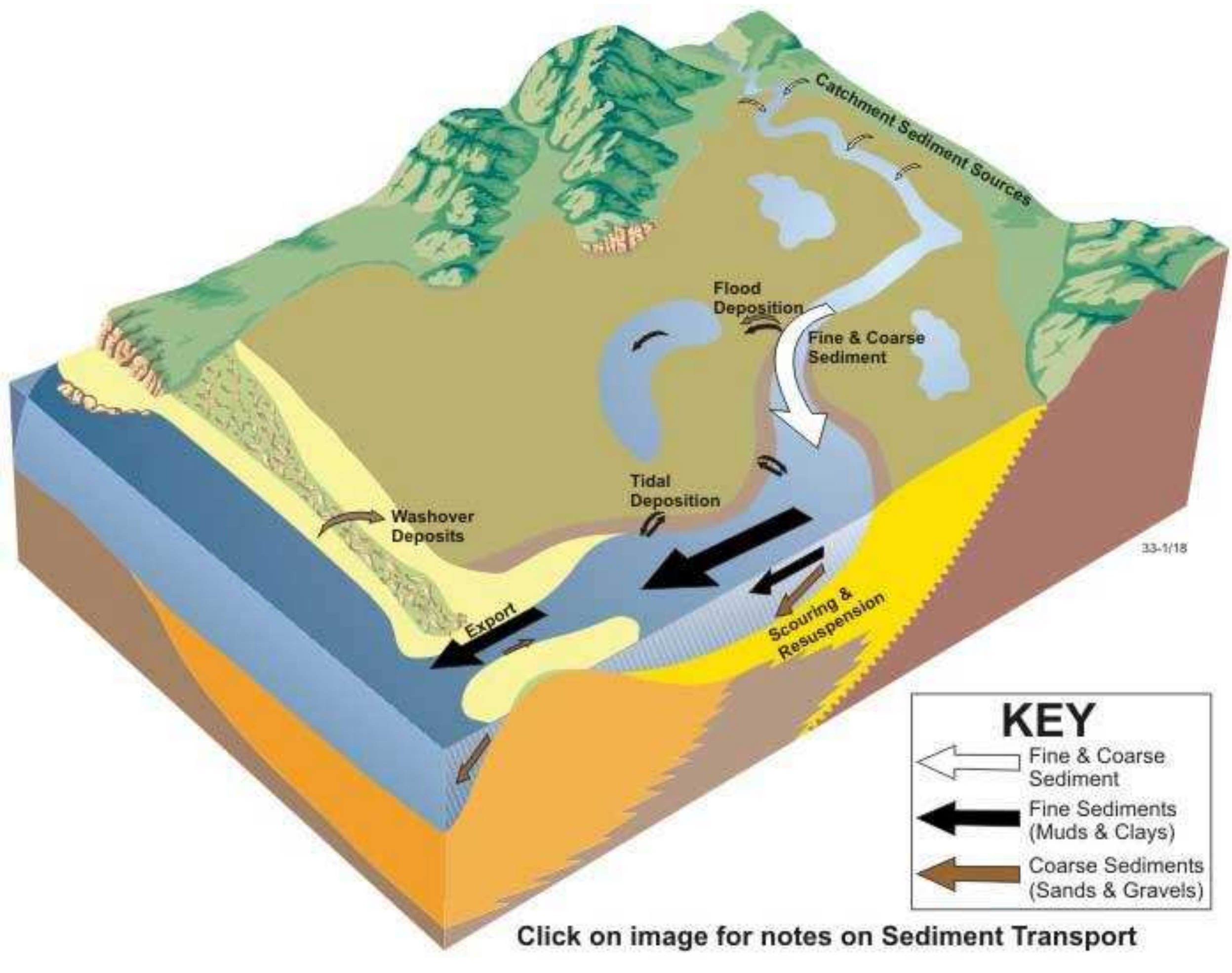


Figure 3-1. Conceptual model of sediment dynamics in Werribee estuary. Source: OzCoasts (http://www.ozcoasts.org.au/).

Table 3-1.
Geomorphological objectives.

ID	Flow component	Role of component	Possible assessment approach
1a	High flow	Maintain bank stability in the upper estuary Maintain suspended sediment dynamics in the middle estuary	Flow to maintain salt wedge dynamics, as defined by vegetation and fish objectives. No unique event required.
1b	Bankfull/Overbank	Maintain the channel and floodplain morphology of all parts of the estuary	Flow corresponding to morphologically defined bankfull level. Inundate most of the area opposite Red Cliffs
1c	Bankfull	Scour of sands at the entrance	Critical velocity for sediment mobilisation

3.2 Vegetation

The Werribee estuary is located in the Werribee Zone of the Victorian Otway Plain Bioregion (Duffy et al. 2002). The Otway plain is located in southern Victoria and extends from east of Princetown and includes outlying areas at Werribee, Glenaire anad Apollo Bay. The Otway Plain is dominated by flat to gently undulating plains of Tertiary deposits. The bioregion comprises a series of coastal plains, river valleys and foothills which are mainly sedimentary in origin.

The estuary is located within a confined gorge in the fluvial sediments of the relict Werribee delta. A low-lying plain, positioned slightly above the normal upper tidal level, is found in a sharp bend in the river at K Avenue (Figure 1-2). This habitat occurs intermittently along the base of the cliffs where the topography rises steeply. Set within this floodplain are shallow pools which are tidal and support saltmarsh communities.

A higher-level floodplain, inundated by flood flows is located between K Avenue and the ford (Figure 1-2). This has largely been cleared for the Werribee Golf Course, however native vegetation remains at the periphery of the Golf Course near the river.

A salt marsh community exists on the low floodplain areas near the entrance of the estuary.

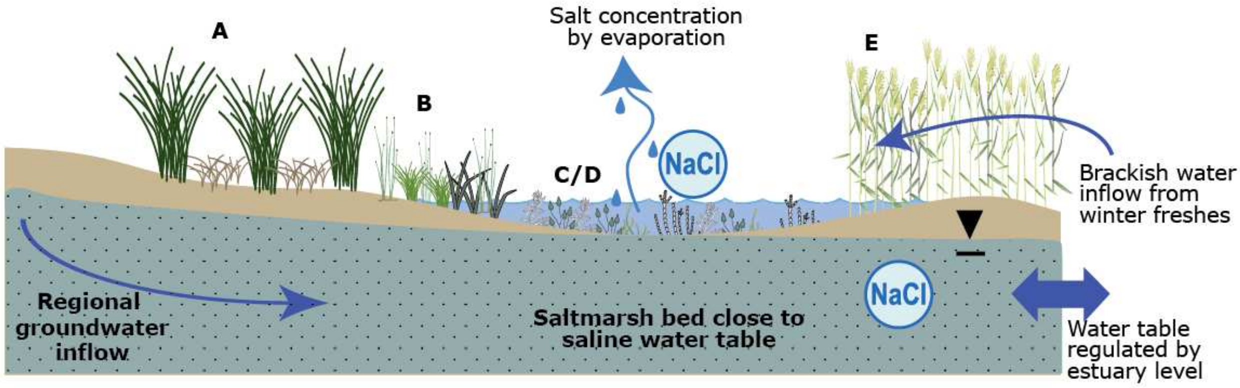
No estuarine species of conservation significance have been reported from the study area (Flora Information System).

3.2.1 Representative Objective - Coastal Saltmarsh EVC 9

Coastal Saltmarsh has and endangered conservation status in the Otway Plain Bioregion. Ecological and hydrological requirements are shown in Figure 3-2 and Table 3-2.

Coastal Saltmarsh occupies low-lying intertidal benches and flats of the estuary between the entrance and the reef 6.5 km upstream.

Near the estuary entrance on the north side there is an area of approximately 9 ha, upstream of Diggers Road. The banks of the estuary slope gently above the normal tide level, providing an area regularly waterlogged by a shallow saline water table, intermittently inundated by high tides and intermittently inundated by high river flows. A smaller patch exists on the south bank. This community is disturbed by vehicle tracks and extensively infested with **Juncus acutus*, which have been controlled to some extent. The dominant native plants are *Sueada australis,* *Disphyma crassifolium, Atriplex semibaccata, Rhagodia candolleana, Halosarcia* sp., *Isolepis nodosa, Juncus kraussii* and *Distichlis distichophylla.* Other weed species present are **Aster subulatus, *Convolvulus* sp., *Coprosma repens* and **Lycium ferocissimum*. A patch of *Phragmites australis* is likely to have colonised this area as a result of stormwater discharge to the flat.



Plant assemblages:

A On rises and higher ground in the floodplain, - *Ghania, Poa spp.*

B *Bolboschoenus, Distichlis, Wilsonia*

C Summer (dry) - Salt flat with samphire *Sarcocornia sp* and *Halosarcia sp.*

D Winter / spring (inundated) - diverse community including: *Chara, Nitella, Selliera*

E *Phragmites australis*

Figure 3-2. Conceptual model of Coastal Salt Marsh ecological and hydrological objectives.

Between the entrance and the K Avenue wetlands the floodplain is generally a narrow shelf at the base of the cliffs which enclose the channel. The flats are waterlogged and support similar species to those described above. *Schoenoplectus validus, Phragmites australis* and *Juncus kraussii* are salt tolerant species that are nevertheless normally excluded from areas inundated by sea water. However, along these benches both of these species grow in areas within the tidal range. Their growth may be supported by fresher groundwater discharging to the watercourse. Groundwater discharge to the river is indicated by local groundwater levels and the growth of *Phragmites australis*, a species dependent on waterlogging, on the cliff face. Groundwater salinities in the region are less than 4000 EC which is well below the concentration tolerated by *Phragmites australis* (Hellings and Gallagher 1992).

Coastal Saltmarsh occupies the lower areas of the K Avenue wetland. This area lies at the upper limit of the normal tidal range; lower lying areas form exposed mudflats at low tide.

Coastal Saltmarsh occupies perennially waterlogged areas which are intermittently inundated. Very high salinities are likely to occur as saline surface water evaporates or shallow groundwater evaporates, depositing salts on and in the soil. Salinisation of these environments is moderated by intermittent high river flows and by the low salinity of the groundwater.

This EVC is likely to have been degraded by reduced inundation by freshwater from peaks in river flow. Intermittently flooded saline habitats develop a high floristic diversity with a high habitat value for wading, grazing and dabbling waterbirds. Plant species which are sparse or absent, but which would be expected with more frequent inundation include *Distichlis disticophylla, Ruppia* sp., *Bolboschoenus caldwellii, Wilsonia* spp., *Frankenia pauciflora* and *Lepilaena* sp. This EVC has also been degraded by ground distubance from vehicles and by weed infestation, particularly by **Juncus acutus*.

Coastal Saltmarsh species are adapted to variable flooding depths and variable and potentially high salinity levels.

3.2.2 Representative Objective - Estuarine Wetland EVC 010

Estuarine Wetland has an Endangered conservation status in the Otway Plain Bioregion. Ecological and hydrological requirements are shown in Table 3-3.

Estuarine Wetland grows on anaerobic peat-rich muds on the edges of estuarine waterbodies with intermediate salinity conditions. Vegetation is determined by fluctuating salinity, which varies in time from occasionally fresh to brackish or saline depending on river flood and marine tide levels. Shrub species such as *Leptospermum lanigerum* and *Melaleuca ericifolia* are typical of this EVC but are absent at the Werribee River.

Estuarine Wetland occupies the floodplain enclosed by the sharp bend in the river at K Avenue, between 4.5 and 6.5 km upstream of the estuary entrance. This area lies approximately 1 m above the level of the daily high tide and is flooded only when estuary levels are particularly high. This will result from high river discharge or a combination elevated discharge and high tides. These events will usually last for a day to several weeks and will be separated by periods of several days to weeks.

The floodplain is underlain by groundwater with a salinity of less than 4000 EC. The groundwater table is higher than the normal estuary level, so that groundwater discharges to the floodplain and will mitigate the higher marine salinities of the estuary downstream of the reef.

These conditions support a sparse reed bed of *Phragmites australis* with an overstorey of *Eucalyptus camaldulensis.* The close proximity of *E. camaldulensis* to marine conditions can only be explained by an alternative low salinity water source. This species temporarily tolerates salinities of up to 30,000 EC but typically occurs in salinities less than 4,000 to 8,000 EC (Marcar et al. 1995). Eucalyptus camaldulensis is not a typical species of the Estuarine Wetland EVC. Other species present at this site are *Isolepis nodosa* and *Poa* sp.

This community is likely to benefit from regular inundation. Additional freshwater recharge will reduce accumulated salts and provide soil moisture to support growth of reeds and other aquatic plants. Flooding promotes *E. camaldulensis* growth, germination and recruitment (Dexter 1978); the absence of any immature trees in the wetland suggests that the current inundation regime is deficient. Regeneration is best promoted by flooding in spring to early summer (Dexter 1978). The trees are currently in poor health, which may also reflect insufficient flooding.

3.2.3 Representative Objective – Floodplain Riparian Woodland EVC 056

Floodplain Riparian Woodland has an endangered conservation status in the Otway Plain Bioregion. Ecological and hydrological requirements are shown in Table 3-4.

Floodplain Riparian woodland grows on the banks and floodplains of rivers and creeks. The soils are fertile and subject to periodic flooding. The EVC benchmark indicates a recruitment interval (i.e. flood interval) of 10 years.

Floodplain Riparian Woodland occupies the floodplain upstream of the reef at the K Avenue wetland to beyond the ford. The floodplain has been extensively developed for the Werribee Golf Course. Significant remnants occur between the golf course and Werribee Park and the river. A smaller area occurs on the opposite bank on the narrow floodplain.

The community is dominated by *Eucalyptus camaldulensis* but includes a number of other woodland trees and tall shrubs including *Acacia melanoxylon, Hymenanthera denticulata, Acacia dealbata, Solanum laciniatum* and *Callistemon brachyandrus*. There floodplain is highly disturbed by vehicle tracks, dumped soil and organic waste from the golf course and by weeds. The main overstorey weeds are **Olea europea, *Fraxinus rotunidflora* and **Schinus molle*. The understorey is dominated by exotic species, particularly **Pennisetum clandestinum, *Piptatherum milliaceum, *Myrsiphyllum asparagoides, *Fumaria capreolata* and **Oxalis pes-caprae*. The floodplain is being rehabilitated by weed control and revegetation.

Along the river bank the understorey is dominated by aquatic species such as *Bolboschoenus caldwellii, Typha sp., Phragmites australis* and *Vallisneria spiralis.* The weed species Juncus acutus is abundant, together with **Nasturtium officinale, *Iris germanica* and **Galenia pubesens.*

At the time of the inspection few flood-dependent species were present in the understorey and this may reflect the infrequency of flood events in the area. The floodplain has a number of shallow billabongs and flood runners which would retain water following a flood and would develop wetland plant communities of species such as *Eleocharis acuta, Marsellia drummondii* and *Crassula helmsii.*

The floodplain community is likely to be sustained by a combination of shallow, low-salinity groundwater and periodic flooding. Rainfall and shallow groundwater will support the growth of *Eucalyptus camaldulensis* between flood events and flooding will promote additional growth (Bacon et al. 1993) and tree recruitment (Dexter 1978). Flooding will maintain the growth of perennial flood-dependent plants such as Callistemon brachyandrus and Juncus spp. and promote the periodic growth of short-lived aquatic species.

The state of the woodland community provides an indication of the adequacy of the current water regime. The Red Gum trees are generally in good health, as are the other flood-dependent woodland species. The scarcity of young *Eucalyptus camaldulensis* is an indication of infrequent flooding. The absence of flood-dependent understorey species indicates that the current interval between floods is too long for these species to persist.

The current water regime may be considered to be maintaining the current ecosystem, but more frequent flooding would promote a more diverse and productive community.

3.2.4 Representative Objective – Sea-grass Meadow EVC 845

Sea-grass Meadow has not been mapped as an EVC in the estuaries of the Port Phillip region. In the Werribee estuary it extends from the mouth to below the shallow reef area with more extensive beds in the lowest 2 km of the estuary. It was observed in shallow sandy areas (<2m depth) but may also occur in deeper waters. Unlike most other EVCs, which have been developed with bioregional benchmarks for the Vegetation Quality Assessment and Wetland

Vegetation Assessment methods, no quality benchmarks for Seagrass Meadow in estuaries of this region have been described.

Sea-grass Meadow consists of “aquatic meadow dominated by stands of Sea-grass Zostera spp.”. The species growing in the Werribee Estuary include *Zostera muelleri* and a *Heterozostera* species (identified as *H. tasmanica* before a taxonomic revision). Two other genera, *Ruppia* and *Lepilaena* (associated with EVC 842) have been recorded in Swan Bay and may also be present at times. Ecological and hydrological requirements are shown in Figure 3-3 and Table 3-5.

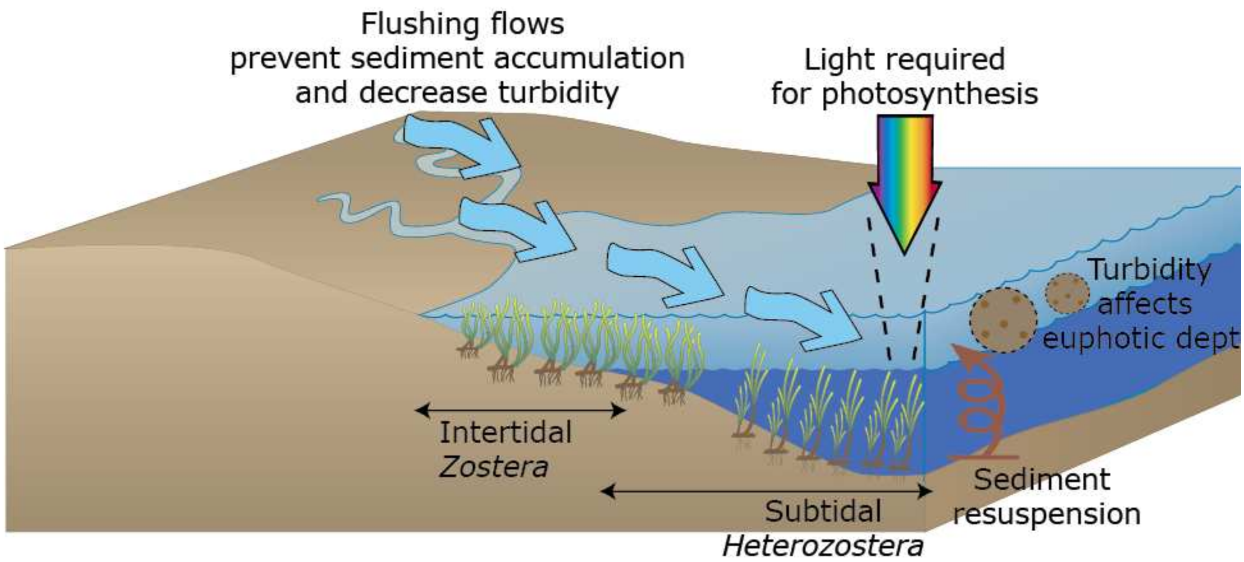


Figure 3-3. Conceptual model of Seagrass ecological and hydrological objectives.

Of the species listed, *H. tasmanica* typically exists where it is not exposed to the atmosphere (Blake et al. 2000). *Z. muelleri* can live in the lower part of intertidal zones and tolerates periods of exposure to the atmosphere (Blake et al. 2000). *Ruppia* tends to be found in shallower waters and tolerates a wide range of salinities (Wommersley 1984). Both *Z. muelleri* and *H. tasmanica* are found in shallower parts of Port Phillip Bay, more so in the southern portion, but also in smaller beds near the estuary entrance (Blake & Ball, 2001).

Leaf length and shoot density of *H. tasmanica* have been shown to decline with decreasing light (Bulthuis, 1983a) and similar results have been found for *Z. muelleri* (Kerr & Strother, 1985). *Z. muelleri* has also been shown to be strongly photosynthetically inhibited as salinity increases or decreases from that of seawater (Kerr & Strother, 1985). Despite this, photosynthesis in both species is maintained over a wide range of temperatures and, at least for *Z. muelleri*, to salinities as low as ~6 (Bulthuis, 1983b; Kerr & Strother, 1985). Low salinities have stimulated germination of several *Zostera* species in laboratory studies while photosynthesis and production are generally greatest at intermediate (10-20) to high, but not hypersaline, salinities (reviewed in Moore & Short, 2006).

Seagrasses colonise mud, silt and sand, using their extensive rhizomes to anchor themselves. The leaves retard currents and increase sedimentation in their vicinity. Seagrass meadows are found in water depths of up to 2.5m in estuaries of western Victoria and South Australia and often occur as a fringing band around the edges of deeper lagoons (Shepherd & Robertson, 1989; Ierodiaconou & Laurenson, 2002). In Port Phillip Bay lower limits of seagrasses are in the vicinity of 5 to 9m depth (Blake & Ball, 2001). In many locations light availability limits the deeper boundaries of seagrass beds and poor light conditions are often given as a cause of seagrass decline. Light penetration may be reduced by high turbidity, smothering by sediment and an increase in epiphyte growth on seagrass leaves (Bulthuis and Woelkerling 1983). Ecological and hydrological requirements that were assessed relate primarily to salinity, inundation and light availability.

Table 3-2.
Ecological and hydrological objectives for Coastal Salt Marsh EVC 9.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors
2a	Flooding by brackish water in spring and by saline water in summer	Promote salt-tolerant charophytes, herbs, grasses and forbs Exclude emergent macrophytes	Salinity of less than 14 in summer / autumn Salinity of less than 4 spring / summer Salinity is only relevant when water levels are high enough to inundate habitat Inundation at least 2 times per month in winter-spring, in 50% of years Inundation at least 1 time per month in 50% of years.	At peak of tidal range. High flow and low flow groundwater influence
2b	Intermittent flooding in winter and spring	Promote salt-tolerant charophytes and submerged vascular macrophytes Exclude emergent macrophytes	Intermittent flooding to a depth of 0.25 to 0.5 m from May to December. Examine hydrology of flows required to achieve 0.25, 0.5 and 0.75 m AHD at XS1	
2c	Shallow flooding in late spring / early summer	Provide habitat for salt-tolerant grasses, sedges, herbs and forbs	Intermittent flooding to a depth of 0.25 to 0.5 m from November to December	
2d	Saline soil conditions in summer	Salts accumulate in summer to exclude salt intolerant sedges. Maintain *Sarcocornia quinqueflora*	Intermittent flooding to a depth of 0.25 to 0.5 m from November to December - see 2 c above Soil salinity (1:5 EC) exceeds 10 g/L in summer and autumn on at least one occasion each year	Groundwater
2e	Waterlogging by relatively low salinity groundwater	Support moderately salt tolerant *Juncus kraussii* at and below high tide level	Groundwater salinity less than 3 g/L discharges to the river.	

Table 3-3.
Ecological and hydrological objectives for Estuarine Wetland EVC 010.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors
2f	Flooding by fresh water	Promote growth and density of *Phragmites australis* and growth and recuruitment of *Eucalyptus camaldulensis*	Flood for at least one day with fresh water in winter to early summer 1 to 2 times per year	Floodplain inundation
2g	Shallow, low salinity groundwater	Maintain growth of *P. australis* and *E. camaldulensis*	Groundwater salinity less than 2 g/L at a higher hydraulic potential than the wetland bed.	Groundwater level River level Groundwater salinity

Table 3-4.
Ecological and hydrological objectives for Floodplain Riparian Woodland EVC 056.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors
2h	Shallow, low salinity groundwater	Maintain growth of *Eucalyptus camaldulensis* and other flood-dependent trees and shrubs	Groundwater <2 g/L within 2 m of the floodplain surface.	Groundwater level River level Groundwater salinity
2i	Flooding by fresh water	Promote growth and recruitment of *E. camaldulensis*. Promote growth of aquatic understorey plants.	Flood for at least one day with fresh water in winter to early summer 1 to 2 times per 2 years. Years without floods allowed up to 60% of years with a maximum interval between flood years of 5 years.	Floodplain inundation
2j	Baseflow	Maintain aquatic plant communities in riparian zone.	Salinity at XS 19 is less than 10, 80% of time.	Inflows to maintain surface water salinity upstream of reef

Table 3-5.
Ecological and hydrological objectives for Seagrass Meadow EVC 845.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors	Possible assessment approaches
2k	Salinities	Seagrass meadows tolerate salinities above and below sea water	Salinity which varies with tide and flow, but has a median salinity of 0.5 to 1.0 times sea water. (15 - 35 Salinity) – will tolerate down to salinities 6) in the lowest kilometre. Freshwater pulses may be trigger for germination. Prolonged fresh conditions will remove *Zostera* and *Heterozostera.*	Flows required to extend salt upstream	1. Prolonged flood events will result in fresh conditions. Lower freshwater inflows will result in saline conditions for much of the Werribee estuary. 2. Evaluate from Salt Wedge Model in terms of extent of salt. 3. Evaluate events from hydrological analysis. 4. This could determine the max. baseflow.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors	Possible assessment approaches
2l	Water Level	*Zostera muelleri*	Stable water levels but mostly inundated	Water level (within normal tidal range)	
2m	Turbidity	Poor light penetration can reduce seagrass photosynthesis and growth	Maintain euphotic conditions up to Red Cliffs bend (5,750 m upstream of estuary entrance).	Flows required to extend salt upstream	See salinity method above
2n	Sedimentation	Excessive sedimentation smothers seagrasses	Provide regular flushing flows to prevent excessive accumulation of sediment downstream of Red Cliffs.	River flow (shear stress to move silt but not large enough to shift/disturb the seagrass (uproot the bed)	1. Sediment transport threshold based on hydraulic analysis 2. Hydrological analysis of events

3.3 Fish and Aquatic Fauna

3.3.1 Introduction

The fish community of the Werribee estuary consists of 64 species (Table 3-6) which inhabit a range of habitats within the estuary (Sherwood et al 2005, DSE FIS Database, Koehn and O'Connor 1990, Hindell 2006).

There three zones within the channel bound section of the Werribee estuary. These zones are:

a) **Marine-dominated zone** which has marine macrophytes (the seagrasses *Zostera* and *Heterozostera*) growing on the bed, extends from the mouth to below the shallow reef area, and has a strong marine (Port Phillip Bay; PPB) influence most of the time. Salinities in this section generally exceeded 30 g/L with only a weak vertical salinity gradient.

   The entrance to the Werribee River estuary is wide (approx. 60 m during inspection) and relatively deep (up to 3 m during inspection). The substratum is silty clays with some sand but little submerged woody debris. Well inside (about 500 m) the estuary there are extensive bands of *Phragmites* on both sides of the channel. *Phragmites* supports juvenile bream in Gippsland, and it could be expected to support small and juvenile fish in this system as well.

   There are significant seagrass beds in the system which are important to fish breeding and recruitment. There are also undercut banks and the open water and deep pools within in the channel it itself and also important fish habitats. A public boat launching ramp is located within a few hundred metres of the entrance of the estuary from Port Phillip Bay at the town of Werribee South, which results in significant disturbance of the sediments near the mouth on busy boating days.

b) **Transitional zone** from the shallow reef area to the bluestone ford which has intermediate salinity (i.e. 10 – 30 g/L), which can be highly stratified, with salinity in the halocline increasing by 8 or more over a depth of 1 to 0.5 m;

   The channel narrows slightly further upstream, and the water appears to become more turbid. Land on the western side of the estuary is managed by Melbourne Water and Parks Victoria and is primarily used for dry land grazing of stock as part of the Werribee Farm, containing the sewerage treatment plant. On the eastern bank of the estuary the dominant land uses are a golf course (upper estuary) and market gardens (lower estuary). There are no tributaries flowing directly into the estuary but several stormwater drains enter from the eastern shore and significant agricultural drains on the western shore. This zone contains several a significant floodplain and wetland zones in a large bend near the Kay Avenue cliffs. The river contains deep pools, some wetlands are inundated by high tides and others only inundated by overbank flows.

c) **A freshwater zone** of the Werribee River, above the bluestone ford, usually with salinities below 2 g/L. The zone is usually well mixed in relation to salinity and salinities are low. The ford construction may have created an artificial barrier between the freshwater zone and the transitional zone.

   The upstream delineation of the estuary is defined by a ford located downstream of the Maltby bypass. Upstream of the ford fresh water forms a deeper long pool. Water drops about 0.5 m after flowing over the ford. About one kilometre below the ford the estuary shallows with a long and wide stony riffle area (usually preventing boat access at low tide).

Table 3-6.
Fish groups in the Werribee Estuary (Sherwood et al 2005, DSE FIS Database, Koehn and O'Connor 1990, Hindell 2006)

Estuary Fish Group	Sub-Types	Species Present
A: Estuarine Residents	n/a	Black Bream [C,R] Blue Spot Goby Estuary Perch [C,R] Glass goby Lagoon goby Tamar Goby
B:Estuarine Dependent	Marine Derived	Congolli (Tupong) [C,R] Elongate Hardyhead King George Whiting [C,R] Mulloway [C,R] Pouched Lamprey Short-headed Lamprey Small-mouthed Hardyhead
	Freshwater Derived (Catadromous)	Common Jollytail Freshwater Herring Short-finned Eel [C,R]
C: Estuarine Opportunists	Marine Derived	Australian Anchovy [C] Australian Herring (tommy rough) [C,R] Australian Salmon [C,R] Blue sprat [C,R] Bridled goby Cobbler Yank flathead [C,R] Greenback flounder [C,R] Half Bridled Goby Little rock whiting Longfin goby Longsnout flounder [C,R] Luderick [C,R] Luminous bay squid [C,R] Pike-head hardyhead Pilchard [C] Prickly toadfish Pygmy leatherjacket Pygmy squid Sandy sprat Sea Mullet [C,R] Silver Trevally [C,R] Silverfish Six spine leatherjacket [C,R] Smooth toadfish Snapper [C,R] Southern fiddler ray [C,R] Spikey globefish Spotted pipefish

Estuary Fish Group	Sub-Types	Species Present
		WA Salmon C,R White trevally C,R Wide-body pipefish Yellow-Eyed Mullet C,R Yellowfin goby E
	Freshwater Derived	Australian Smelt Big-headed Gudgeons Brown trout R E Chinook salmon R E Common carp E Eastern Gambusia E Goldfish E Macquarie Perch R T Mountain galaxias Redfin perch R E River Blackfish R Roach E Southern Pigmy Perch Tench E

C These species have commercial fisheries value; R These species have recreational fisheries value

E Exotic species; T Translocated native species

3.3.2 Fish Conservation Values of the Estuary

There are no locally native species of conservation value in the Werribee Estuary but there are 27 species which are important either as a recreational or commercial fisheries species (Table 3-6). Significantly, 10 of these fish species are either exotic or not native to the catchment.

3.3.3 Biology and distribution of fish

The fish within estuary can be divided into 3 groups according to their biology and distribution (Figure 3-4). These groups include some species which live solely within the estuary or in freshwater and saline environments, including:

- Estuarine Residents (6 species)
- Estuarine Dependent (marine derived = 7 species; freshwater derived = 3 species)
- Estuarine Opportunists (marine derived = 34 species; freshwater derived = 14 species)

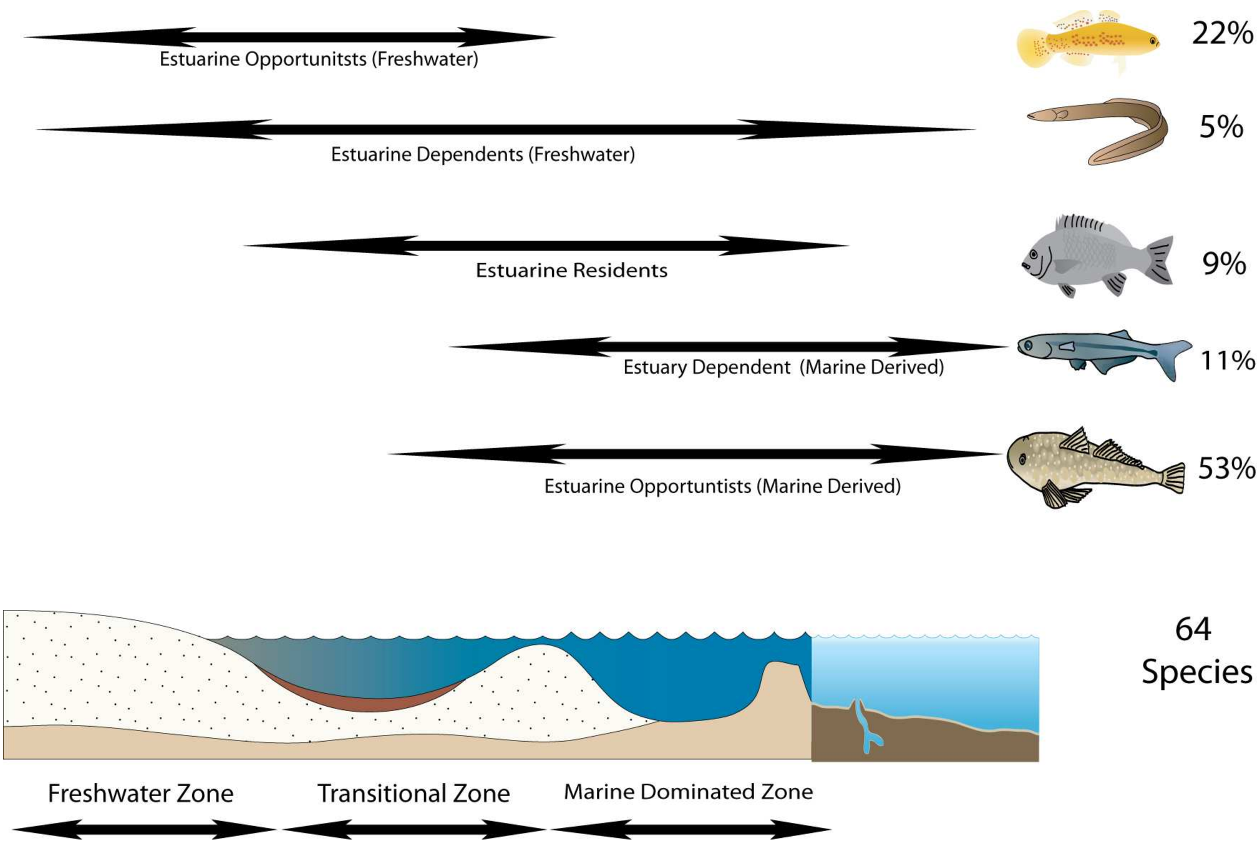


Figure 3-4. Fish groups and distribution in the Werribee Estuary

Estuarine Residents are a range of estuarine specialised fish which utilise the abundant resources of the estuary and complete their entire life cycle in the estuary complex. They may penetrate upstream into freshwater and can persist for some-time.

Estuarine Dependent species are those fish which are dependent upon the estuary for spawning, as a nursery ground for their young, for shelter and/or for feeding. These species depend upon the estuary (created by freshwater flows) for one part of their life cycle. These fish are derived from either the freshwater (catadromous) and marine (anadromous) ecosystems.

> *Marine derived* (some are Anadromous) fish are estuarine dependent species which mostly live in the sea but migrate into the estuary to breed or recruit in the estuary (e.g. Lampreys – breeding; King George Whiting juvenile recruiting habitat).
>
> *Freshwater derived* (Catadromous) fish are those species which mostly live in freshwater, and which migrate downstream to breed in the estuary (e.g. galaxiids or in the case of eels, in the sea) and then return upstream.

Estuarine Opportunists are fish which live primarily in either marine or freshwater environments but opportunistically exploit the resources of the estuary. They are likely to be present within the estuary on a regular basis. These fish visit the estuary opportunistically to access food, shed parasites, and/or avoid unfavourable environments. These species are not likely to have a specific dependence on estuary but the estuary does provide rich resources and a refuge from disturbance, and therefore contributes to the growth and condition of these fish. These fish would stay in the lower to mid-zones of the estuary (utilising marine habitats such as seagrass) until conditions become too fresh. Their use of the estuary may be largely unrelated to flow but their persistence within the estuary is dependent upon the salinity as these species will be displaced from the estuary during high freshwater inflows. These fish would be eaten by piscivorous birds (e.g. Cormorants). In the Werribee, the marine derived Estuarine Opportunists dominate the fish fauna, reflecting the permanently and widely open mouth and the marine conditions within the lower estuary.

3.3.4 Representative Objective – Black bream (*Acanthopagrus butcheri*) – Estuarine Resident

Black Bream are common in and around large structural elements within estuaries. They are considered as the only true estuarine sparid in Australia and have a wide salinity tolerance and may move into the freshwater reaches of estuaries (Kailola et al. 1993). Ecological and hydrological requirements are shown in Figure 3-5 and Table 3-7.

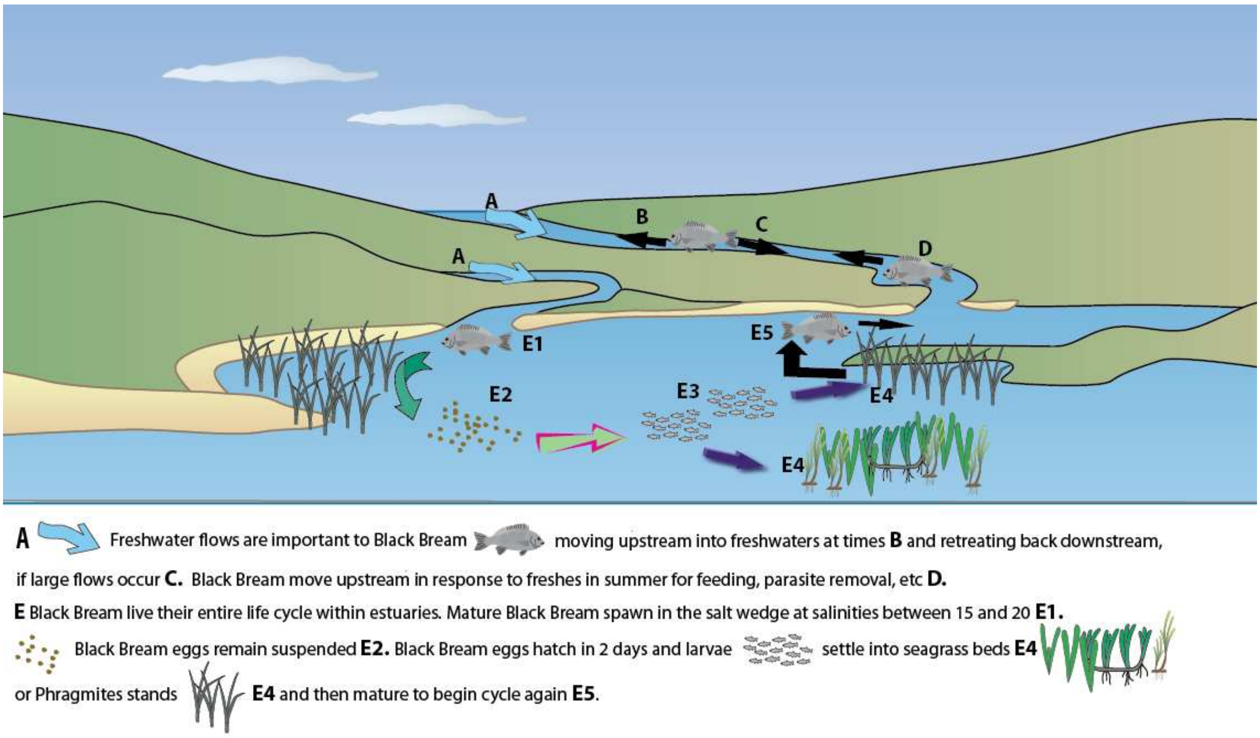


Figure 3-5. Black Bream conceptual model, ecological and hydrological objectives.

Spawning

The life cycle of black bream is usually completed within a specific estuary, however, there may be some movement of black bream between estuaries (Butcher and Ling 1958). Spawning period for black bream extends from August to December, though the timing and the period of spawning is thought to vary between estuaries (Kailola *et al.* 1993). Spawning is thought to occur in the upper reaches of estuaries near the interface between fresh and brackish water (Cadwallader and Backhouse 1983; Ramm 1986), although actual spawning areas are unknown.

Water temperature and salinity appear to be of importance in determining the timing and success of spawning (Winstanley 1985). Optimal salinity and temperature for spawning varies spatially and may be somewhere in the vicinity of 11 to 22 g/L and 21℃, respectively (Butcher 1945; Ramm 1986). Spawning success may also be higher when spring rainfall and river flow were low and when water temperatures were high in October (Hobday and Moran 1983), but the water quality requirements for successful spawning and survival of eggs/larvae are not well understood.

Eggs are planktonic and, as a function of their buoyancy (negative in freshwater and positive in saltwater), are most abundant in waters with salinities greater than 15 g/L (Ramm 1986). Nicholson *et al.* (2004) found that bream eggs are neutrally buoyant in salinities 16 – 20 g/L, and therefore float in the halocline. Eggs generally hatch two days after fertilisation, but embryos fail to develop in salinities below 5 g/L (Ramm 1986).

Recruitment

Larvae remain in the water column for approximately one month before settling into shallow macrophyte beds at between 10 to 15 mm in length (Ramm 1986). Shallow seagrass/algae beds appear to be important nursery areas for juvenile black bream, as these areas support high abundances of food (Poore 1982). The relative importance of each macrophyte species as nursery habitat is not well understood. Seagrass beds are predominant in many estuaries, and are suggested to be important nursery areas for black bream in the Gippsland Lakes (Rigby 1984). Ramm (1986) reported juvenile black bream in association with *Ruppia spiralis* and *Zostera muelleri* seagrass beds in the Gippsland Lakes. The smallest black bream juveniles recorded in Ramm's study were located in beds of *Z. muelleri*.

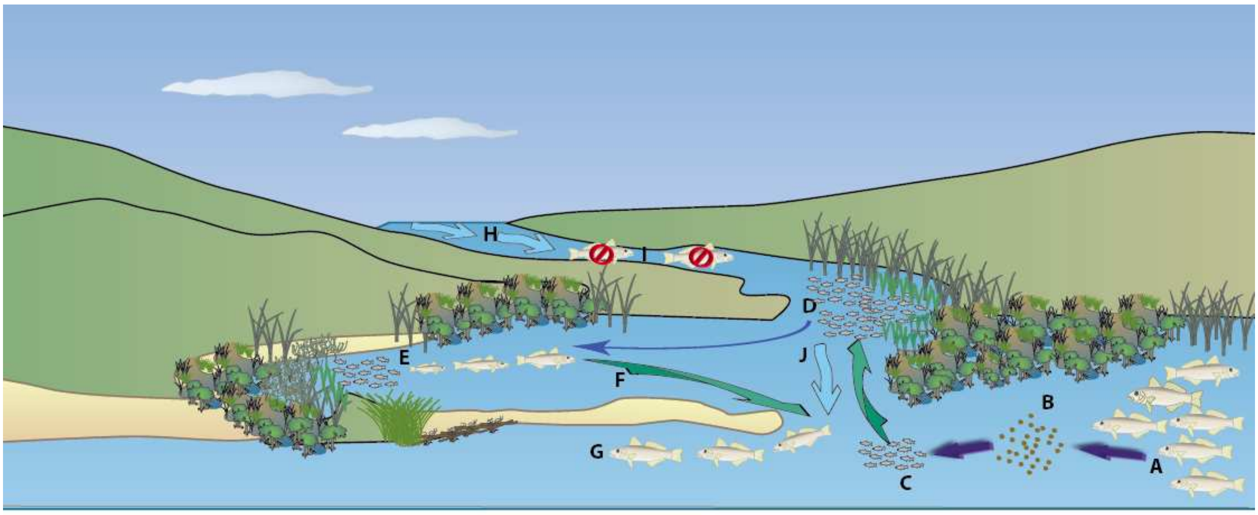
Larvae and juveniles appear to be more abundant in salinities less than 28 g/L, Ramm (1986) suggests these lifestages tolerate a wide range of salinity (from 0 to 32 g/L). Larger juveniles and adults may be found in association with a range of habitats within estuaries, including; unvegetated sand and mud, rocky sand, macrophytes and structures such as snags, rocks and pylons (Hobday and Moran 1983). Hobday and Moran (1983) suggest black bream juveniles and adults move to deeper water in winter.

Life history with reference to freshwater flows and salt wedge dynamics

The movement, spawning and recruitment of black bream are all likely to related to freshwater flows. Black bream are estuarine fish, and while capable of withstanding low salinities, will generally avoid such conditions. Subsequently, high flows events that reduce the salinity in/of the system will probably force fish to retreat downstream until the flows subside (this was observed during the survey period). The salt wedge is likely to be the critical habitat for spawning, with fish preferring water between 15 and 20 g/L. A degree of turbidity associated with the salt wedge may be important in providing shelter for larval and juvenile fish. The movement of the salt wedge up and down the estuary is likely to be critical in shaping the recruitment success of the species, particularly if the salt wedge and valuable nursery habitat do not overlap in time and space. Given the relatively narrow range of salinities required by the eggs for not only buoyancy but also the development of the embryo, the flow of freshwater into the system will be crucial in establishing salinities and small scale salt wedge dynamics required for successful reproduction.

3.3.5 Representative Objective – King George whiting (*Sillaginodes punctata*) – Estuarine Dependent (Marine Derived)

Ecological and hydrological requirements for King George whiting are shown in Figure 3-6 and Table 3-8



A King George Whiting are estuarine dependent species which breeds in marine waters B and their larvae move into estuaries in August to October C. Larvae recruit to seagrass and juveniles remain in protected areas D but as they grow they inhabit more open waters E. Sub-Adult fish F move out of Estuary prior to reaching breeding age G. High freshwater flows H prevent fish moving up into the mid and upper Estuary I and high flows are required to open mouth so larvae can migrate into Estuary.

Figure 3-6. King George whiting conceptual model, ecological and hydrological objectives.

Distribution

King George whiting are a demersal species found from northern New South Wales to the south-west coast of West Australia, including the north coast of Tasmania (Paxton *et al.* 1989). Juvenile fish are restricted to bays and inlets, while adults are found in open coastal waters (Kailola *et al.* 1993).

Habitat

Juvenile fish prefer shallow vegetated habitats (especially seagrass) in sheltered estuaries and embayments, while older fish are common in deeper sandy patches among vegetation.

Reproduction and spawning

King George whiting from Victorian waters are spawned between May to July (Jenkins and May 1994). Fish do not use bays or inlets for spawning (Jenkins 1986), but coastal spawning location(s) or habitats of King George whiting are not yet known. A significant proportion of Victoria's King George whiting population may be spawned in South Australian waters (Jenkins *et al.* 1998).

Recruitment

Larvae settle into shallow seagrass and algal habitats (Jenkins and Wheatley 1998), but the relative value of particular habitats varies with location. Sheltered seagrass/algal habitats in areas where currents deliver fish larvae are the most important (Jenkins *et al.* 1997a). In highly protected environments, such as Swan Bay, newly settled individuals have been found in bare unvegetated mud patches within seagrass beds (Jenkins *et al.* 1997b). Juveniles remain closely associated with shallow seagrass and algal habitats up to approximately five months after settlement, then move to unvegetated sand patches amongst vegetated habitats (Jenkins and Wheatley 1998). Older juveniles venture into deeper water, where they are more common over sandy, muddy areas with patchy seagrass and algae (Jenkins, pers. comm.).

Migration

Sub-adult King George whiting (3 – 4 years old) migrate out of bays and inlets prior to reaching maturity (Jones and Retallick 1990).

3.3.6 Representative Objective – Common Jollytail (*Galaxias maculatus*) - Estuarine Dependent (Freshwater Derived)

Ecological and hydrological requirements for King George whiting are shown in Figure 3-7 and Table 3-9.

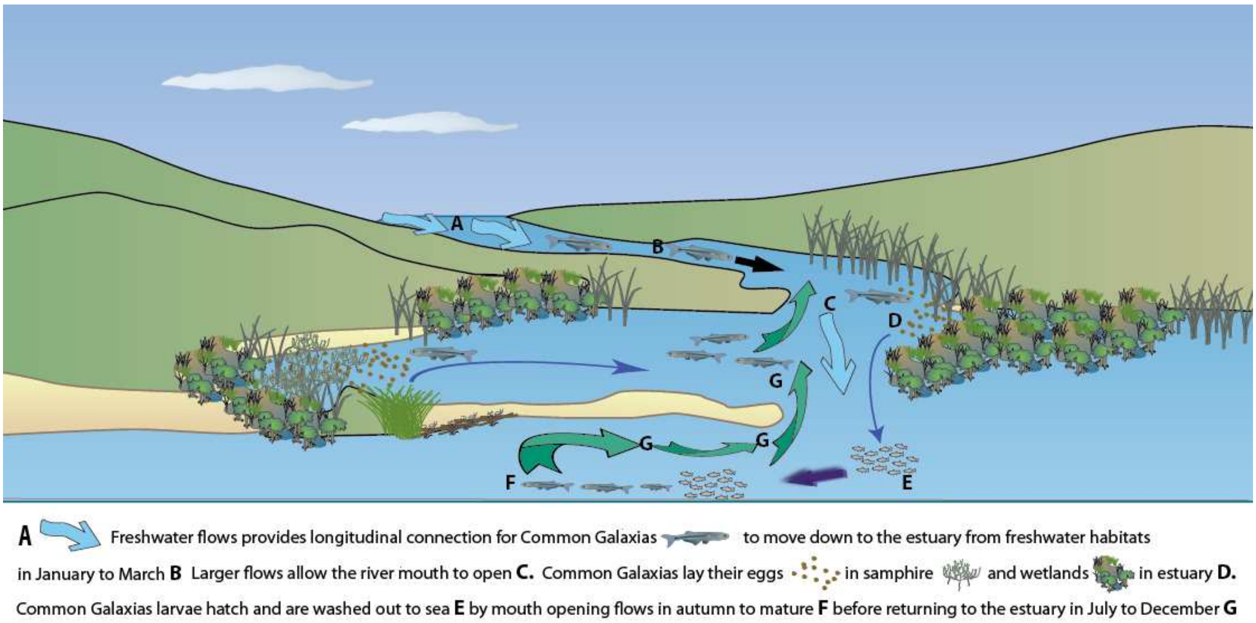


Figure 3-7. Common Jollytail conceptual model, ecological and hydrological objectives.

Distribution

Common Jollytails are a widespread and often abundant species in Australia found in coastal lakes and streams at low altitudes from Adelaide in the west to Southern Queensland in the east (McDowall and Fulton 1996). They are also present in New Zealand and South America having a Gwandanian distribution. They are a significant species in the ecosystem as a food source for other fish and birds and would be a significant invertebrate predator (Koehn and O'Connor 1990; McDowall 1996; Merrick and Schmida 1984).

Habitat

Common jollytails are able utilise a wide range of habitats, has a preference for still or slow moving waters. They are capable to withstand freshwater to very high salinities well above that of sea water. They are known to also occur in landlocked populations (Koehn and O'Connor 1990; McDowall 1996; Merrick and Schmida 1984).

Movement

Adults move downstream to the estuary to spawn in autumn to spawn on full or new moon and the high spring tide. The eggs hatch and the small, slender larvae are washed out to sea. The juveniles spend the winter at sea and return to freshwater after about 5 to 6 months later (Treadwell and Hardwick 2003; McDowall and Fulton 1996).

Reproduction

Common jollytails spawns amongst vegetation (grasses, samphire and other low vegetation) around river estuaries when under water at high tide. Most adults die after spawning. The eggs remain out of water for two weeks or more until the next spring tides, the eggs hatch on being re-inundated and the larvae migrate (or are washed out) to sea (McDowall and Fulton 1996). Eggs can tolerate and hatch in salinities ranging from fresh to seawater (Cadwallader and Backhouse 1983).

Table 3-7.
Ecological and hydrological objectives for Black Bream.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors	Possible assessment approaches
3a	Adult fish habitat	Maintain estuarine salinities	Salinity range of 5 to 30 present over at least 50% of longitudinal section 80% of the time	Freshwater inflows to create estuarine conditions (5 to 30 salinity)	1. Report frequency of estuarine conditions for low flow in December to May (steady state inflow over a spring/neap cycle). 2. Refer to natural conditions for reality check.
3b	Salt wedge	Spawning/egg survival	Salinity between 15 and 20 anywhere upstream of XS 2 DO >5 mg/L in bottom water during spawning season Sep to Dec	Presence of halocline between 15 and 20 Top (0.1 m) water salinity less than 10 AND bottom (0.5 m above bottom) salinity greater than 25. Oxygenated waters	1. Salinity of 20 no further down than XS 2 at the surface on the ebb of the spring tide 2. Halocline present as described by longitudinal plots (2dv) 3. Use residence time to approximate DO - set maximum residence time of 2 days anywhere in water below halocline.
3c	Seagrass	Refuge/feeding for settlement and post settlement juveniles	Inundated vegetation near salinity 15-20	Specify flow band which positions the (former) halocline near the required vegetation type (seagrass)	Determine flow band to provide halocline between XS3 and XS1 for seagrass beds

Table 3-8.
Ecological and hydrological objectives for King George whiting.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors	Possible assessment approaches
3d	Entrance of larvae to estuary	Allow migration to estuary from the sea	Open Mouth August to late October	Not an issue at Werribee	Not an issue at Werribee
3e	Larval fish habitat in estuary	Provide habitat for larval to survive and grow	Up to 5 months (settlement in spring summer Jenkins and May 1994, Jenkins, Wheatley and Poore 1996) shallow sea grass and macroalgae. Salinities greater than 25 in bottom water DO greater than 5 mg/L in bottom water during this period. Phagmites may provide habitats at high tide, or if they are permanently inundated, but no great evidence of this. KGW will but prefer access to seagrass or other subtidal vegetation. Though there is some evidence that fish use unvegetated mud/sand in sheltered area – e.g. Corio Bay.	Salinity greater than 25 in bottom 1 m more than 80% of the time, below XS4. DO/residence time KGW primarily marine species, so probably likely to be restricted to lower regions of estuary.	Use residence time to approximate DO - set maximum residence time of 2 days anywhere in water below XS4 in bottom 1 m (below halocline)

Table 3-9.
Ecological and hydrological objectives for Common Jollytail.

ID	Physical habitat component	Role of habitat component	Conditions required	Physical factors	Possible assessment approaches
3f	High Flow Fresh	Migration to estuary in autumn before spring tides	Flow cue to migrate downstream	Require access to estuary over riffles - upstream riffle depth at least 0.3 m min At least 2 events in autumn (to provide 2 opportunities) 2 events of min 3 days	Thalweg depth at ford 0.3 m min Also refer to requirement for high flow freshes in the upstream freshwater reach. 2 events of min 3 days.
3g	Flooded samphire or estuarine floodplain vegetation	Adults spawning	Spring tide in autumn following migration event	Inundation of >1 m wide emergent vegetation or samphire at the upper extent of the intertidal zone once every two weeks (on tides)	Same as 2a, 2b and 2d from vegetation section.
3h	Estuary Mouth State	Marine Migration by larvae	30-50 cm deep river mouth Mouth open during May to July (downstream movement)	Require open mouth	Not an issue at Werribee
3i	Estuary Mouth State	*Migratory cue to return to estuary*	*uncertain*	*met by flows required to provide passage?*	No assessment required
3j	Estuary Mouth State	Freshwater Migration to estuary from sea by juveniles	30-50 cm deep river mouth Mouth open during July to December (upstream migration)	Require open mouth	Not an issue at Werribee entrance
3k	Riffles, stream bars, flow freshes	Migration from estuary to freshwater reaches by juveniles	Flow cue to migrate upstream – probably flow freshes (low and high)	Require access to upstream reaches over riffles - upstream riffle depth at least 0.3 m min. At least 2 events in spring (to provide 2 opportunities)	Thalweg depth thalweg depth >30cm at ford

3.4 Summary of Hydraulic Analyses

This section presents the key results derived from the two numerical simulations of the Werribee River estuary (Tide Model and Flood Model). A full description of the hydraulic modelling work and a presentation of more detailed results can be found in Appendix 2.

3.4.1 Tide Model Results

The key estuary hydrodynamic characteristics to be resolved by the Tide Model were water level variations and the dynamics of the salinity structure. Water levels and salinity vary with freshwater inflow discharge and tidal fluctuations.

The Werribee River estuary is 8.25 km long and flows within a relatively narrow, clearly defined channel. This morphology suits a two-dimensional vertical (i.e. laterally averaged) hydrodynamic model. RMA-10 software (ver. 7.3, King, 2006) was used to construct and execute a 2DV vertically stratified, finite element representation of the estuary.

Longitudinal Salinity Profiles

The salinity profiles on the ebb and flood of the spring tide for the first three inflow cases are shown in Figure 3-8 to Figure 3-10.

Qualitative comparison to measured salinity profiles

Sherwood et al. (2005) measured salinity profiles at six locations along the Werribee estuary at monthly intervals between August 2004 and May 2005. Based on these observations, the following conclusions were drawn about the salinity regime in the estuary (Sherwood et al., 2005, p.13):

> *"The lower estuary (i.e. site 3 and below; < 3.6 km upstream) had a strong marine (Port Phillip Bay; PPB) influence throughout the survey period. Salinities in this section generally exceeded 30 with only a weak vertical salinity gradient (Figure 4).*
>
> *A shallow (< 1 m) freshwater lens (salinity < 10) was present in the upper estuary on all surveys except for the 28th April 2005. On this occasion, all water in the estuary had a salinity > 20. The maximum observed downstream extent of the freshwater lens was on 27th January and 24th March 2005 when water of salinity < 10 reached below site 4 (i.e. greater than 2.8 km downstream of the ford). The estuary was highly stratified in its upper reaches with salinity in the halocline increasing by 8 or more over a depth of 1 - 0.5 m on most surveys.*
>
> *Water of intermediate salinity (i.e. 10-30) was generally confined to the middle section of the estuary (approximately 4-6 km) or to bottom waters above the shallow reef area (i.e. above 6.7 km)."*

Flow released by the Lower Werribee Diversion Weir delivers around 1 ML/day unless there is a high flow event. Hence, a qualitative calibration can be undertaken by comparing the model predictions at 1 ML/day (Figure 3-8) to the measured data of Sherwood et al. (2005). The measured data are indeed consistent with the predicted salinity profiles and consequently a high degree of confidence can be placed in the model results.

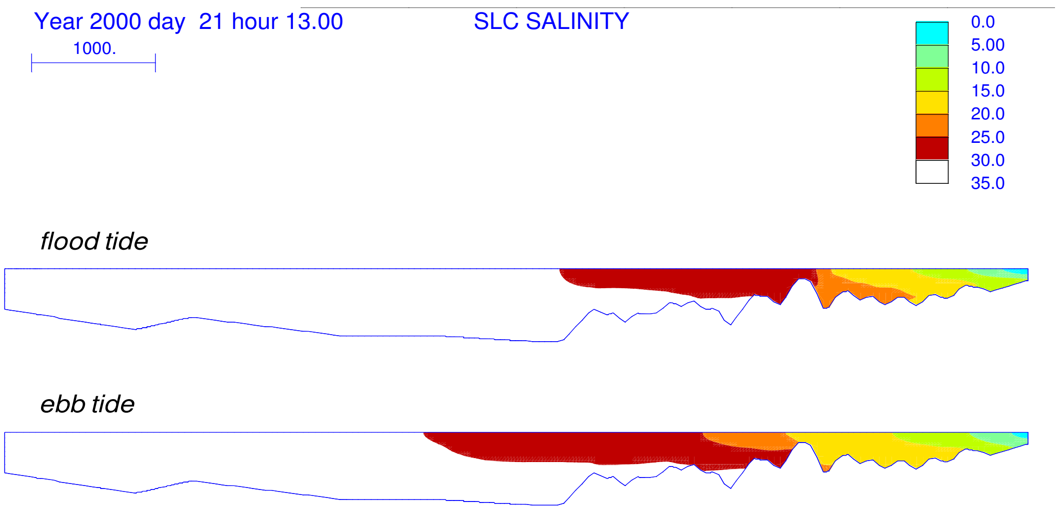


Figure 3-8. Salinity distributions at ebb and flood of the spring tide with 1ML/day inflow discharge. Legend shows salinity range represented by each colour.

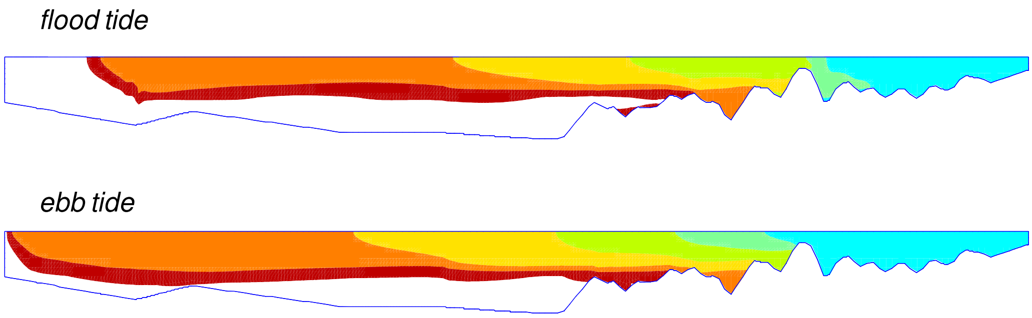


Figure 3-9. Salinity distributions at ebb and flood of the spring tide with 20ML/day inflow discharge.

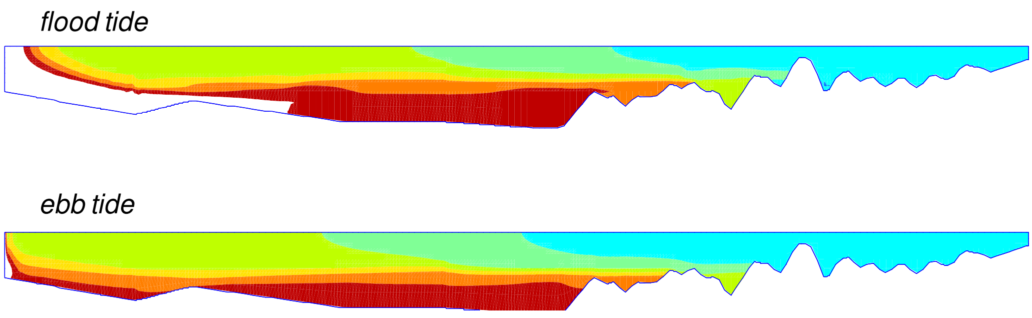


Figure 3-10. Salinity distributions at ebb and flood of the spring tide with 50 ML/day inflow discharge. Note scale in metres shown at the bottom of the plot.

Analysis of Residence Times

Hydrodynamic simulations were undertaken with the Tide Model incorporating a numerical tracer to estimate residence times at various locations in the Werribee estuary under four different steady freshwater inflow discharges (Table 3-10). Results were extracted at five locations (Sites A-E) as shown in Figure 3-11.

The approach used was to set an initial concentration of a conservative dissolved substance (tracer) in the waters of the estuary. Fresh water inflows and the tidal boundary were assumed to have zero concentration of the tracer and an advection-dispersion transport formulation was used to transport the substance through the estuary under the influence of the hydrodynamic flow field. The change in the concentration of the tracer through time at locations within the estuary characterised the time taken for various sections of the estuary to be 'flushed' with 'new' saline water from the ocean boundary or 'new' fresh water from the upstream inflow boundary.

The **e-folding** time is commonly used to provide a practical measure of the time interval taken for a certain volume/parcel of water in the estuary to be exchanged with new water. The e-folding time is defined as the time interval in which an initial quantity decays to 1/e or 36 percent of its initial value. For environmental studies, this is considered to provide a quantitative measure of the time of exposure to pollution/physical stresses in semi-enclosed water bodies.

The numerical tracer simulations undertaken have adopted low dispersion coefficients (this drives the amount of mixing or exchange that occurs but is not influenced by the hydrodynamics) to provide a conservative estimate of the flushing/residence times in the estuary. Wind induced overturning and other turbulent mixing processes may result in lower residence times than those calculated.

Table 3-10.
Variation of residence time (estimated as the e-folding time in days) with freshwater inflow discharge along the Werribee Estuary.

	Site A Entrance	Site B Lower Straight	Site C Island below Bend	Site D Red Cliffs	Site E Golf Course
Flow	*e-folding time (days)*				
1 ML/day	0.5	1.0	4.2	4.9	6.2
20 ML/day	0.5	0.8	2.7	4.0	3.1
50 ML/day	0.5	0.8	3.0	4.5	0.5
100 Ml/day	0.5	2.7	3.6	1.4	0.3

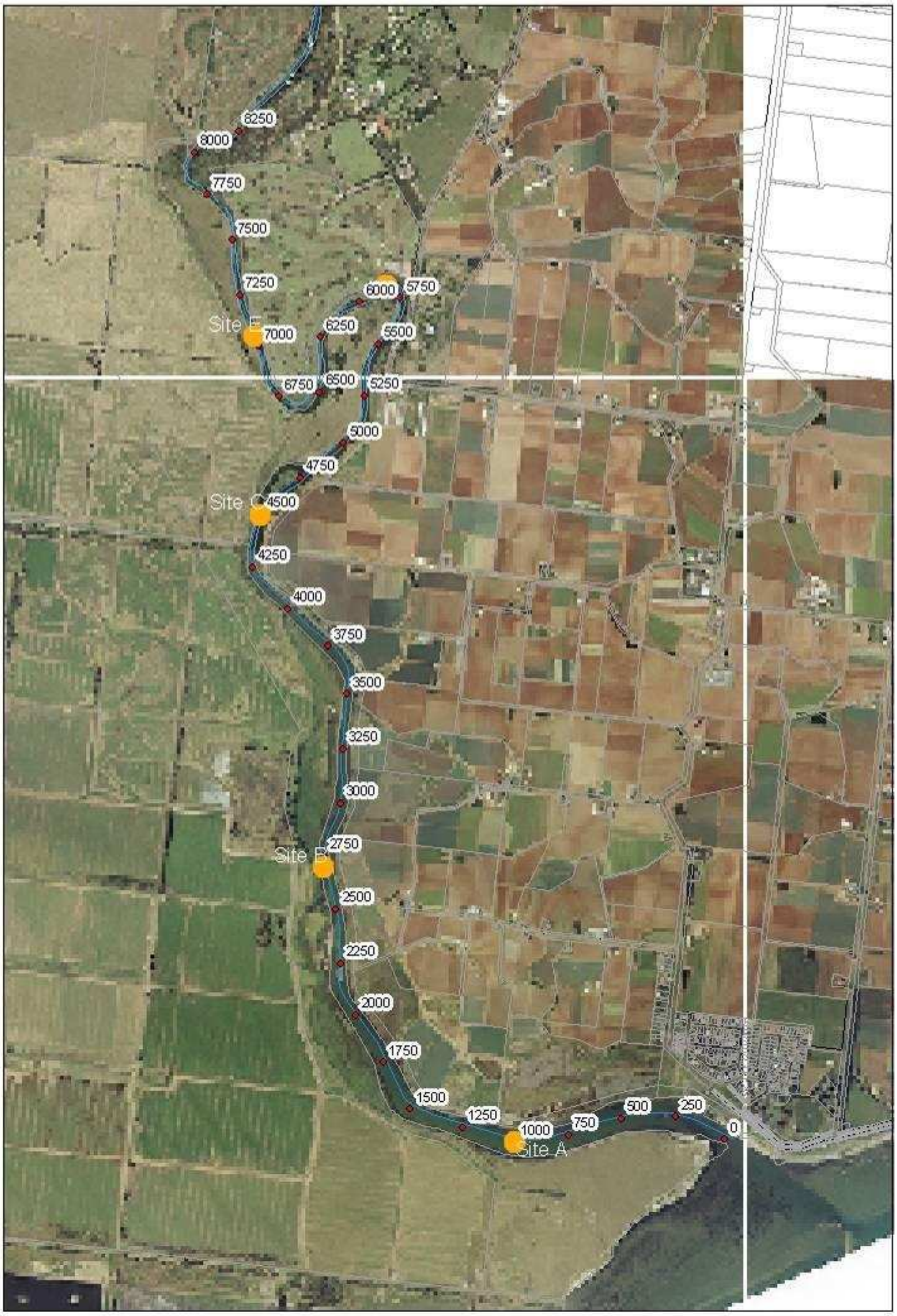


Figure 3-11. Map of the Werribee River Estuary showing the distance upstream of the entrance and the location of Sites A – E at which data were extracted from the Tide Model.

Residence times were found to be higher in the upper estuary than the lower estuary, with the e-folding time typically decreasing as flow (inflow discharge) increased (Table 3-10). An exception to this trend was that at Sites B and C residence time increased when flow was increased from 50 to 100 ML/day (Table 3-10). This result was attributed to the fact that at 100 ML/day a strong freshwater surface flow was present (Figure 3-12), trapping salt water in the bottom layer for extended periods. This trapping would likely decrease at higher flows as the freshwater layer thickened and ultimately flushed salt from the estuary entirely. Consequently, increases in residence time with flow would be likely to occur over only a small band of inflow discharges, and would be expected to fall rapidly once flow sufficient to flush the lower estuary occurs.

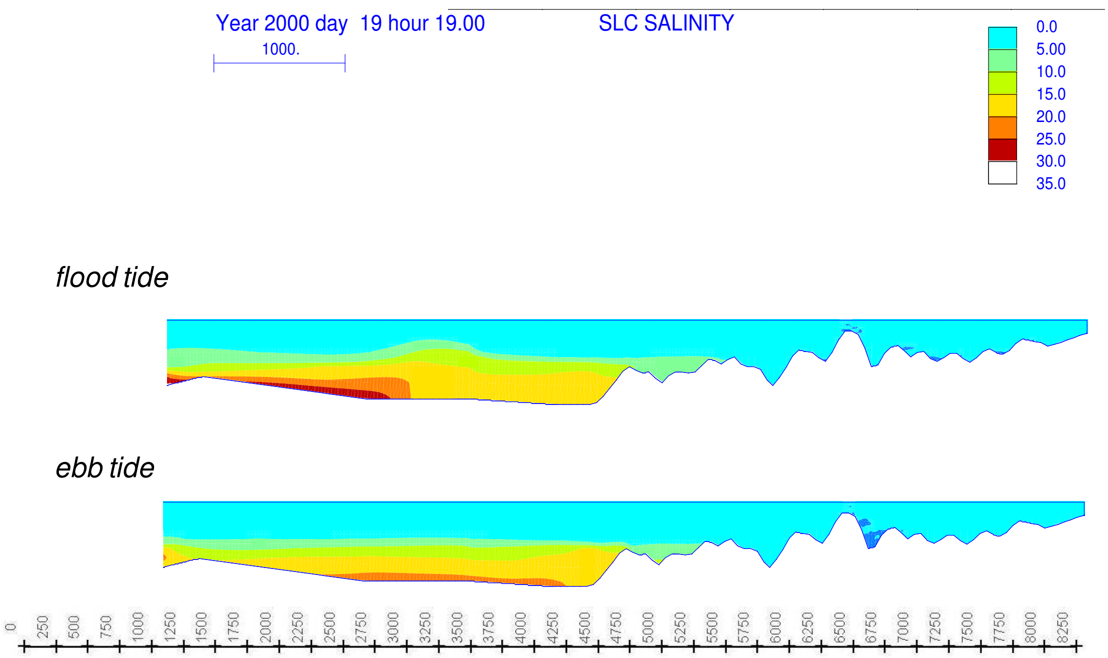


Figure 3-12. Longitudinal salinity profiles on an ebb and a flood tide with a constant freshwater inflow discharge of 100 ML/day.

The modelled residence time results were broadly consistent with the trends in measured dissolved oxygen (DO) levels reported by Sherwood et al. (2005). They observed that low DO tended to be found in the bottom waters of the mid- to upper-estuary, which were associated with the locations having higher predicted residence times.

Saline flushing

In order to resolve the question of what inflow discharge would flush the estuary of salt water, a ramp inflow discharge starting at 50 ML/day and increasing to 500 ML/day was run with the Tide Model. A repeating spring tide sequence was run as the downstream boundary to provide maximum tidal energy to push salt into the estuary. It was found that at around 180 ML/day salt was unable to penetrate beyond the high point in the long profile at 1,500 m from the estuary entrance. A freshwater flow of around 340 ML/day was required to prevent salt water from pushing beyond the entrance bar (located at ~250 m).

Extent of Estuarine Conditions

During the Scientific Expert Panel workshop it became evident that it would be useful to divide the estuary into three zones according to the salinity of the water. The three zones and the associated salinity levels were:

- Marine: salinity > 30
- Estuarine: 5 < salinity < 30
- Fresh: salinity < 5

The length of the study region (i.e. the estuary) over which estuarine conditions were predicted was assessed using the longitudinal salinity distributions (e.g. Figure 3-8 to Figure 3-10). The results were summarised in terms of the absolute length over which estuarine conditions were found and the percentage of the estuary that this represented (Table 3-11). These results showed that moderate freshwater inflow discharges (20 – 50 ML/day) maximised the length over which estuarine conditions prevailed.

Table 3-11.
Predicted length along the river that estuarine conditions were found (also percentage of total length of 8,250 m). Estuarine conditions defined as: 5 > salinity > 30; somewhere in the vertical profile.

	Predicted Estuarine Length (m)	
Inflow Discharge	**Ebb**	**Flood**
1 ML/day	3,000m (36%)	2,000m (24%)
20 ML/day	6,750m (82%)	6,250m (76%)
50 ML/day	6,250m (76%)	6,500m (79%)
100 ML/day	5,500m (67%)	5,500m (67%)

3.4.2 Flood Model

The objective of simulation with the Flood Model was to estimate the inflow discharge required to cause various overbank water levels at different points along the estuary. A two-dimensional model was developed using the LIDAR data (0.25 m contour surface), with this level of topographic resolution necessary given the complexity of the overland flow paths across the golf course and around the bend downstream of the golf course.

a) Model Calibration Result

The model was calibrated to the 2005 flood event which peaked at just over 16,500 ML/d (see Appendix 2 for a detailed description). Anecdotal evidence and photographs of the Golf Course during the 2005 flood extent was available for calibration. The roughness values in the channel and on the floodplain were altered so as to achieve a similar level of inundation across the Golf Course as observed in 2005. At the flood peak the model results showed flood water inundating approximately half of the golf course (Figure 3-13). The key positive indications of calibration were the activation of two overland flow paths (as indicated).

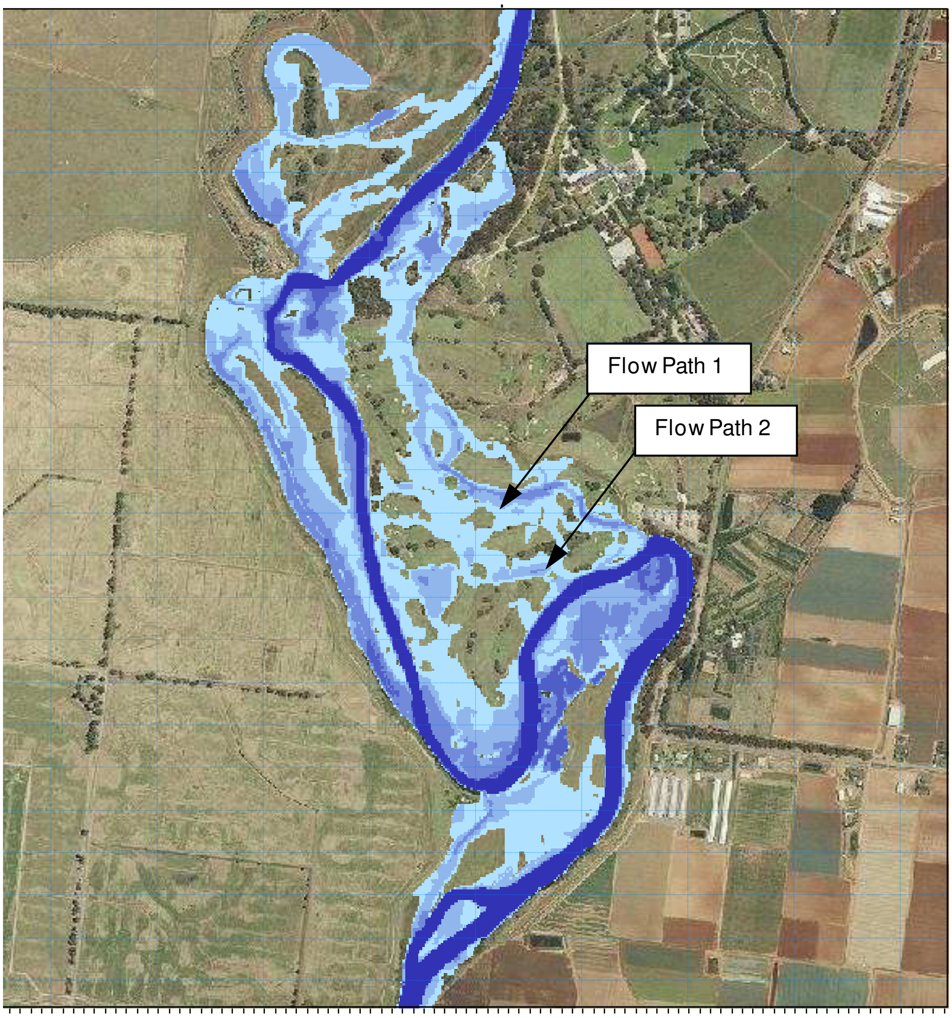


Figure 3-13. Calibrated model inundation at the peak of the February 2005 flood event over the Golf Course and the downstream bend.

b) Sample Model Results

The ramp simulation predicted the approximate relationship between the extent of inundation (or water level) and the peak discharge of the flood. That is, it was assumed that the ramp inflow was gradual enough that inflow discharge at a particular time could be equated to peak flood discharge). Based on this assumption, charts were produced to estimate the peak flood discharge required to attain given inundation extents at key locations along the estuary.

Snapshots of the inundation at different points through the ramp simulation (Figure 3-14) show:

- 8,500 ML/day resulted in approx. 25% of area inundated with two flow paths actively bypassing the bend.

- 10,000 ML/day resulted in approx. 50% of area inundated with most of the northeast corner under water (area opposite Red Cliff).
- 14,000 ML/day resulted in general inundation of bend area, only higher ground in the middle of the bend and at the downstream end (adjacent to the island) remain dry.

Sediment Transport Analysis

Sediment-entrainment theories predict the mobilisation of unconsolidated sediments (silts, sands, gravels, cobbles etc). It is normally assumed that particles will be flushed out when the threshold of motion for some percentage of the particles is reached. One method of predicting when particles will become entrained in the flow is based on the Hjulstrom curves, which relate particle size to mean velocity required for erosion, deposition and transportation (Gordon et al., 2004, p.192). The critical velocity (in m/s) for initiation of sediment movement (for particles >1 mm diameter) is $V_c = 0.155 \sqrt{d}$, where d is the average particle diameter in millimetres. The Hjulstrom curve also predicts the limits for erosion of fine sands down to clay size sediment, and these values can be read from the curve (Gordon et al., 2004, p.192). The velocity near the bed is predicted by $V_b = 0.7\ V$, where V is the mean channel velocity (Gordon et al., 2004, p. 193). The mean channel velocities required for bed sediment entrainment were estimated fr a range of particles sizes on the basis of these relationships (Table 3-12).

A rational analysis of sediment transport potential was undertaken for a range of sediment sizes using mean channel velocities predicted by Flood Model simulation results. The criterion was that bed material would become unstable when $V_b > V_c$.

Silt-sized material requires higher discharges to initiate entrainment compared to sand-sized material (Figure 3-15). Medium to coarse sands may be moved by:

- inflow of around 2,000 ML/day at Red Cliffs (Site D)
- inflow of around 5,500 ML/day in the lower estuary below the island (Site C) and above the last bend (Site B); and
- inflow of around 8,100 ML/day near the estuary entrance

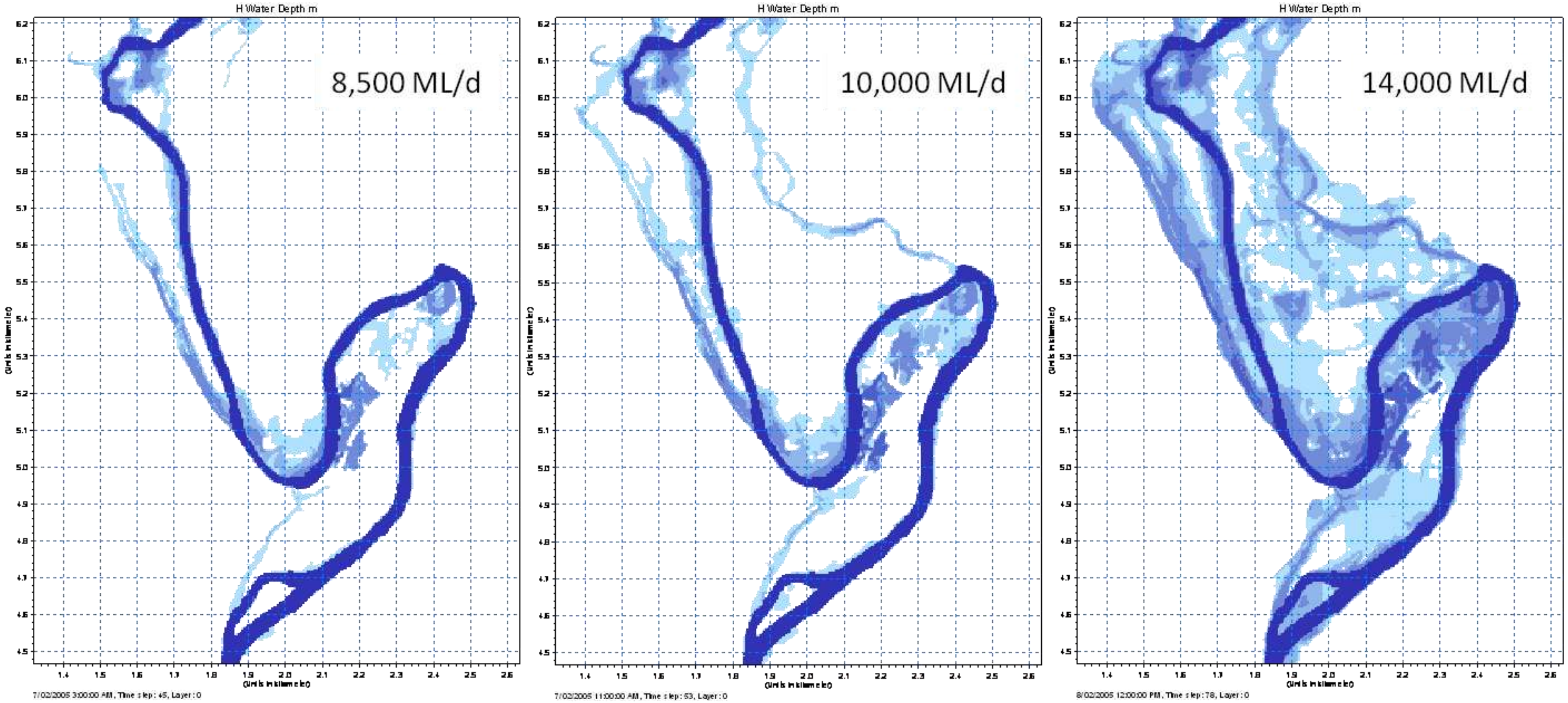


Figure 3-14. Snapshots of inundation of the top half of the estuary at three different points through the discharge ramp.

Table 3-12.
Mean channel velocities required to initiate sediment transport, for range of bed material particle sizes. Velocities rounded to one significant figure.

Size class (Wentworth)	Diameter range (mm)	Mean channel velocity to initiate sediment movement (m/s)	
		Lower size range	Upper size range
Very fine silt	0.0078 – 0.0039	1.0	1.4
Fine silt	0.0156 – 0.0078	0.7	1.0
Medium silt	0.0312 – 0.0156	0.5	0.7
Coarse silt	0.0625 – 0.0312	0.3	0.5
Very fine sand	0.125 – 0.0625	0.3	0.3
Fine sand	0.25 – 0.125	0.2	0.3
Medium sand	0.5 – 0.25	0.2	0.2
Coarse sand	1 – 0.5	0.2	0.2
Very coarse sand	2 – 1	0.3	0.2
Very fine gravel	4 – 2	0.4	0.3
Fine gravel	8 – 4	0.6	0.4

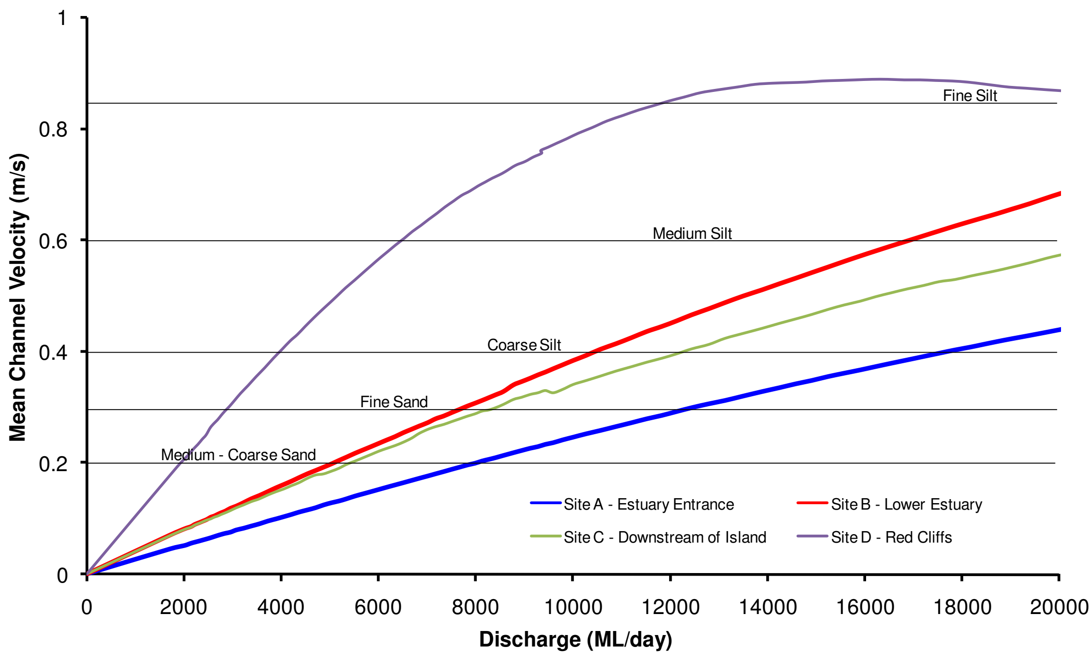


Figure 3-15. Inflow discharge versus mean channel velocity at various locations along the Werribee River Estuary. Horizontal lines indicate velocity thresholds required to mobilise sediment size of the middle of the size class range.

Note that sediment transport methods are recognised as approximations only, especially in estuarine locations where flocculation processes are important and cohesive sediments can be dominant in bed and bank substrates. The sediment transport analysis employed here assumed substrates were not bound by clay, but this is almost certainly incorrect for some zones of the estuary. An investigation of suspended sediment transport and deposition processes in the Werribee estuary (Lloyd et al. 2007b) clearly indicated that there is a significant contribution of fine sediment from the river to the estuary. A more detailed examination of estuarine sediment transport and deposition processes was beyond the scope of the current work. Further investigation is warranted to establish a method to estimate flushing flows from estuarine sea grass beds. Any method should consider cohesive floccs and also the discharge required to scour sea grass beds.

4 HYDROLOGICAL ANALYSIS

4.1 Geomorphological Objectives

All three defined geomorphological objectives (Table 3-1) are linked with ecological objectives. The High flow objective (1a), which requires maintenance of salt wedge dynamics is met by the range of ecological objectives that also require maintenance of this process. The other two objectives were specified using hydraulic criteria. Objective 1b required flow to reach the top of the banks once every two years on average and also to flow over the floodplain at less frequent intervals. This was in common with vegetation Objectives 2f and 2i. Objective 1c required scour of sand-sized material at the mouth once per year on average, and this was common with vegetation Objective 2n. Thus, hydrological analysis for the geomorphological objectives was incorporated into the analysis undertaken for the vegetation objectives.

4.2 Vegetation Objectives

4.2.1 Objective 2a: Coastal Salt Marsh – flooding by brackish water in spring and by saline water in summer

This component requires a number of hydrological events to be achieved:

- Low flow [summer/autumn]: achieve a surface salinity of <14 near entrance, which requires ≥49 ML/d
- High flow [winter/spring]: achieve a surface salinity of <4 near entrance, which requires ≥101.5 ML/d

The impact of regulation was apparent for these flow components (Figure 4-1). Also apparent was the high inter-annual variability for these components. The annual and inter-annual specifications for these components (Table 4-1) were made on the basis of the statistics for the natural series.

The Low flow and High flow components are not expected to prevail for the entire season. This is especially the case for the Low flow component, which was achieved for a minority of the time in the natural series. The magnitude of this component is too high for it to be considered a true Low flow component, and it would be more appropriate to consider it as a Low flow fresh. The duration of these components is at the recommended magnitude for the entire season, or natural, whichever is lower.

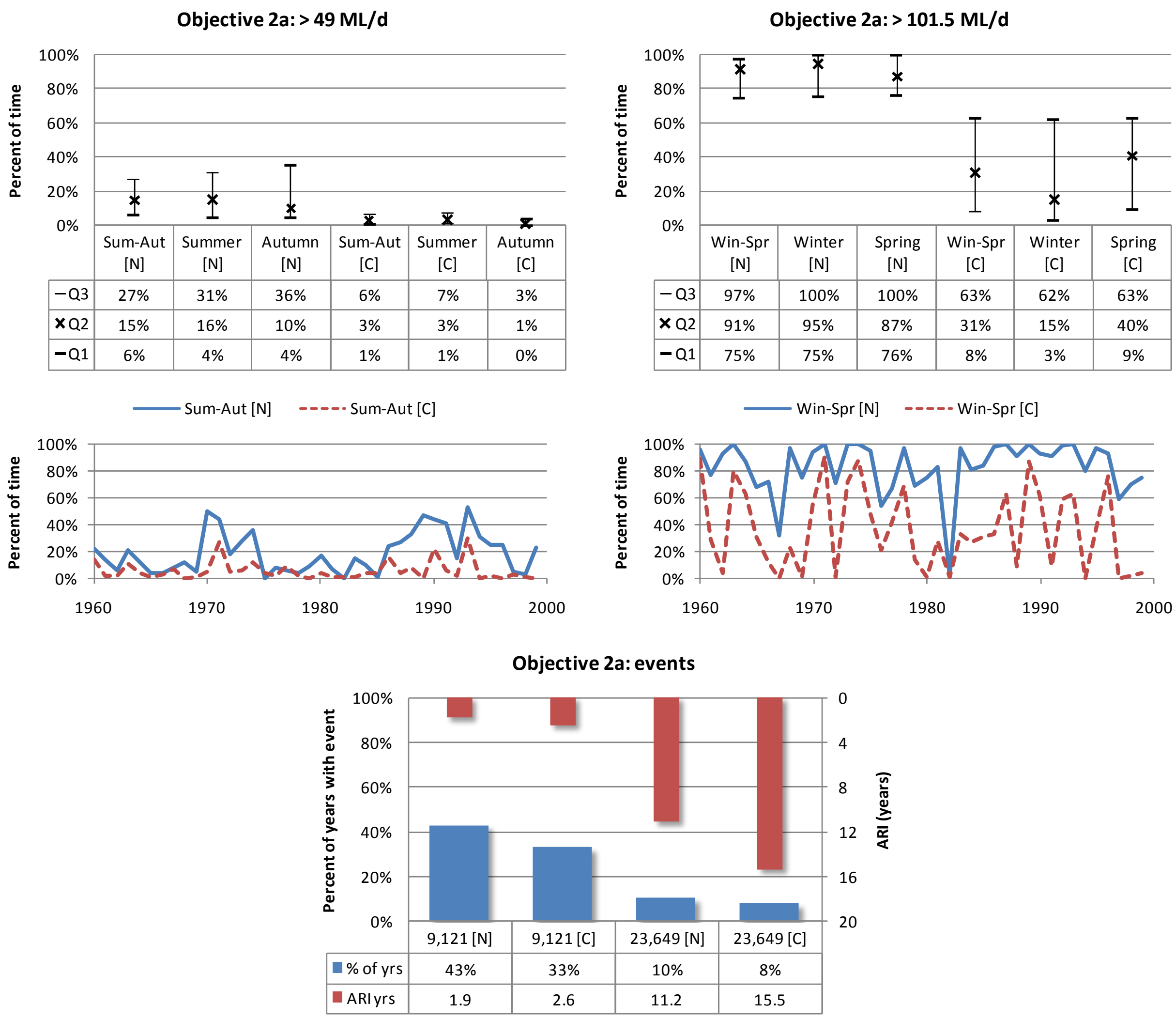


Figure 4-1. Hydrological distribution of hydraulically determined potential Low flow, High flow and Bankfull/Overbank components to meet Objective 2a. [N] is REALM natural series and [C] is REALM current series. ARI is average recurrence interval.

Table 4-1.
Objective 2a hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Low flow 2	49	na	All season, or natural if less	Dec-May	10% of the time 5 yrs in 10	81%	0%
High flow	101.5	na	All season, or natural if less	Jun-Nov	50% of the time 5 yrs in 10	100%	26%

4.2.2 Objective 2b and 2c: Coastal Salt Marsh – intermittent flooding in winter and spring

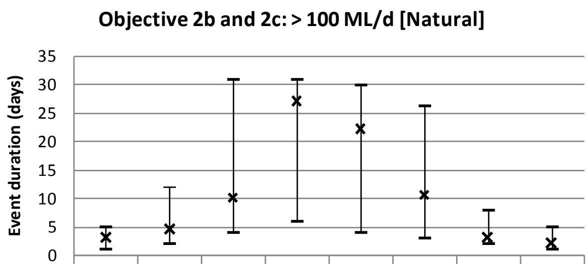
These objectives together cover the months from May to December, with 2b applying from May to October and 2c applying from November to December. The requirement was to achieve intermittent flooding to a depth of 0.25, 0.5 and 0.75 mAHD at XS1 (close to the entrance). The Tide Model determined that water level never exceeded 0.5 m or 0.75 mAHD due to tidal fluctuations alone. The exceedance of 0.25 mAHD due to tides was increased by river flows, such that at 1 ML/d it was exceeded for 2% of the time over the neap-spring tide cycle and at 100 ML/d it was exceeded for 59% of the time over the tide cycle. Thus, hydrological analysis was undertaken for three thresholds:

- 100 ML/d (for the 0.25 mAHD threshold),
- 9,121 ML/d (for the 0.5 mAHD threshold), and
- 16,881 ML/d (for the 1.0 mAHD threshold).

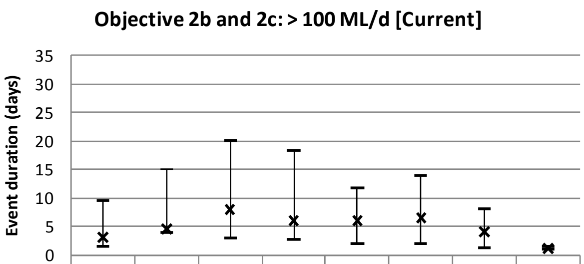
The impact of regulation on the duration and frequency of these components was apparent (Figure 4-2). For the 100 ML/d threshold, event duration was mostly reduced in the months of July to October, but as a percentage of total time in the month, all months had reductions. The percentage of years having the event was markedly reduced for each month (Figure 4-3). The frequency of occurrence was variable throughout the time series and somewhat reduced in the current series compared to the natural (Figure 4-2).

The two higher thresholds are too high to be termed freshes, and more correctly fall into the category of Bankfull and Overbank. The frequency of occurrence of these events was low (hence, why duration plots were not presented here), and not much affected by regulation (Figure 4-3).

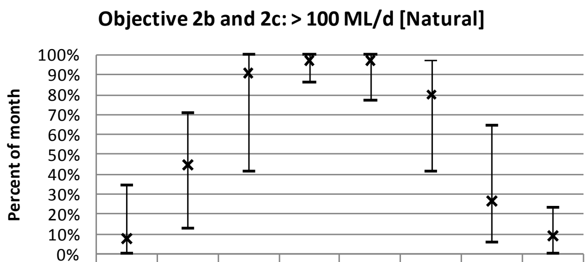
The annual and inter-annual specifications for these components (Table 4-2) were made on the basis of the statistics for the natural series. For the bankfull and overbank components, no distinction was made in the timing for objectives 2b and 2c, even though strictly speaking, they were specified for different seasons. The reason is that these events would have been even rarer had they been further seasonally restricted.



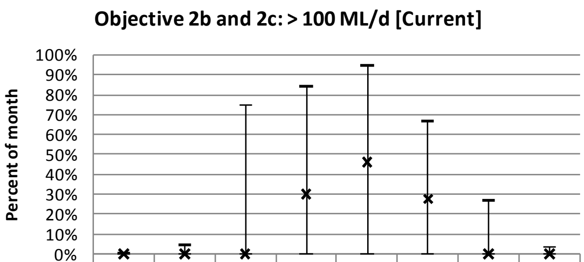
	May	June	July	Aug	Sep	Oct	Nov	Dec
Q3	5	12	31	31	30	26	8	5
Q2	3	5	10	27	22	11	3	2
Q1	1	2	4	6	4	3	2	1



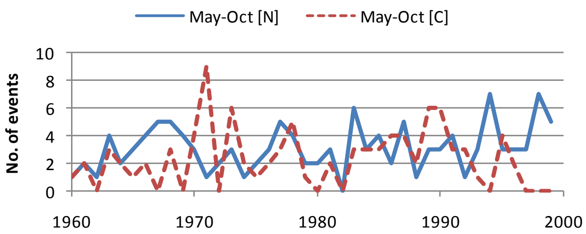
	May	June	July	Aug	Sep	Oct	Nov	Dec
Q3	10	15	20	18	12	14	8	2
Q2	3	5	8	6	6	7	4	1
Q1	2	4	3	3	2	2	1	1



	May	June	July	Aug	Sep	Oct	Nov	Dec
Q3	35%	71%	100%	100%	100%	97%	64%	23%
Q2	8%	45%	90%	97%	97%	80%	27%	9%
Q1	0%	13%	41%	86%	77%	41%	6%	0%



	May	June	July	Aug	Sep	Oct	Nov	Dec
Q3	0%	4%	74%	84%	94%	66%	27%	3%
Q2	0%	0%	0%	30%	46%	27%	0%	0%
Q1	0%	0%	0%	0%	0%	0%	0%	0%



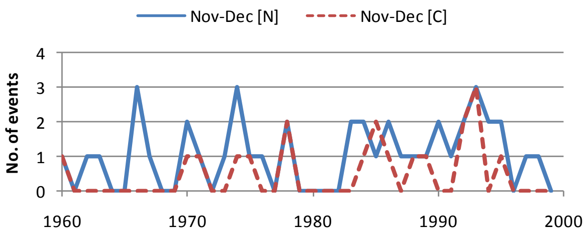


Figure 4-2. Hydrological distribution of hydraulically determined potential High flow fresh to meet Objective 2b and 2c. [N] is REALM natural series and [C] is REALM current series.

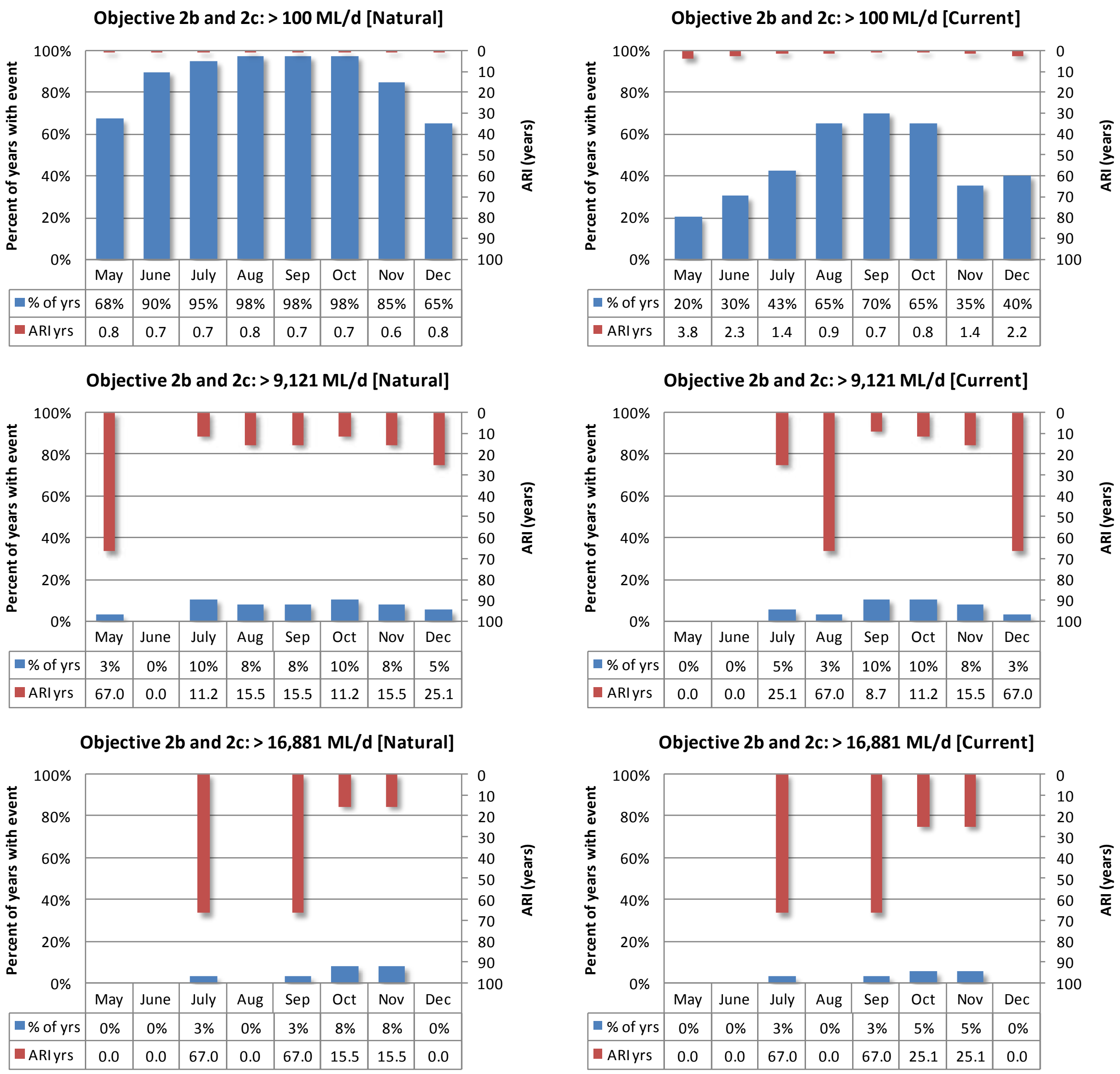


Figure 4-3. Monthly distribution of frequency of hydraulically determined potential High flow fresh to meet Objective 2b and 2c.

Table 4-2.
Objective 2b and 2c hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
High flow fresh [2b]	100	3	4	May-Oct	3 events per yr 5 yrs in 10	97%	55%
High flow fresh [2c]	100	2	2	Nov-Dec	2 events per yr 5 yrs in 10	100%	10%
Bankfull [2a & 2c]	9,121	1 in 2 yr ARI	1 day	May-Dec	na	100%	80%
Overbank [2a & 2c]	16,881	1 in 5 yr ARI	1 day	May-Dec	na	100%	74%

4.2.3 Objective 2f and 1b: Estuarine Wetland – floodplain (overbank) inundation on inside of Golf Course bend

This objective is intended to provide floodplain inundation, with four flood inundation levels required. These levels correspond to approximately 25, 50, 75 and 100 percent of the land on the inside of the Golf Course bend (Red Cliffs) becoming inundated. There was no seasonal requirement for this objective. Objective 1b is a geomorphic objective to maintain the channel and floodplain form. Overbank flows are expected to cause some scour of channel and floodplain features and redistribute sediment. The following flood magnitudes were considered:

- 6,000 ML/d fills the deeper holes and inundates the flatter bank areas (equivalent to morphological bankfull)
- 8,500 ML/d inundates approximately 25 percent of the floodplain area
- 10,000 ML/d inundates approximately 50 percent of the floodplain area
- 14,000 ML/d inundates approximately 75 percent of the floodplain area
- 18,000 ML/d inundates almost the entire floodplain area

These bankfull and overbank events were somewhat impacted by regulation, with a reduction in flood frequency being apparent in the current series (Figure 4-4). Note that, for example, an event of 2 year ARI does not have flooding in every year of record, and an event of 2 year ARI does not have flooding in 50 percent of years. Rather, because of multiple events in some years, these two example ARIs correspond to 65 percent of years and 40 percent of years with events respectively (Figure 4-4). These events all had a median duration of 1 day.

The specifications for these components (Table 4-3) were made on the basis of the statistics for the natural series.

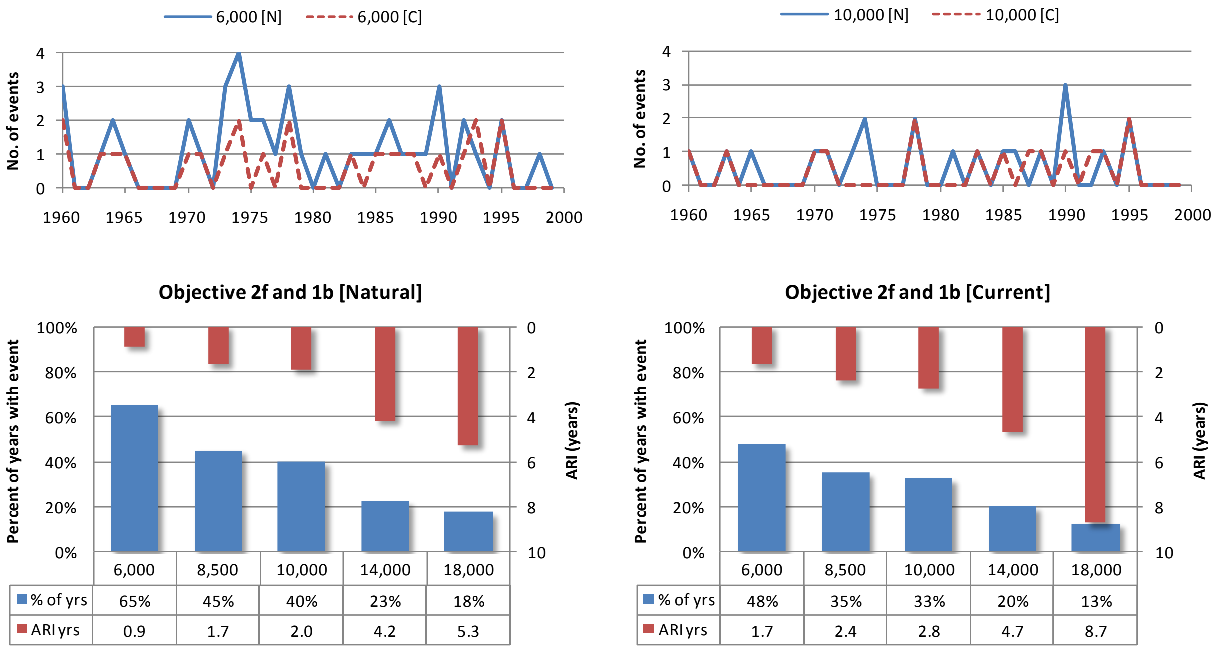


Figure 4-4. Hydrological distribution of hydraulically determined potential overbank events to meet Objective 2f and 1b. [N] is REALM natural series and [C] is REALM current series.

Table 4-3.
Objective 2f and 1b hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Overbank 1	8,500	1 in 1.7 yr ARI	1 day	Anytime	na	100%	70%
Overbank 2	10,000	1 in 2.0 yr ARI	1 day	Anytime	na	100%	71%
Overbank 3	14,000	1 in 4.2 yr ARI	1 day	Anytime	na	100%	90%
Overbank 4	18,000	1 in 5.3 yr ARI	1 day	Anytime	na	100%	61%

4.2.4 Objective 2i and 1b: Floodplain Riparian Woodland – floodplain (overbank) inundation at upstream extent of estuary

This objective is intended to promote the growth and recruitment of *Eucaplyptus camaldulensis* and growth of understorey plants located at the upstream extent of the estuary (XS20). Three events are required, one occurring more than once per year, one being 1 to 1.5 year ARI and one being approximately 5 year ARI event. The larger event will prevent terrestrialisation and promote Red Gum across the entire Riparian Woodland Zone. There was no seasonal requirement for this objective. Being overbank events, these events also satisfy the geomorphological Objective 1b. This objective allowed years without floods, but only up to a 5 year long interval.

The hydraulic analysis identified that the Woodland commenced inundation at 3,000 ML/d. The elevation of 1 mAHD is achieved at 3,124 ML/d and the elevation of 1.5 mAHD is achieved at 4,329 ML/d. At this discharge inundation has progressed to the interior of the Woodland zone. Four higher flooding thresholds were also investigated to give a total of six thresholds:

- 3,124 ML/d an elevation of 1 mAHD is achieved
- 4,329 ML/d an elevation of 1 mAHD is achieved
- 5,000 ML/d inundation deepens and becomes more extensive
- 8,000 ML/d inundation of the corner area almost complete
- 9,000 ML/d general inundation of the bend
- 14,000 ML/d full inundation of the Woodland area

These overbank events were somewhat impacted by regulation, with a reduction in flood frequency being apparent in the current series (Figure 4-5). These events all had a median duration of 1 day, except for the three lowest magnitude events which had a median duration of 2 days in the current series.

In the natural series, only the 14,000 ML/d event had intervals between flood longer than 5 years (11% of 5-year rolling sequences), while this was more common in the current series (2% for 8,000 ML/d, 7% for 9,000 ML/d, and 20% for 14,000 ML/d events).

On the basis of the calculated flood frequencies, three events were selected to provide the required conditions for the objective: 5,000 ML/d, 8,000 ML/d and 14,000 ML/d.

The specifications for these components (Table 4-4) were made on the basis of the statistics for the natural series. Note that Overbank 3 here corresponds with Overbank 3 for Objective 2f and Overbank 2 is close to Overbank 1 for Objective 2f (Table 4-3). Overbank 1 here is close to High flow fresh for Objective 2n (Table 4-7).

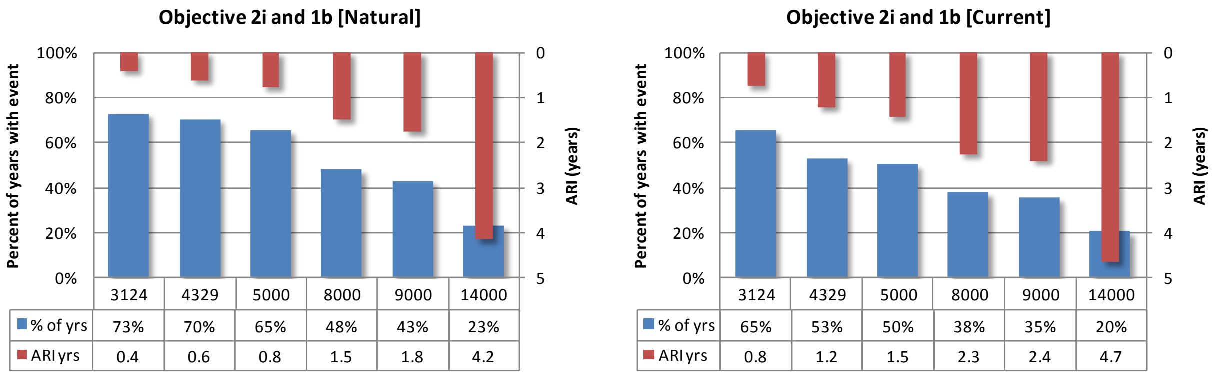


Figure 4-5. Hydrological distribution of hydraulically determined potential overbank events to meet Objective 2i and 1b. [Natural] is REALM natural series and [Current] is REALM current series.

Table 4-4.
Objective 2i and 1b hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Overbank 1	5,000	1 in 0.8 yr ARI	1 day	Anytime	na	100%	55%
Overbank 2	8,000	1 in 1.5 yr ARI	1 day	Anytime	na	100%	66%
Overbank 3	14,000	1 in 4.2 yr ARI	1 day	Anytime	na	100%	90%

4.2.5 Objective 2j: Floodplain Riparian Woodland – surface salinity of 9 in vicinity of Woodland zone

This objective requires maintenance of surface water salinity of less than 10. This is a baseflow component and applies for the entire year, so it is both a Low flow and High flow component. The hydraulic model indicated that the objective was met by flows of at least 9 ML/d.

The distributions of flows greater than the threshold were examined for each month (Figure 4-6). This clearly indicated two of the major impacts of regulation. Firstly, winter baseflows are reduced in the current series, but not so much that flows greater than the threshold of 9 ML/d are affected (the exceptions being August and September). Secondly, although one of the summer passing flows from Werribee Diversion Weir is 1 ML/d, if the irrigation allocation is greater than 130 percent, the release is 10 ML/d, which is just above the threshold for Objective 2j. Apparently the 10 ML/d passing flow was active for most of the summers in the modelled time series, although this has not been the case in recent years (most of which are not represented in the REALM time series, which ends in 1999). Thus, the statistics indicate that overall, the duration of summer low flows exceeding 9 ML/d has been longer under the regulated regime than under the natural regime (Figure 4-6).

The percentage of time in summer that flows exceeded the 9 ML/d threshold was highly variable throughout the natural time series (Figure 4-6). The years where the irrigation allocation was persistently below 130 percent and the passing flow was reduced to 1 ML/d are apparent – there were only 8 such years in the time series (Figure 4-6).

The specifications for these components (Table 4-5) were made on the basis of the statistics for the natural series.

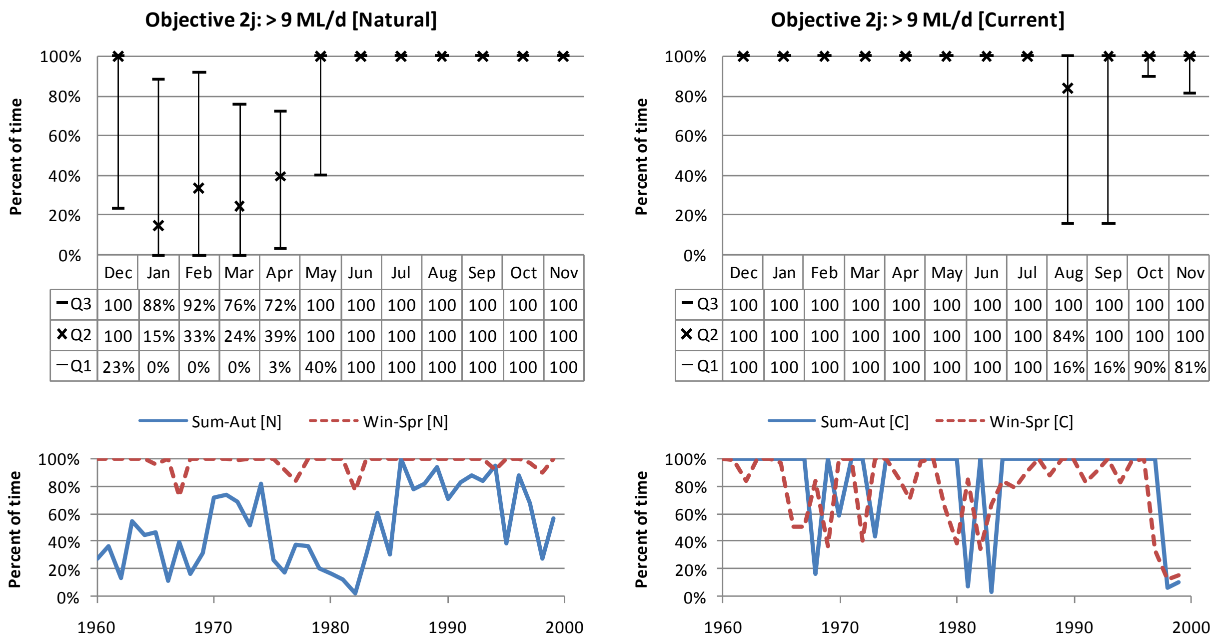


Figure 4-6. Hydrological distribution of hydraulically determined potential Low flow and High flow components to meet Objective 2j. [N] is REALM natural series and [C] is REALM current series.

Table 4-5.
Objective 2j hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Low flow	9	na	All season or natural if less	Dec-May	30% of the time 5 yrs in 10	90%	100%
High flow	9	na	All season or natural if less	Jun-Nov	100% of the time 5 yrs in 10	100%	10%

4.2.6 Objective 2k and 2m: Seagrass Meadow – salinity at least 15 and low turbidity up to Red Cliffs

This objective covers all seasons. The objective requires high salinity and low turbidity water suitable for seagrass to extend up the estuary to Red Cliffs. The hydraulic model indicated that this can be achieved by flow being less than 50 ML/d. Obviously, due to seasonality of flows, the upstream extent of the desirable level of salinity will naturally vary throughout the year, with the upstream extent being greater in summer compared to winter. Also, this objective would be assisted by any form of regulation that reduced baseflows. For this objective, the hydrology was examined for each of the four main hydrological seasons. This objective is for an upper limit on baseflow, so for the winter seasons it is counterpoint to the High flow component and for the summer seasons it is a counterpoint to the Low flow component. (Note that Objective 2a requires a Low flow component for flow greater than 49 ML/d magnitude). This means that while the Low flow and High flow components are still required in the estuary (i.e. flow exceeding a baseflow threshold), this component refers to the period of time when flow is less than the given threshold.

In the natural series, there was a clear seasonal demarcation of this flow component (Figure 4-7). In summer and autumn it was met most of the time, but it was not often met in winter and spring (Figure 4-7). In the current series, regulation has reduced baseflows markedly, causing this component to be met more often, with the biggest change occurring the in the winter and spring months (Figure 4-7).The percent of time that flow was less than 50 ML/d was variable throughout the time series, but under regulation variability reduced in summer and autumn and increased in winter and spring (Figure 4-7).

The annual and inter-annual specifications for these components (Table 4-6) were made on the basis of the statistics for the natural series. Note that these components easily comply in the current series.

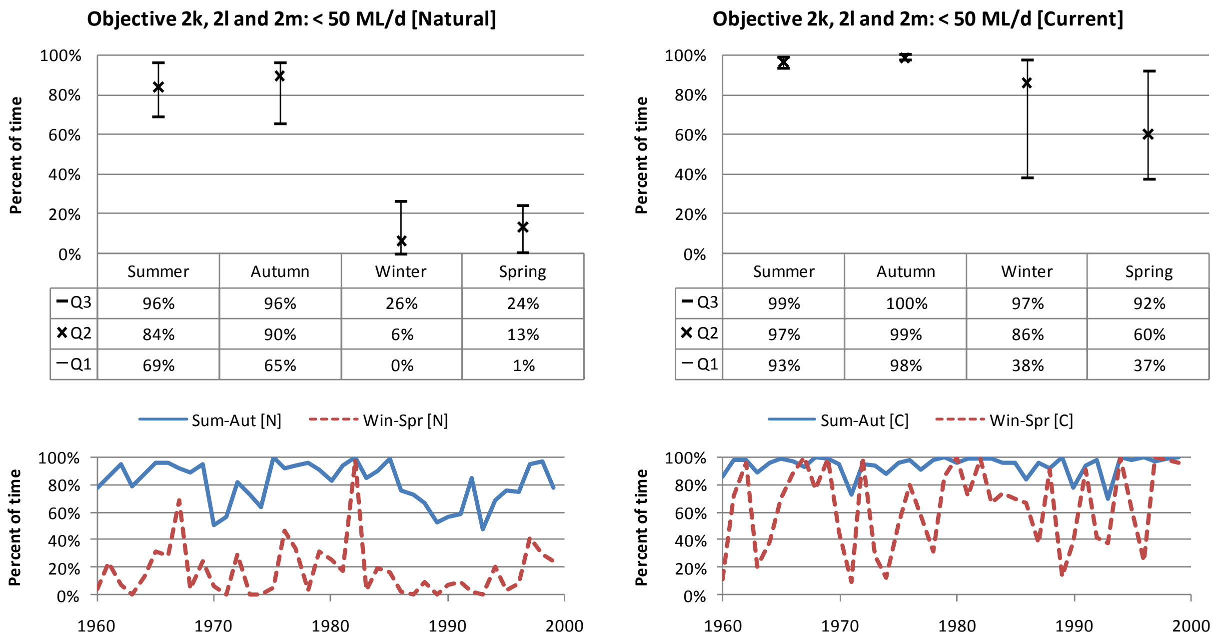


Figure 4-7. Hydrological distribution of hydraulically determined potential upper baseflow limit to meet Objective 2k. [N] is REALM natural series and [C] is REALM current series.

Table 4-6.
Objective 2k and 2m hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Low flow	≤ 50	na	Only when other components not required	Dec-May	65% of the time 5 yrs in 10	100%	100%
High flow	≤ 50	na	Only when other components not required	Jun-Nov	5% of the time 5 yrs in 10	97%	100%

4.2.7 Objective 2n and 1c: Seagrass Meadow – mobilise sediments on bed downstream of Red Cliffs

This objective requires that accumulated sediments are removed from the base of seagrass beds downstream of Red Cliffs. This aligns with the geomorphology objective 1c, which is to mobilise the bed material in order to maintain channel form and physical habitat quality for benthic fauna. The hydraulic model determined that this could be achieved with a flow exceeding 5,500 ML/d, with the objectives not requiring any particular seasonality. The magnitude of this event is such that it does not cause significant overbank inundation, so it is termed High flow fresh, even though it can occur in any season.

The median duration of these events in the natural series was 1 day and 1.5 days in the current series. The frequency was 0.9 years ARI in the natural series and 1.6 years ARI in the current series. So, while there has been a reduction in the frequency of this component with regulations, it still occurs reasonably frequently (Figure 4-8).

The specifications for this component (Table 4-7) were made on the basis of the statistics for the natural series.

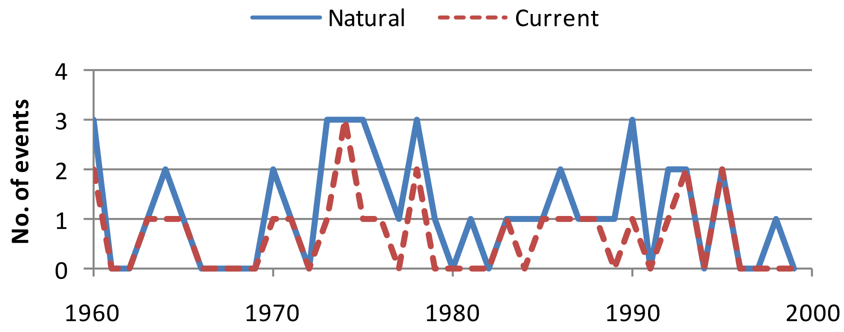


Figure 4-8. Time series of occurrence of events >5,500 ML/d to meet objectives 2n and 1c for the REALM natural and current series'.

Table 4-7.
Objective 2n and 1c hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
High flow fresh	5,500	1 (1 in 0.9 yr ARI)	1 day	Anytime	na	100%	57%

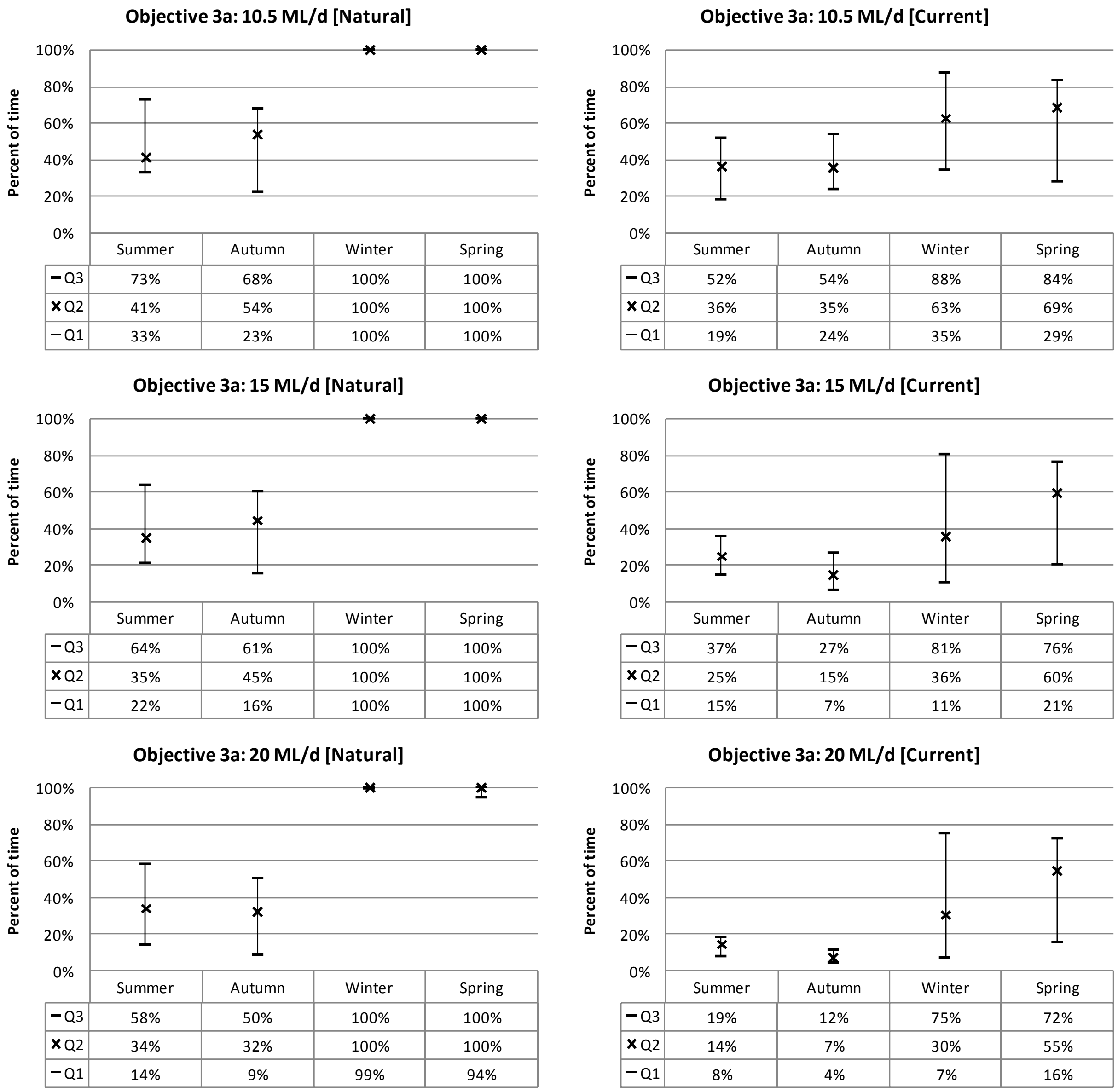
4.1 Fish Objectives

4.1.1 Objective 3a: Black Bream – salinity range 5 to 30 over at least 50 percent of length for 80 percent of the time

A flow of 10.5 ML/d was estimated to create estuarine salinity conditions for at least 50 percent of the estuary length, but in terms of area, the estuary was still constrained under this flow. Thus, two other thresholds were examined: 15 ML/d and 20 ML/d. These thresholds were examined for each of the four main seasons. This objective relates to baseflow conditions, so is both a Low flow and High flow component.

The natural series showed quite a marked demarcation between winter and summer seasons for the flow thresholds (Figure 4-9). The same degree of distinction was not apparent in the current series, mainly because of the reduced winter baseflows. The Natural series was not particularly sensitive to the thresholds over the range 10.5 to 20 ML/d (Figure 4-9). Certainly, for winter this threshold was exceeded nearly all of the time. In the summer periods these thresholds were exceeded for at lest 30 percent of the time in most years. The current series showed reduced duration for the two higher thresholds (Figure 4-9). These results indicate that the threshold of 10.5 ML/d would be easier to meet in the current arrangements due to the conditional 10 ML/d passing flow at Werribee Weir. However, a larger area of suitable estuarine conditions is created by a flow of 20 ML/d.

The recommended baseflow was 15 ML/d (Table 4-8). This flow provides for a margin or error in the hydraulic model prediction and creates an expansion of estuarine area over that predicted to occur at 10.5 ML/d. It is important to recognise that there is no possibility of supplying this flow component for 80 percent of the time in summer-autumn. This recommended duration did not occur in the natural series, which was characterised by very low summer flows, 41 percent of years experiencing a period of negative hydrological balance (evaporation exceeding inflows), and frequent cease-to-flow (see Issues Paper, Lloyd et al., 2007b). Thus, although the recommended Low flow was 15 ML/d, it should not be expected that this will be achieved very often in summer-autumn period. Under the 'or natural' recommendation for baseflows, the summer-autumn flow will be less than 15 ML/d in most years for somewhere between 25 and 75 percent of the time.



Objective 3a: 10.5 ML/d [Natural]

	Summer	Autumn	Winter	Spring
Q3	73%	68%	100%	100%
Q2	41%	54%	100%	100%
Q1	33%	23%	100%	100%

Objective 3a: 10.5 ML/d [Current]

	Summer	Autumn	Winter	Spring
Q3	52%	54%	88%	84%
Q2	36%	35%	63%	69%
Q1	19%	24%	35%	29%

Objective 3a: 15 ML/d [Natural]

	Summer	Autumn	Winter	Spring
Q3	64%	61%	100%	100%
Q2	35%	45%	100%	100%
Q1	22%	16%	100%	100%

Objective 3a: 15 ML/d [Current]

	Summer	Autumn	Winter	Spring
Q3	37%	27%	81%	76%
Q2	25%	15%	36%	60%
Q1	15%	7%	11%	21%

Objective 3a: 20 ML/d [Natural]

	Summer	Autumn	Winter	Spring
Q3	58%	50%	100%	100%
Q2	34%	32%	100%	100%
Q1	14%	9%	99%	94%

Objective 3a: 20 ML/d [Current]

	Summer	Autumn	Winter	Spring
Q3	19%	12%	75%	72%
Q2	14%	7%	30%	55%
Q1	8%	4%	7%	16%

Figure 4-9. Hydrological distribution of hydraulically determined potential baseflow thresholds to meet Objective 3a. [Natural] is REALM natural series and [Current] is REALM current series.

Table 4-8.
Objective 3a hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Low flow	15	na	All season or natural if less	Dec-May	20% of the time 5 yrs in 10	97%	71%
High flow	15	na	All season or natural if less	Jun-Nov	100% of the time 5 yrs in 10	100%	10%

4.1.2 Objective 3b: Black Bream – presence of a halocline, and surface salinity less than 20 no further downstream than 1 km upstream from entrance

This objective is intended to provide conditions suitable for spawning and egg survival. The relevant season is September to December. This component required the presence of a halocline, which was defined as a region where surface water salinity was less than 10 and the bottom water salinity was greater than 25. The hydraulic model indicated that this objective would be met while flows were less than 40 ML/d. Thus, this component represents an upper limit on spring High flows. To provide additional data, three thresholds were examined: 30 ML/d, 40 ML/d and 50 ML/d. It is noted that the hydraulic model predicted that at 50 ML/d, the surface salinity of 20 on the ebb tide (spring) is found at the entrance. Theoretically then, flows greater than 50 ML/d create conditions where this objective is not met at all in the estuary.

The flow series' were not particularly sensitive to variations in the threshold between 30 and 50 ML/d. It is apparent that in the natural series, this objective was not often met (Figure 4-10). In the current series the objective is met more frequently due to regulation reducing the spring baseflows. The flow component showed considerable variability in the time series, with variability higher in the current series (Figure 4-10).

More often than not, in the natural series, this flow component was not met. The recommendation for this component was set in line with the duration apparent in the natural series, which means that this component easily complied in the current series (Table 4-9).

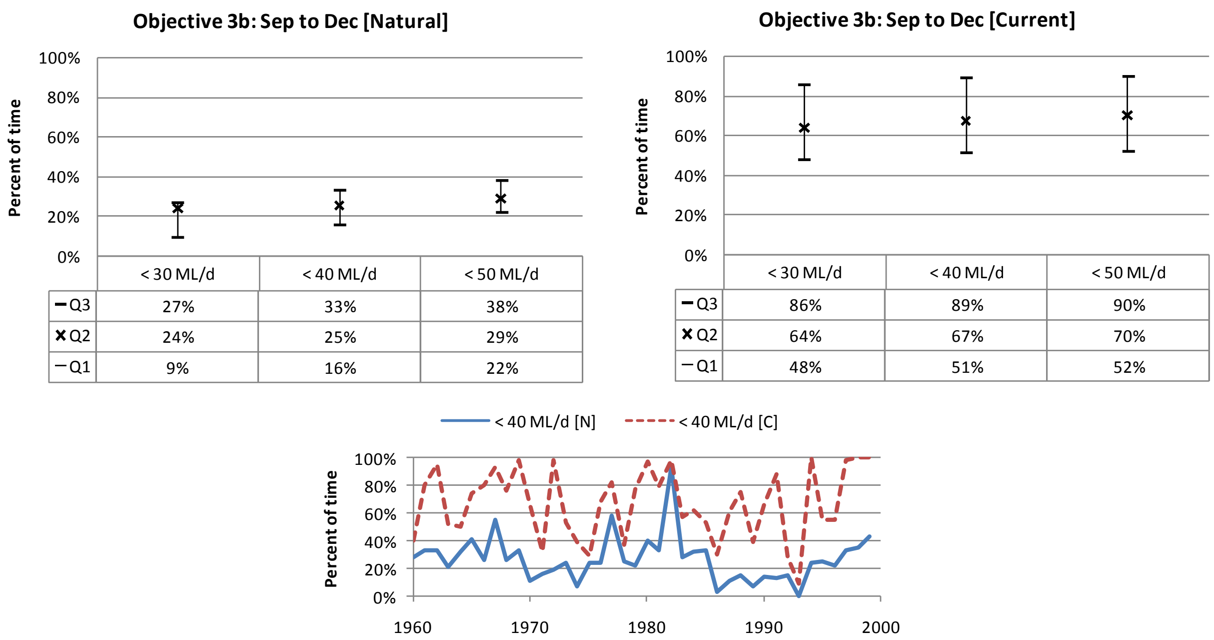


Figure 4-10. Hydrological distribution of hydraulically determined potential upper baseflow thresholds to meet Objective 3b. [Natural] is REALM natural series and [Current] is REALM current series.

Table 4-9.
Objective 3b hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Low flow	≤ 40	na	Only when other components not required	Sep-Dec	15% of the time 5 yrs in 10	90%	100%

4.1.3 Objective 3c: Black Bream – halocline present between 1 and 2.75 km upstream from entrance

This objective is intended to provide refuge and feeding for settlement and post-settlement juveniles. The hydraulic model predicted that the minimum discharge required to meet this objective was 50 ML/d and to reduce the degree of washout the maximum discharge was 80 ML/d. The relevant season is September to December. This flow component was interpreted as a High flow fresh. As such, it requires to be defined with event duration and annual frequency. Three event durations were considered: 1, 2 and 3 days.

These events, being constrained to a narrow discharge band, were of short duration. Setting the minimum required duration to 1 day gave a median event duration of 2 days in the natural series. Setting the minimum duration to 2 days gave a median event duration of 3 days, and setting the minimum duration to 3 days gave a median event duration of 4 days. In the current series, the median event durations were one day shorter than in the natural series.

The flow component showed considerable inter-annual variability in both the natural and current series' (Figure 4-11). The effect of increasing the event duration requirement was to markedly reduce the frequency of the events (Figure 4-11). It was the very narrow allowable discharge band which made this flow component quite uncommon for events with a duration of more than 1 day.

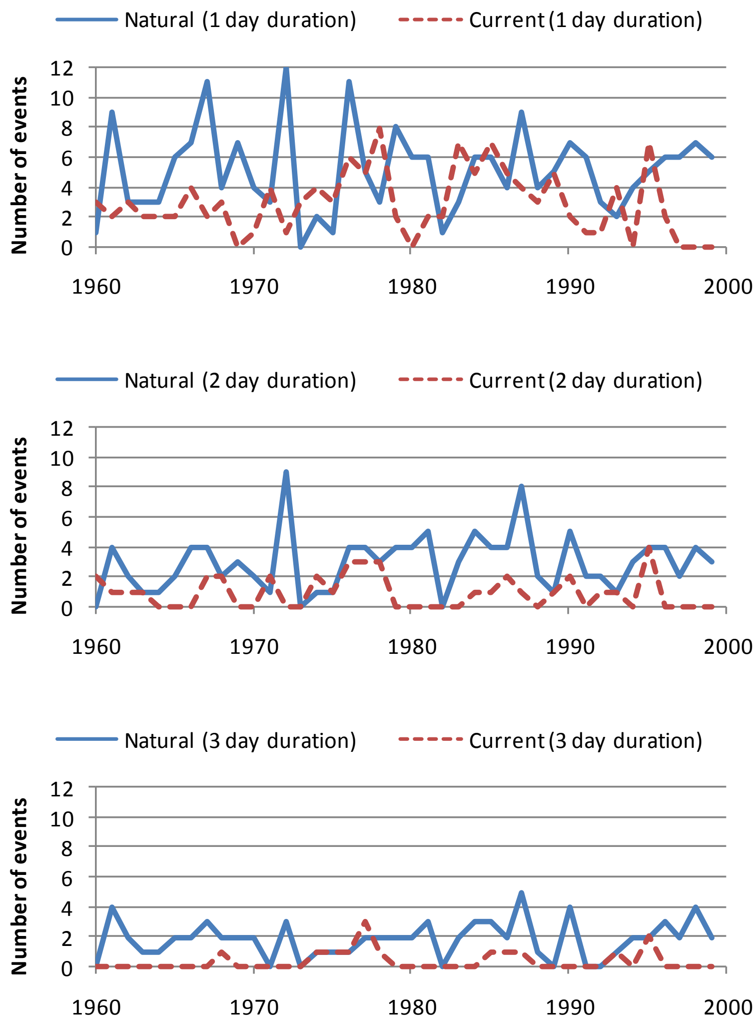


Figure 4-11. Hydrological distribution of hydraulically determined potential baseflow component to meet Objective 3c. [Natural] is REALM natural series and [Current] is REALM current series.

Table 4-10.
Objective 3c hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
High flow fresh	50 < Q < 80	2	2	Sep-Dec	2 events per year 5 yrs in 10	100%	16%

4.1.4 Objective 3e: King George Whiting – salinity greater than 25 in bottom water and maximum residence time 2 days for water deeper than halocline (bottom 1 m) downstream of 2.75 km from entrance

This objective was intended to provide larval fish habitat in the lower end of the estuary. The hydraulic model indicated that these conditions would be met by freshwater inflows less than 59 ML/d. The relevant season is the spring – summer period. As spring and summer were hydrologically distinct in the natural series, these two periods were analysed separately.

In the natural series, the flow component was met much more often in summer than in spring (Figure 4-12). This difference was less stark in the current series, owing to regulation reducing spring baseflows. There was a high degree of variability in the time series for this component for the spring period.

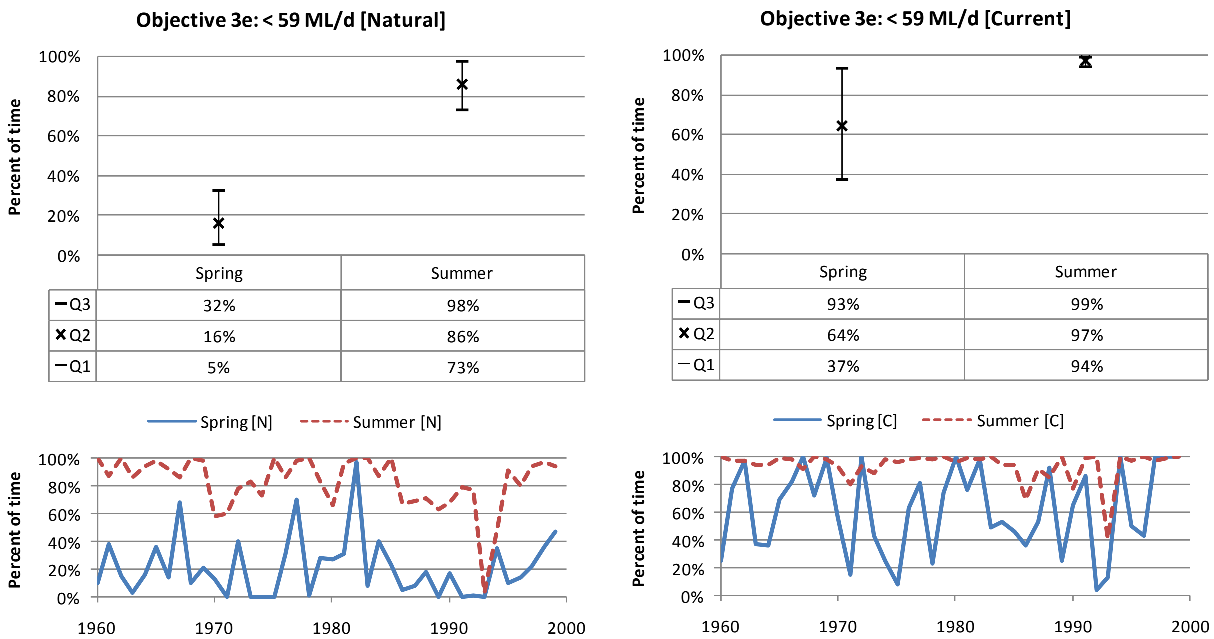


Figure 4-12. Hydrological distribution of hydraulically determined potential upper baseflow limit to meet Objective 3e. [N] is REALM natural series and [C] is REALM current series.

The specifications for this component (Table 4-11) were made on the basis of the statistics for the natural series. The recommendations were different for the spring and summer periods.

Table 4-11.
Objective 3e hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
High flow	≤ 59	na	Only when other components not required	Sep-Nov	10% of the time 5 yrs in 10	84%	100%
Low flow	≤ 59	na	Only when other components not required	Dec-Feb	70% of the time 5 yrs in 10	94%	100%

4.1.5 Objective 3f: Common Jollytail – access over ford for migration

This component allows Common Jollytail access for migration from river to estuary in autumn. The hydraulic requirement is 0.3 m over the thalweg. As autumn is a low flow period, a second hydraulic threshold was evaluated, being 0.2 m over the thalweg. A simple estimate using the Manning equation suggested that the threshold flow was 174 ML/d for 0.3 m flow depth and 89 ML/d for 0.2 m flow depth. These are the minimum flows required to allow fish passage. As this is an event rather than a baseflow, the flow component was evaluated for three event durations: 1, 2 and 3 days.

Events of 0.3 m depth fish passage over the ford in autumn were not particularly common in the natural series, particularly for events longer than one day duration (Figure 4-13). There was high inter-annual variability in the time series of these events. In the current series the frequency of these events was markedly reduced (Figure 4-13). Lowering the depth requirement to 0.2 m significantly increased the frequency of events, but they still did not occur every year (Figure 4-13).

The flow recommendation was based on meeting the requirement of 0.3 m depth (174 ML/d) (Table 4-12), even though it will not be possible to meet this every year, and the event durations will be low.

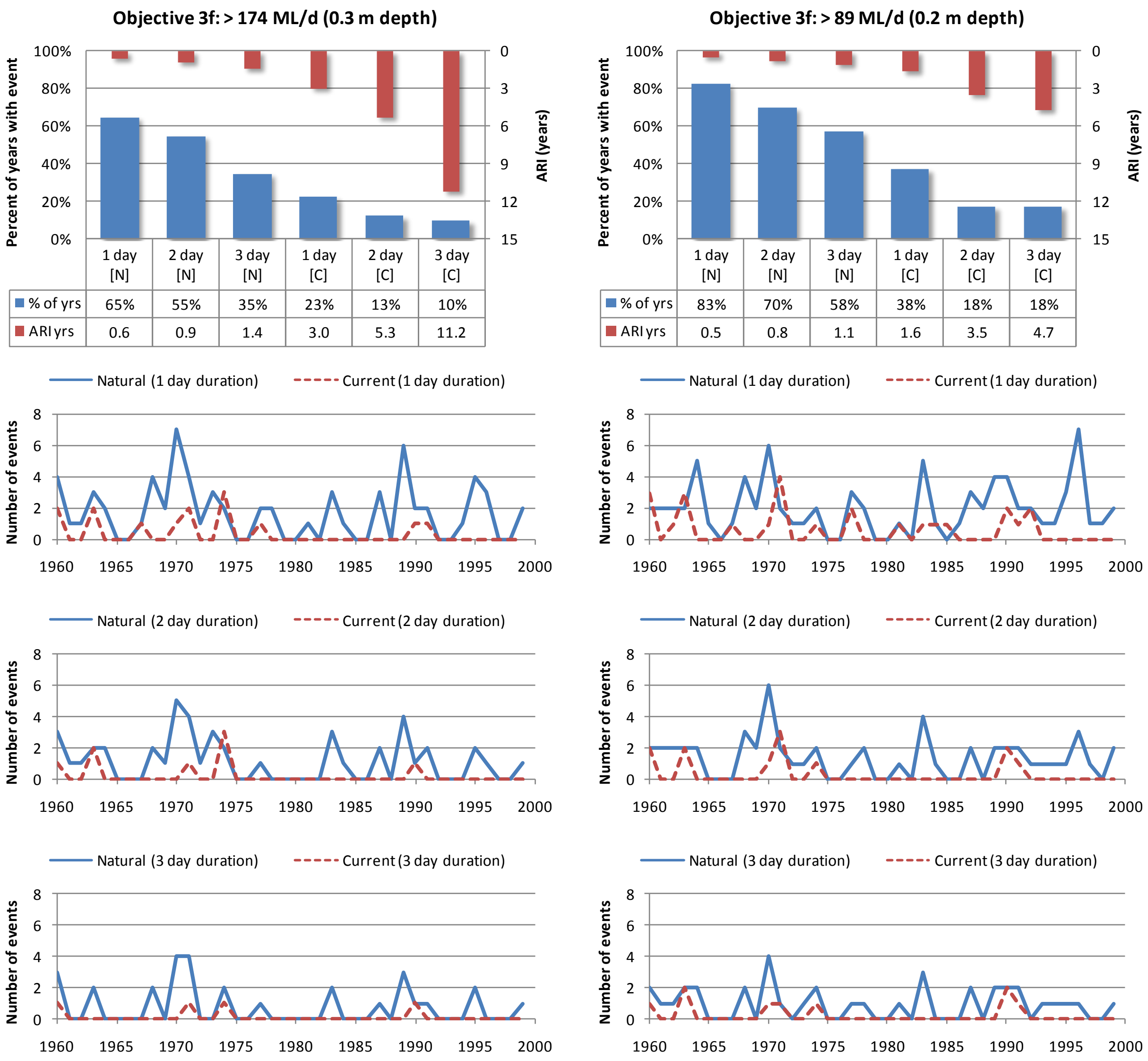


Figure 4-13. Hydrological distribution of hydraulically determined potential components to meet Objective 3f. [N] is REALM natural series and [C] is REALM current series.

Table 4-12.
Objective 3f hydrological specifications. Unless specified, requirements are minimums.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance	
						Natural	Current
Low flow fresh	174	1	1	Mar-May	1 event per year 5 yrs in 10	97%	0%

5 FLOW RECOMMENDATIONS

The following sections outlines the flow requirements to met the range of ecological and geomorphological objectives established by this project. Each section has explanatory text followed by a table of the requirements. Unless specified, flow requirements listed are minimums.

5.1 Low Flows

Low flows represent the baseflow component of estuary inflow hydrology in the summer-autumn period.

Low flows must be specified to regulate the salinity of the estuary, which is important to Black Bream (**Objective 3a**). These fish will only remain in the estuary while salinities exceed 5 in the summer-autumn period. It is recommended that salinity exceeds 5 in most of the estuary (50%) for most of the time (65%), which requires a flow of ≤ 50 ML/d between December and May.

Submerged and emergent aquatic vegetation is an important part of the upstream section of the estuary. These plants are predominantly freshwater species and rely on persistent, low flows in summer and autumn to maintain freshwater conditions (**Objective 2j**). This is achieved by a discharge of more than 9 ML/d.

The low coastal salt marsh requires inundation (**Objective 2c**) with relatively fresh water (**Objective 2a**) to maintain a diverse plant community. Suitable river salinities of less than 14 are achieved at the mouth at a discharge more than 49 ML/d. At this discharge, the marsh habitat will be subject to frequent inundation (at an inflow of 1 ML/d water levels exceed the 0.25 m AHD threshold to inundate the habitat 2% of the neap-spring tide cycle, and 59% of the cycle at an inflow of 100 ML/d). At an intermediate flow of 49 ML/d, regular inundation will occur to provide reliable shallow flooding.

Habitat for larval King George Whiting requires the provision of saline water (greater than 25) below the halocline in the lower end of the estuary (**Objective 3e**). These conditions are achieved when estuary inflows are less than 59 ML/d and should be provided at least 80% of the time in the summer-autumn period. Similar salinities support seagrass communities by maintaining the required ambient salinity (**Objective 2k**) and clear-water conditions (**Objective 2m**).

The geomorphic objective to maintain salt wedge dynamics (**Objective 1a**) is implicitly achieved by the recommendations for **Objectives 3a and 3e**.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance		Flow Objectives	
						Natural	Current	Primary	Secondary
Low flow	9	na	All season or natural if less	Dec-May	30% of the time 5 yrs in 10	90%	100%	2j	
Low flow	49	na	All season, or natural if less	Dec-May	10% of the time 5 yrs in 10	81%	0%	2a, 2c	
Low flow	≤ 50	na	Only when other components not required	Dec-May	65% of the time 5 yrs in 10	100%	100%	3a	
Low flow	≤ 59	na	Only when other components not required	Dec-Feb	70% of the time 5 yrs in 10	94%	100%	3e	2k, 2m, 1a

5.2 Low Flow Freshes

Low flow freshes represent the elevated flows which occur in the summer-autumn period following rain events. These events provide a migration cue for Common Jollytail (**Objective 3**f). To successfully negotiate their way from the estuary to the riverine reaches of the catchment, freshes must provide a depth of more than 0.2 m at the ford. A frequency of 2 events in autumn, each of 2 days duration is recommended to support reliable migration events. This objective is met by a flow magnitude of 89 ML/d.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance		Flow Objectives	
						Natural	Current	Primary	Secondary
Low flow fresh	89	2-4	2	Mar-May	1 event per year 5 yrs in 10	70%	5%	3f	

5.3 High Flows

High flows represent the baseflow component of estuary inflow hydrology in the winter-spring period. As described above, saline conditions must be maintained in the estuary to provide Black Bream habitat (**Objective 3a**). If salinity is too low, fish will leave the estuary. It is recommended that salinity exceeds 5 in most of the estuary (50%) for most of the time (80%), which requires a flow of 15 ML/d between December and May.

Submerged and emergent riverine, aquatic vegetation is an important part of the estuary upstream of the reef. These plants are predominantly freshwater species and rely on persistent, low flows in summer and autumn to maintain freshwater conditions (**Objective 2j**). This is achieved by a discharge of more than 9 ML/d, and is therefore achieved and exceeded by the recommended flow of 15 ML/d for **Objective 3a**.

Spawning and egg survival in Black Bream requires a persistent halocline in the estuary (**Objective 3b**). To provide surface water salinity less than 10 and a bottom salinity more than 25 can only be maintained while estuary inflows are less than 40 ML/d and this objective places an upper limit on spring High flows between September to December.

A salinity of more than 25 within 1 m of the bottom is also required by King George Whiting larvae in the spring period (**Objective 3e**). This is maintained while flow is less than 59 ML/d, and is therefore also met by the the flow recommendation for Objective 3b.

Seagrass require a salinity of more than 15 in the early winter-spring period to support growth (**Objective 2k**) and clear-water conditions (**Objective 2m**). A flow of less than 50 ML/d will ensure a salinity of more than 15 upstream as far as Red Cliffs

The geomorphic objective to maintain salt wedge dynamics (**Objective 1a**) is implicitly achieved by the recommendations for **Objectives 2j. 2k, 2m 3a, 3b and 3e.**

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance		Flow Objectives	
						Natural	Current	Primary	Secondary
High flow	15	na	All season or natural if less	Jun-Nov	100% of the time 5 yrs in 10	100%	10%	3a	2j (9ML) 1a
High flow	≤ 40	na	Only when other components not required	Sep-Dec	15% of the time 5 yrs in 10	90%	100%	3b	3e, 1a
High flow	≤ 59	na	Only when other components not required	Jun-Nov		97%	100%	2k and 2m, 3e	1a

5.4 High Flow Freshes

Without flushing flows, seagrass is vulnerable to smothering by bottom sediment. These flows also maintain the depth and shape of the estuary channel. Flows required to mobilise bed material to maintain seagrass beds (**Objective 2n**) and maintain channel form (**Objective 1c**) must exceed 5,500 ML/d and may occur at any time of year. Such flows occur with an annual recurrence interval of 0.9.

Intermittent inundation (**Objective 2b**) of the coastal salt marsh is required in winter-spring. A lower salinity of 4 (**Objective 2a**) is recommended as the target, which is only achieved at flows exceeding approximately 100 ML/d. These events are required at least 5 times per season.

The geomorphic objective to maintain salt wedge dynamics (**Objective 1a**) is implicitly achieved by the recommendation for **Objectives 2a and 3c.**

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance		Flow Objectives	
						Natural	Current	Primary	Secondary
High flow fresh	50 < Q < 80	2	2	Sep-Dec	2 events per year 5 yrs in 10	100%	16%	3c	
High flow fresh	100	8	1	May-Dec	8 events in 50% of years			2a, 2b	1a
High flow fresh	5,500	1 (1 in 0.9 yr ARI)	1 day	Anytime	na	100%	57%	2n and 1c	

5.5 Overbank Flows

Large, infrequent overbank flows are responsible for many of the physical habitat features in the estuary (**Objective 1b**). These flows have sufficient energy to transport sediment from the main channel, maintaining its width, depth and form. Overbank flows also deposit material on the floodplain, maintaining the depth of floodplain sediments and floodplain physical habitat features. Overbank flows are defined by the lowest flow at which the bank is overtopped - 5,000 ML/d - and are required at the natural frequency to maintain the natural channel form.

The estuary floodplain supports vegetation which depends on intermittent flooding - a *Eucalyptus camaldulensis* and *Phragmites australis* community at K Road (**Objective 2f**) and the Riparian Woodland (**Objective 2i**) adjacent to the golf course (XS20). Inundation will fill billabongs, promote vegetation growth and provide aquatic habitat for a range of floodplain fauna including frogs and waterbirds. An annual flow of 5,000 ML/d is recommended to fill peripheral channel depressions and flats at the edge of the channel. A larger, less frequent flow of 8,500 ML/d is recommended to inundate 25% of the floodplain and sustain plant communities in lower-lying areas. An infrequent flow of 18,000 ML/d inundates almost the entire floodplain. The natural frequency for these events, 1 in 5.3 years, should be maintained.

Component	Magnitude (ML/d)	Frequency (per season)	Duration (days)	Season	Inter-annual frequency	Compliance		Flow Objectives	
						Natural	Current	Primary	Secondary
Overbank	5,000	1 in 0.8 yr ARI	1 day	Anytime	na	100%	55%	2f, 2i	
Overbank	8,500	1 in 1.7 yr ARI	1 day	Anytime	na	100%	70%	2f, 2i 1b	
Overbank	18,000	1 in 5.3 yr ARI	1 day	Anytime	na			2f, 2i, 1b	

5.6 Recommendations Not Required

A number of objectives that were proposed in the Issues Paper did not require flow objectives. These objectives are summarised in Table N. below.

Objective	Reason for No Objective
2g	Groundwater-related objective. Is not directly controlled by flow.
2l	Relates to normal tidal water level range
2k	Groundwater-related objective. Is not directly controlled by flow.
2h	Groundwater-related objective, Is not directly controlled by flow.
2e	Groundwater-related objective. Is not directly controlled by flow.
2d	Groundwater-related objective. Is not directly controlled by flow.
3d	Relates to estuary entrance opening. Not relevant at Werribee River.

6 CONCLUSIONS

The method adopted for the estuary flow determinations included site inspections, defining zones and habitats in the estuary, identifying groups of fish and plants with similar flow requirements, developing conceptual models of ecology-flow relationships and using the expertise of a broad scientific panel to make flow recommendations.

Fourteen important flow components have been identified with detailed flow specifications for the Werribee Estuary. Cease to flows events did occur in the Werribee Estuary but are not required by any ecological objective. The low flow regime is very important with 4 specifications made to meet specific requirements for vegetation and fish ecology. High flows are important to maintain the depth and shape of the estuary channel, to flush sediment from seagrass and vegetation as well as ecological objectives for aquatic vegetation. One low flow and three high flow freshes are recommended to meet fish migration and breeding triggers well as ecological objectives for coastal salt marsh. Three overbank events are recommended to briefly inundate riparian trees and shrubs and to maintain the geomorphology of the estuary channel.

This pilot application of the draft Estuary FLOWS method has shown that it is capable of producing flow recommendations for the estuary although with some refinements of the method. Detailed information on the method refinements will be found in a subsequent report "Estuary FLOWS Method Report."

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8 APPENDIX 1 – TOPOGRAPHIC SURVEY

Topographic survey was undertaken by Redborough Mapping Service in August 2007. The survey data was reduced to Australian Height Datum (AHD) and is provided in digital form on the accompanying data disc to the report.

8.1 Site locations

See attached maps (Figure 8-1 and Figure 8-2).

8.2 Specification

- Survey cross-sections at locations indicated on accompanying maps.
- Surveys to provide sufficient detail to characterise the detailed morphology of the channel and a short distance onto the accompanying floodplain (to enable cross-section to be tied into existing 0.25 m floodplain contours)
- All cross-sections within a site to be surveyed to AHD and point locations given in UTM (GDA 94)
- Convention is left bank on left, looking downstream.
- Cross-sections to be at right angles to the general direction of flow in the channel (as per lines shown on accompanying maps).
- Cross-section survey to extend as indicated on each map (and as described in point 2 above).
- Surveys to include water surface elevation on the day of the survey (indicating the time of day when the survey as made).
- As a minimum, the data must be provided in text file format (either comma separated values, .csv, or tab delimited, .txt) and in GIS format (either ARCGIS or MapInfo are acceptable).
- Hard copy plans are NOT required but an electronic report is required with a brief description of the work including:
    - identification of projections, height controls, and statement of positional and level accuracy/precision;
    - plans of survey data;
    - tables of all data recorded; and
    - survey dates and equipment used.

Notes:

The attached plans show the location of 21 primary cross-sections, 11 secondary cross-sections and 1 long-profile (see Figure 8-1 and Figure 8-2). Please note that these cross-section have been carefully located to pick up the principal features of the estuary channel, but are not intended to be prescriptive to the metre, but indicate the location (and bearing) of the cross-section to within about +/-10 metres.

Ideally we would like a survey of all of the cross-sections shown. However, costs are an issue in this study and therefore please provide a quotation for each of the following two scenarios:

Scenario 1:
Survey of 21 Primary Cross-Sections + Primary Long Profile (see Figure 8-1)

Scenario 2:
Survey of 32 Primary and Secondary Cross-Section + Primary Long Profile

NOTE: Scenario 1 was selected based on the quotations received.

8.3 Survey – Technical Details

The Horizontal reference grid was MGA 94 Zone 55.

The Vertical reference was Australian Height Datum.

The hydrographic survey equipment was the Ceeman data measurement and recording system, which provides full hydrographic standard survey measurement and will meet or exceed the IHO S-44 Order 1 specification.

This equipment was specifically designed for use in shallow water and can measure depths to as little as 0.6m below the surface.

All standard checks of equipment performance, as specified by IHO S44, were applied and recorded during the course of field operations.

Data reduction for tide was provided by the Ceedata system which provides for the quality assurance of the data by software routines that allow the verification of the horizontal and vertical recorded measurements.

Horizontal accuracy of the DGPS is +/-1m. Vertical accuracy of the single beam, duel frequency transducer is +/- 0.1m on both frequencies.

NKGPS (Networked Kinermatic Global Positioning System) Survey is used for land survey and is accurate to +/- 20mm in al 3 dimensions. This system was used to provide sufficient detail of the banks to enable cross sections to be tied to existing contours.

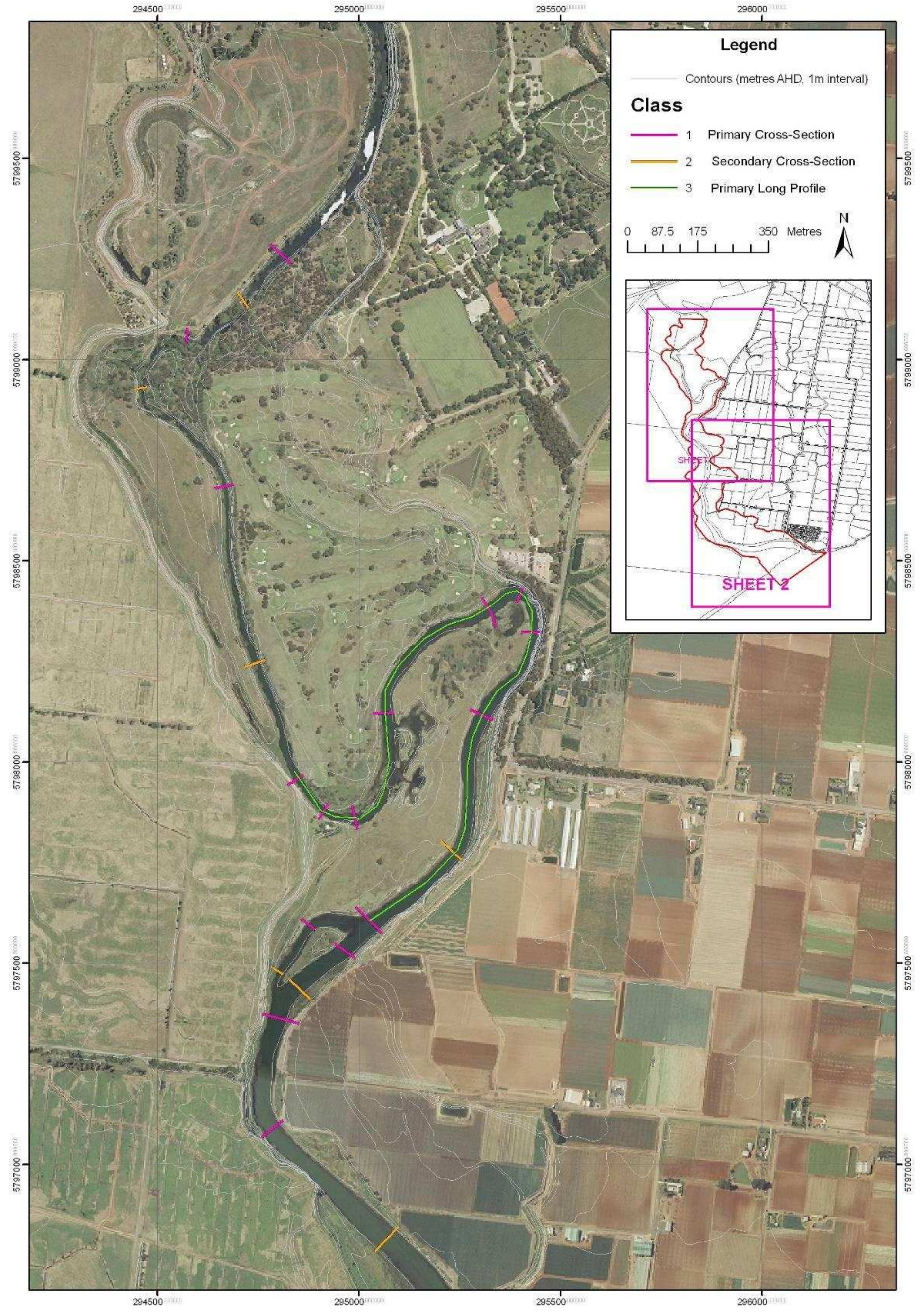

Figure 8-1 Definition of cross-section locations at the upper end of the Werribee River Estuary

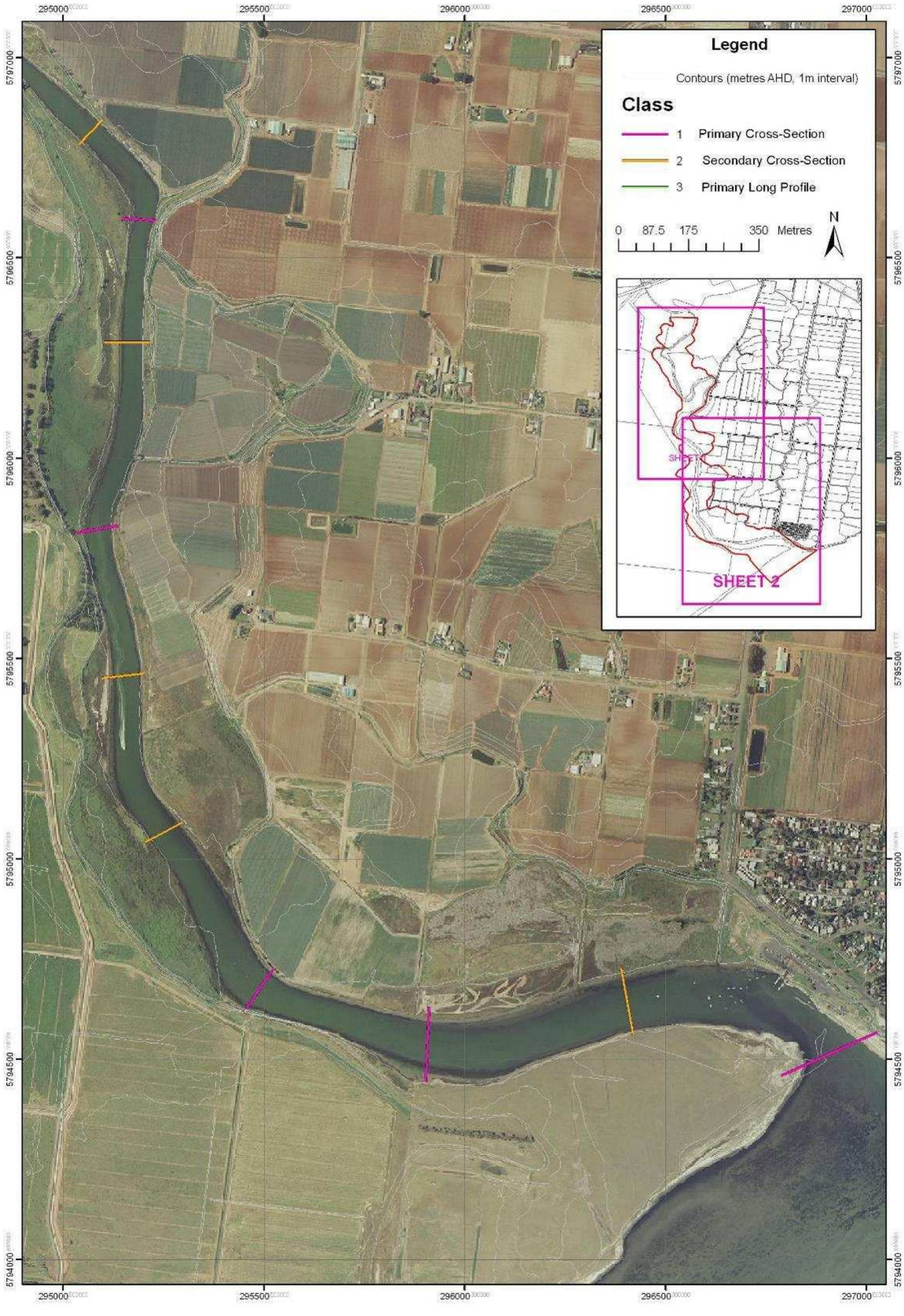

Figure 8-2. Definition of cross-section locations at the lower end of the Werribee River Estuary

9 APPENDIX 2 – DETAILED HYDRAULIC ANALYSES

This section presents a detailed report on the hydraulic modelling work undertaken for this project, including discussion of existing knowledge relevant to the hydrodynamics of the Gellibrand River Estuary.

To develop a sufficient understanding of the hydrodynamics of the estuary a joint focus on field measurements and the use of appropriate numerical models was required. Field measurements were taken to provide sufficient data for the construction and calibration of the numerical models. Ultimately, two numerical models were produced:

- **Tide Model**: A two-dimensional vertical (2DV) simulation was developed using RMA-10 software. The model was used to predict the interaction of freshwater inflows and tidal fluctuations on water levels, velocity profiles and the salinity structure of the estuary.
- **Flood Model**: A one-dimensional model was developed using MIKE-11. This model was used to provide a preliminary estimate of the relationship between flood discharge magnitude and the water depths and inundation extents they produce over the floodplains and wetlands adjacent to the estuary channel.

9.1 Overview of Field Data Collection

Two sets of field measurements were collected:

- Topographic / hydrographic surveys were completed of the estuary channel and adjacent floodplains.
- Automatic tide gauge recorders were deployed at four locations along the Gellibrand River estuary.

This section presents an overview of the field measurement exercise.

a) Survey

For this pilot study a coupled topographic-hydrographic survey was commissioned that included 21 cross-sections (Figure 9-1). At each cross-section a hydrographic survey of the river bed was completed, with topographic surveys of the left and right banks and onto the floodplains. Cross-sections were located to capture key morphological changes along the length of the estuary channel, in particular around the bend where there are several rocky shoals (see xs11 – xs17 in Figure 9-1).

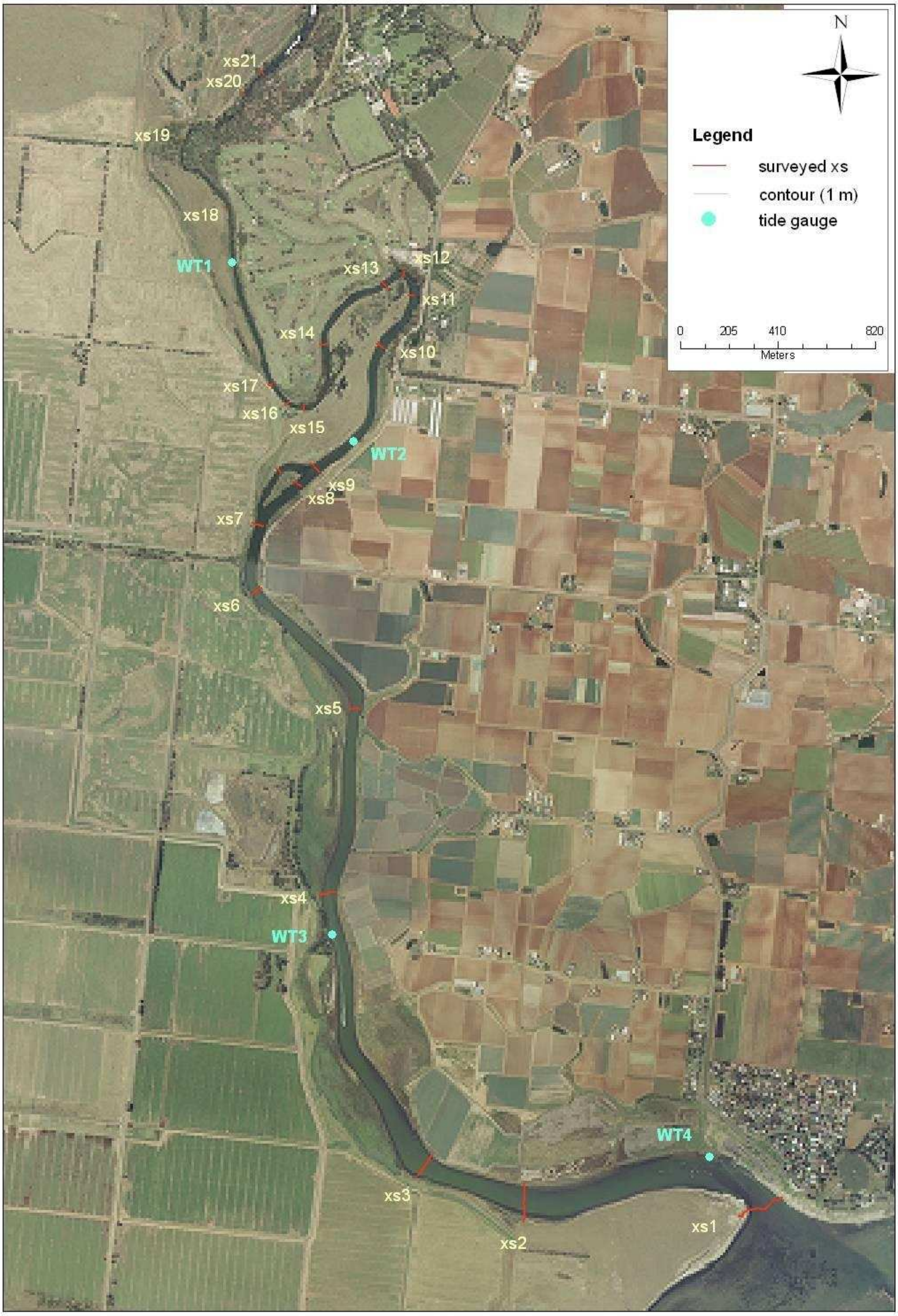

Figure 9-1 Map of the Werribee River Estuary showing the location of surveyed cross-sections (red with yellow numbers) and tide gauge positions (WT1 – 4).

b) Tide Gauging

Four RBR[2] logging pressure recorders (Model DR-1050[3]) were deployed along the Werribee River estuary (Figure 9-1), from upstream to downstream the locations were:

- WT1: Golf course (7.3 km upstream of estuary entrance).
- WT2: Prickly pear (5.1 km upstream of estuary entrance); and
- WT3: Clover corner (2.5 km upstream of estuary entrance);
- WT4: Boat ramp (0.3 km upstream of estuary entrance);

Each RBR recorder was mounted within a stilling well and locked to a 15kg ballast structure. The instrument and ballast were then positioned within the estuary and tethered by stainless steel cable to a pier, post or other permanent structure to enable retrieval. The loggers were deployed on the 10th of August and retrieved on the 20th of August, 2007. The short duration of the deployment was necessitated by project deadlines. The data obtained was adequate for calibration of the hydraulic model, although a deployment of 30 – 60 days is recommended for future Estuary Flow studies.

The RBR gauges are unvented and therefore require barometric correction. Barometric pressure readings were downloaded from the Laverton RAAF station (Bureau of Meteorology station ID: 0870031) which is located less than 14 km northeast of the estuary. The elevation of the instruments was not surveyed. Consequently the water level results could only be approximately reduced to Australian Height Datum (mAHD). Water levels were reduced approximately to datum by:

- simulating the measured inflow discharge sequence with the Flood Model to estimate the water surface profile over the period of the tide gauge record setting the downstream boundary to mean sea level (i.e. without tidal influence); and
- setting the mean gauged water surface elevation equal to the predicted mean water surface elevation as per the Flood Model simulation.

The tide gauge records were corrected using the above method to approximately Australian Height Datum (Figure 9-2).

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[2] RBR: Richard Brancker Research (www.rbr-global.com)

[3] The DR-1050 is a small, self-contained, submersible depth or pressure recorder. The DR-1050 is calibrated to an accuracy of ± 0.05 % full scale using NIST traceable standards. Each unit employs an absolute pressure gauge, with ranges selectable from 10 dBars (10 metres of water) to 6,600 dBar. Flash memory ensures data retention for 20 years even if the batteries run out. 8MB of storage provides sufficient memory for 2,400,000 samples and a full set of samples can be taken by a single set of batteries.

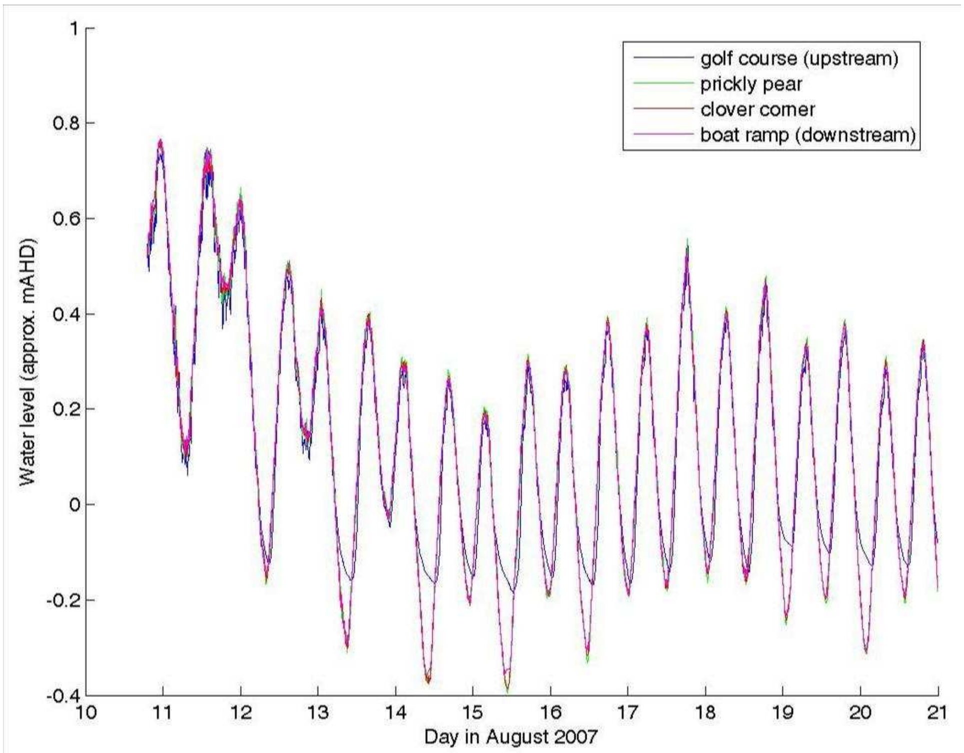

Figure 9-2. Measured tide gauge data at four sites along the Werribee River estuary corrected approximately to Australian Height Datum.

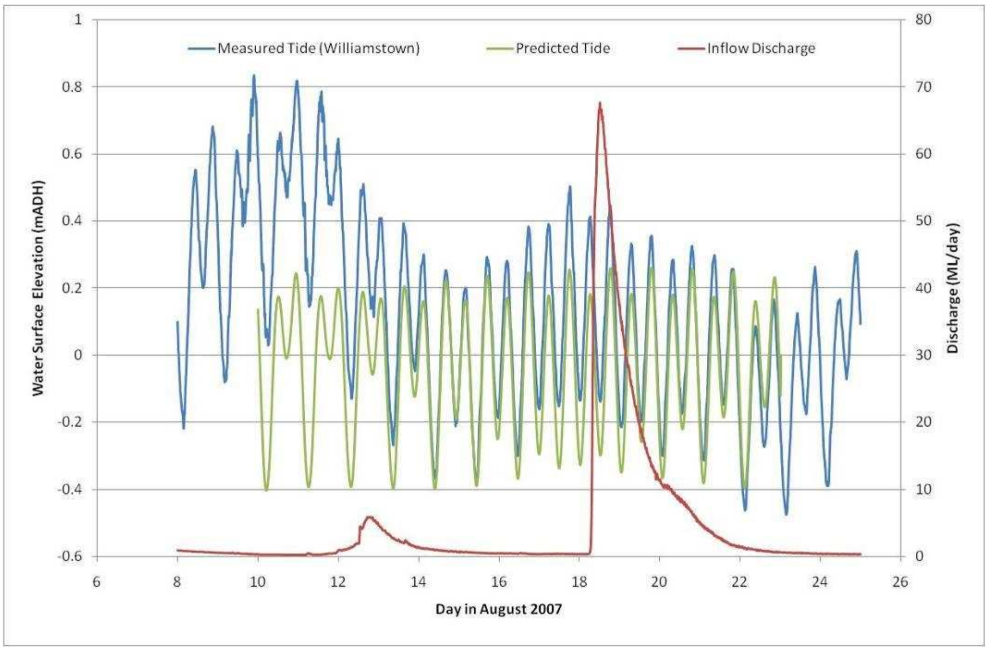

Figure 9-3. Tidal fluctuations measured at Williamstown (blue) compared to the predicted tidal variation (green) over the period of tide gauge deployment. Also shown is the inflow discharge hydrograph (red, right axis) measured at Werribee (Diversion Weir, #231204).

Measured tidal elevations were obtained from the Williamstown tide recorder[4] spanning the period the RBR instruments were deployed (Figure 9-3). The predicted tidal variation was constructed from the Williamstown tidal constituents published in the Australian National Tide Tables (Australian Hydrographic Service, 2004). Comparison of the measured and predicted tidal variations highlight tidal anomalies. The inflow discharge from the nearest upstream gauge on the Werribee River [Werribee River@Werribee (Diversion Weir), #231204] measured over the deployment period is also shown in Figure 9-3.

The measured tidal fluctuations measured at the three downstream sites are virtually indistinguishable. The most upstream location ('golf course') differs in that the ebb tides do not fall below -0.2 mAHD. This indicates that drainage of water from the upper reach of the estuary is being inhibited by the rock bar at around XS15 (see Figure 9-1).

The tides measured at Williamstown deviate substantially from the predicted tides. Indeed, on the day the RBR instruments were placed in the estuary a very strong easterly wind was blowing. A superelevation of around 0.6 m above the predicted tide was measured on the 10th of August. The tidal fluctuations did not return to predicted values until the 15th of August with a second period of superelevation commencing soon thereafter. This comparison demonstrates the importance of wind and other climatic influences on the tidal variation in Port Phillip Bay.

The inflow discharge hydrograph to the Werribee estuary (Figure 9-3) shows a very low baseflow broken by one small flow event (peak ~6 ML/day) near the start of the record and one larger event (peak ~67 ML/day) toward the end of the record. The second event is thought to have led to slightly higher water levels being recorded by the 'golf course' RBR on the 19th of August and into the 20th (Figure 9-3).

The measured data series just described were used to calibrate the Tide Model.

9.2 Tide Model

The key estuary hydrodynamic characteristics to be resolved by the Tide Model are water level variations and the dynamics of the salinity structure. Water levels and salinity vary with freshwater inflow discharge and tidal fluctuations.

The Werribee River estuary is long (8.25 km) and flows within a relatively narrow, clearly defined channel. This morphology is an ideal candidate for a two-dimensional vertical (i.e. laterally averaged) hydrodynamic model. RMA-10 software (ver. 7.3, King, 2006) was used to construct and execute a 2DV vertically stratified, finite element representation of the estuary.

a) Model Construction

Five key elements were required to define the 2DV Gellibrand Tide Model:

1. Channel and floodplain geometry – derived from survey data measured for this project in combination with existing LIDAR data of the estuary catchment.

[4] Maintained by the Australian Bureau of Meteorology; located approximately 23 km northeast of the Werribee estuary entrance to Port Phillip Bay.

2. Downstream boundary condition – reconstructed tidal water levels based on constituents published for Williamstown (Australian Hydrographic Service, 2004).
3. Upstream boundary condition – a freshwater inflow hydrograph was defined by discharge recorded by the nearest upstream gauge (Werribee River@Werribee(Diversion Weir) – #231204) for the purpose of calibration. Subsequently, inflow discharge was the main variable used in model sensitivity testing; the test scenarios are described later.
4. Atmospheric conditions – variations in wind and barometric pressure were outside the scope of the modelling; assumed zero wind speed and constant barometric pressure.
5. Hydraulic roughness of the channel – initial roughness estimates were made with reference to published studies, these were refined during the calibration process. Hydraulic resistance (also called 'stream roughness') is a measure of the friction generated between flowing water and the channel boundary. A wide range of approaches are available to estimate flow resistance in channels and floodplains (Arcement and Schneider, 1989; Coon, 1998; Duncan and Smart, 1999) and also in estuaries specifically (McDowell and O'Connor, 1977; Tsanis et al., 2007). In the first instance roughness values should be assigned to the channel and floodplains using multiple approaches (as recommended by Coon, 1998; Lang et al., 2004). Values for the channel were refined through calibration of the Tide Model.

A preliminary estimate of channel resistance was made with reference to Chow's Table (Chow, 1959), measurements presented by Hicks and Mason (1991) and professional experience. The estuary was divided into three different sections on the basis of field observations. The lower ~6 km (Figure 9-1: XS1 – 11) is a relatively wide channel of the estuary was assigned a Manning's n of 0.024. The middle section between XS11 and XS16 (Figure 9-1) has a rough, gravel bed with shoals and was assigned a starting roughness of 0.038. The upper reach is quite narrow but deep (regularly > 2 m), and flow is occasionally inhibited by large wood in the channel. Consequently this section was assigned a starting value of 0.030. The magnitude of the hydraulic resistance was refined via calibration to water level fluctuations measured by the tide gauges (see next).

b) Model Calibration

The Tide Model was run in one-dimensional mode to calibrate propagation of the tidal wave up and down the estuary. The boundary conditions were specified so as to reproduce as closely as possible conditions measured during the tide gauge deployment.

The objective of calibration was to minimise the difference between the model output and the measured tide gauge data. The key features that the model aimed to reproduce included: the tidal range; timing of flood and ebb tides; and the attenuation of the flood wave as it moved upstream. Calibration was achieved by making adjustments to the hydraulic roughness along the reach and also by refining the representation of the estuary entrance (esp. level of the invert and hydraulic roughness).

The calibration results achieved are shown in Figure 9-4. The tidal variation at the three downstream sites (WT2-4) was almost identical (Figure 9-2), and the model replicated this characteristic accurately. At these sites, the amplitude and timing of the model quite closely replicates the measured data.

At the most upstream site (WT1) the truncation of the ebb is very well reproduced, as are the peak magnitudes of the predicted flood tide. A great deal of work went into refining the sill level of the rock bar in the model and the flow resistance characteristics to achieve this level of calibration. The model predictions diverge from the measured traces on the 18th of August. This divergence occurs at the time the upstream discharge increases rapidly (see Figure 9-3) and it is thought likely that the hydrograph that arrived at the estuary was somewhat different from that measured in Werribee. Consequently, the divergence is not considered an indication of poor model calibration.

c) *Modelled Scenarios*

A series of standard scenarios were run with the calibrated Tide model. The scenarios examine the sensitivity to inflow discharge of water level fluctuations and the salinity structure. The model was run for four different freshwater inflow discharges: 1, 20, 50 and 100 ML/day. The estuary entrance is maintained in an open state by regular dredging, therefore a constant entrance cross-sectional area was defined (based on survey data). The downstream tidal boundary was defined by a repeating spring-neap tidal cycle (based on constituents for Williamstown from: Australian Hydrographic Service, 2004).

These simulation runs produced data on variations in water depth along the estuary as well as the variation in salinity and velocity through the water column. A series of output plots and animations were prepared to provide the Scientific Expert Panel with an overview of the sensitivity of the Gellibrand River Estuary to inflow discharge. The primary output comprised:

- Longitudinal salinity profile: animation and snapshots at particular times.
- Time series variation of vertical salinity profiles (top, middle and bottom parts of the water column) at discrete locations along the estuary.
- Variation of velocity (top, middle and bottom parts of the water column) at discrete locations along the estuary. This data may also be used to estimate shear stresses for preliminary sediment transport estimates.
- Residence time measured by the 'e-folding time'. This gives a practical measure of the time interval taken for a certain volume/parcel of water in the estuary to be exchanged with new water (Abdelrhman, 2005; Monsen et al., 2002). E-folding time is defined as the time interval in which an initial quantity decays to 1/e or 36% of its initial value. The e-folding time was reported at key locations along the estuary to indicate the variability of residence time with location and inflow discharge.

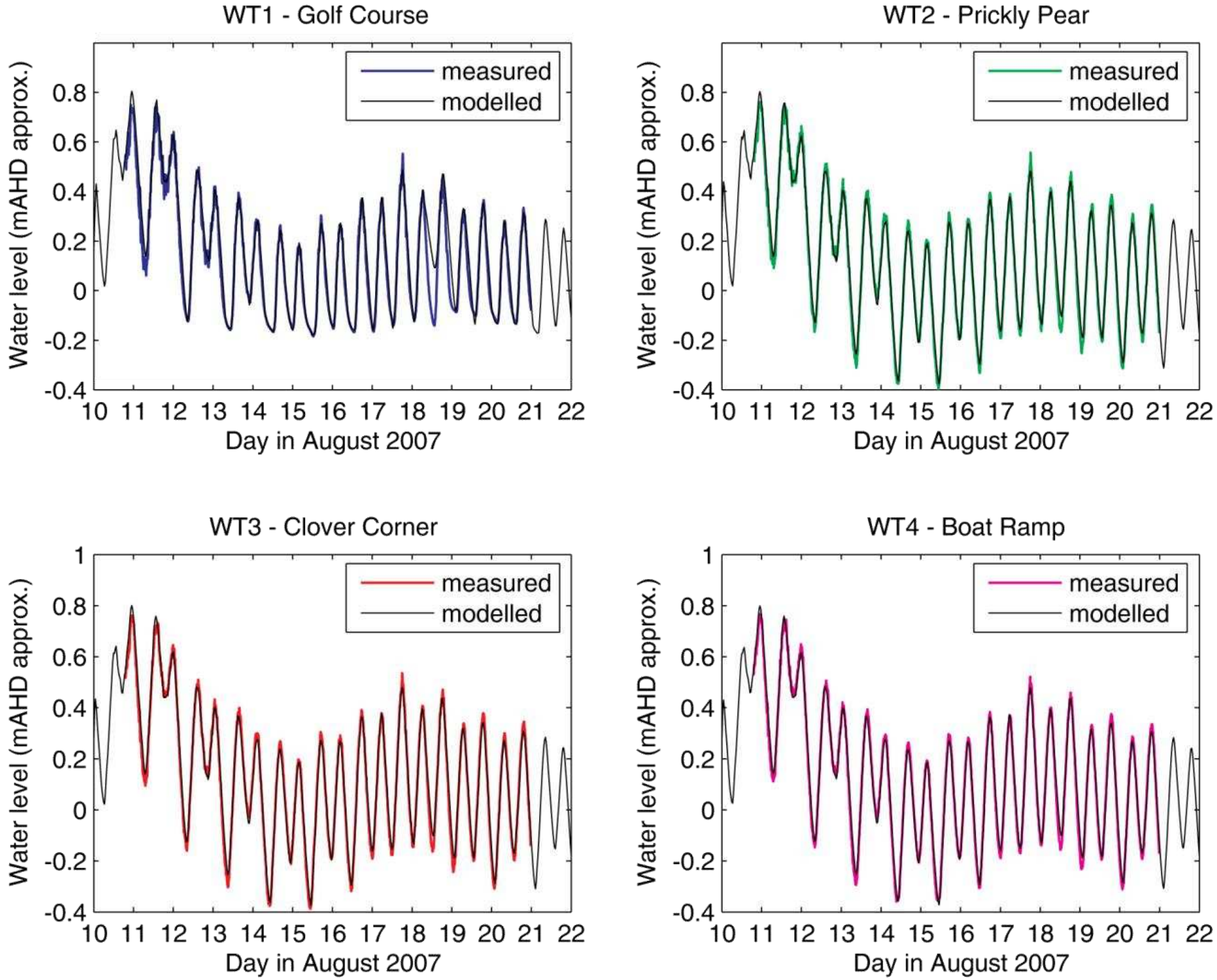

Figure 9-4. Results of model calibration at the four tide gauging stations showing measured and predicted water levels.

- Saline recovery rates were qualitatively observed via animations of the salinity profile. The time taken to develop an equilibrium salinity profile was estimated based on the initial 4 weeks of simulation, which started with the estuary completely fresh.

A series of more specific evaluations were undertaken to support the development of the final flow recommendations by the Scientific Panel. These evaluations involved extracting salinity/velocity/water depth time series at particular locations of interest and providing key statistics of the series (e.g. maximum, minimum, mean).

d) Sample Model Results

This section shows a sample of results obtained from the Tide Model simulations. These are intended to provide the reader with an indication of the type of information that the Scientific Panel had to work with. The salinity profiles on the ebb and flood of the spring tide for the first three inflow cases are shown in Figure 9-5 to Figure 9-7 (and also Figure 9-9 later).

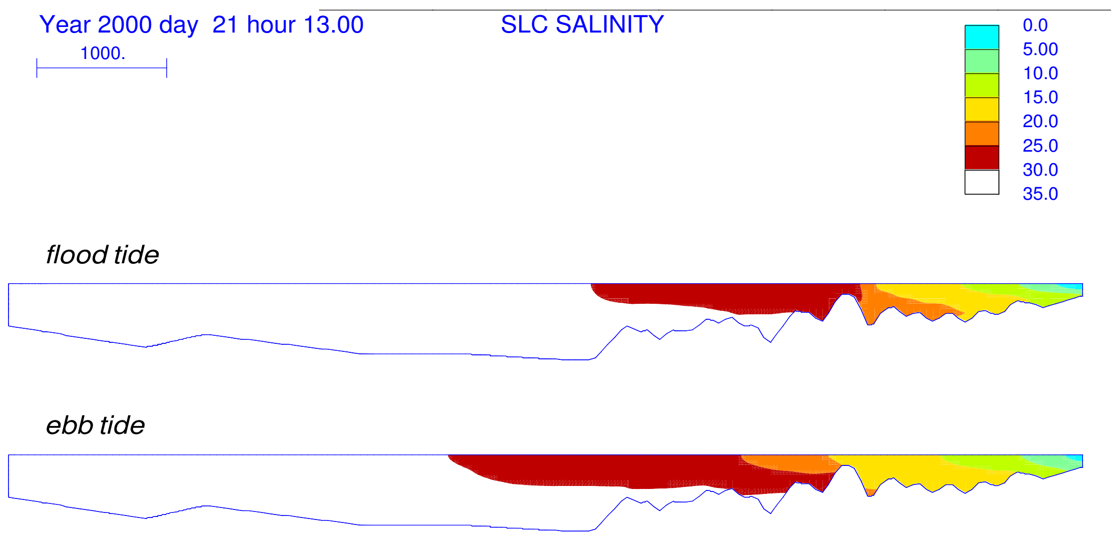

Figure 9-5. Salinity distributions at ebb and flood of the spring tide with 1ML/day inflow discharge. Legend shows salinity range represented by each colour.

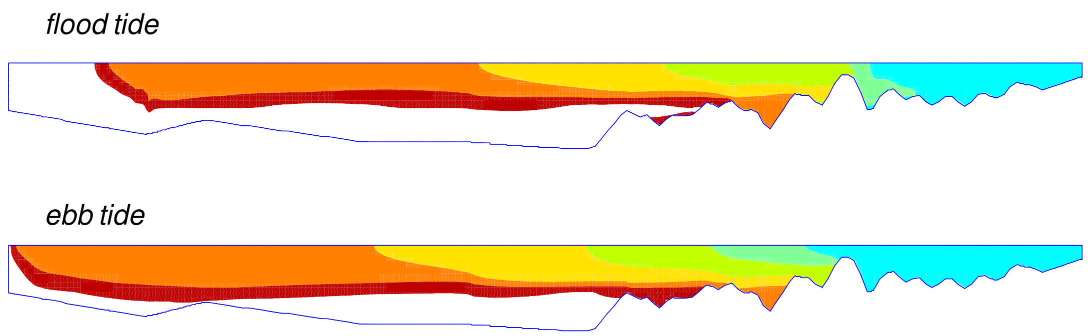

Figure 9-6. Salinity distributions at ebb and flood of the spring tide with 20ML/day inflow discharge.

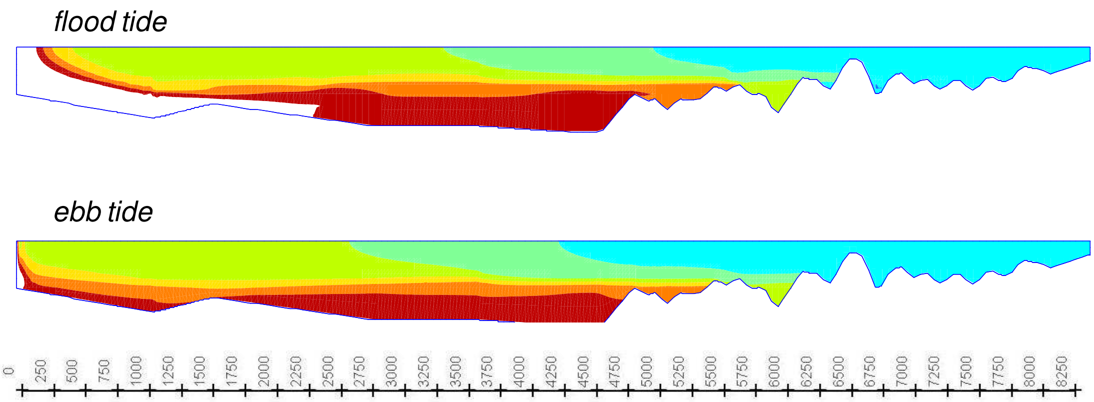

Figure 9-7. Salinity distributions at ebb and flood of the spring tide with 50 ML/day inflow discharge. Note scale in metres shown at the bottom of the plot.

Analysis of Residence Times

Hydrodynamic simulations were undertaken with the Tide Model incorporating a numerical tracer to estimate residence times at various locations in the Werribee estuary under four different steady freshwater inflow discharges (Table 9-1). Results were extracted at five locations (Sites A-E) as shown in Figure 9-8.

The approach used was to set an initial concentration of a conservative dissolved substance (tracer) in the waters of the estuary. Fresh water inflows and the tidal boundary are assumed to have zero concentration of the tracer and an advection-dispersion transport formulation is used to transport the substance through the estuary under the influence of the hydrodynamic flow field. The change in the concentration of the tracer through time at locations within the estuary characterises the time taken for various sections of the estuary to be 'flushed' with 'new' saline water from the ocean boundary or 'new' fresh water from the upstream inflow boundary.

The **e-folding** time is commonly used to provide a practical measure of the time interval taken for a certain volume/parcel of water in the estuary to be exchanged with new water. The e-folding time is defined as the time interval in which an initial quantity decays to 1/e or 36% of its initial value. For environmental studies, this is considered to provide a quantitative measure of the time of exposure to pollution/physical stresses in semi-enclosed water bodies.

The numerical tracer simulations undertaken have adopted low dispersion coefficients (this drives the amount of mixing or exchange that occurs but is not influenced by the hydrodynamics) to provide a conservative estimate of the flushing/residence times in the estuary. Wind induced overturning and other turbulent mixing processes may result in lower residence times than those calculated.

Table 9-1.
Variation of residence time (estimated as the e-folding time in days) with freshwater inflow discharge along the Werribee Estuary.

	Site A Entrance	Site B Lower Straight	Site C Island below Bend	Site D Red Cliffs	Site E Golf Course
Flow			*e-folding time (days)*		
1 ML/day	0.5	1.0	4.2	4.9	6.2
20 ML/day	0.5	0.8	2.7	4.0	3.1
50 ML/day	0.5	0.8	3.0	4.5	0.5
100 Ml/day	0.5	2.7	3.6	1.4	0.3

Residence times were found to be higher in the upper estuary than the lower estuary, with the e-folding time typically decreasing as flow (inflow discharge) increased. An exception to this trend was that at Sites B and C residence time increased when flow was increased from 50 to 100 ML/day. This result was attributed to the fact that at 100 ML/day a strong freshwater surface flow is present (Figure 9-9), trapping salt water in the bottom layer for extended periods. This trapping is likely to decrease at higher flows as the freshwater layer thickens and ultimately flushes salt from the estuary entirely. Consequently, increases in residence time with flow are only likely to occur over a small band of inflow discharges, and are expected to fall rapidly once flow sufficient to flush the lower estuary occurs.

The modelled residence time results are broadly consistent with the trends in measured dissolved oxygen (DO) levels reported by Sherwood et al. (2005). They observed low DO tended to be found in the bottom waters of the mid to upper estuary, which are associated with the locations having higher predicted residence times.

Saline flushing

In order to resolve the question of what inflow discharge would flush the estuary of salt water a ramp inflow discharge starting at 50 ML/day and increasing to 500 ML/day was run with the Tide Model. A repeating spring tide sequence was run as the downstream boundary to provide maximum tidal energy to push salt into the estuary. It was found that at around 180 ML/day salt was unable to penetrate beyond the high point in the long profile at 1500 m from the estuary entrance. A freshwater flow of around 340 ML/day was required to prevent salt water from pushing beyond the entrance bar (~250 m).

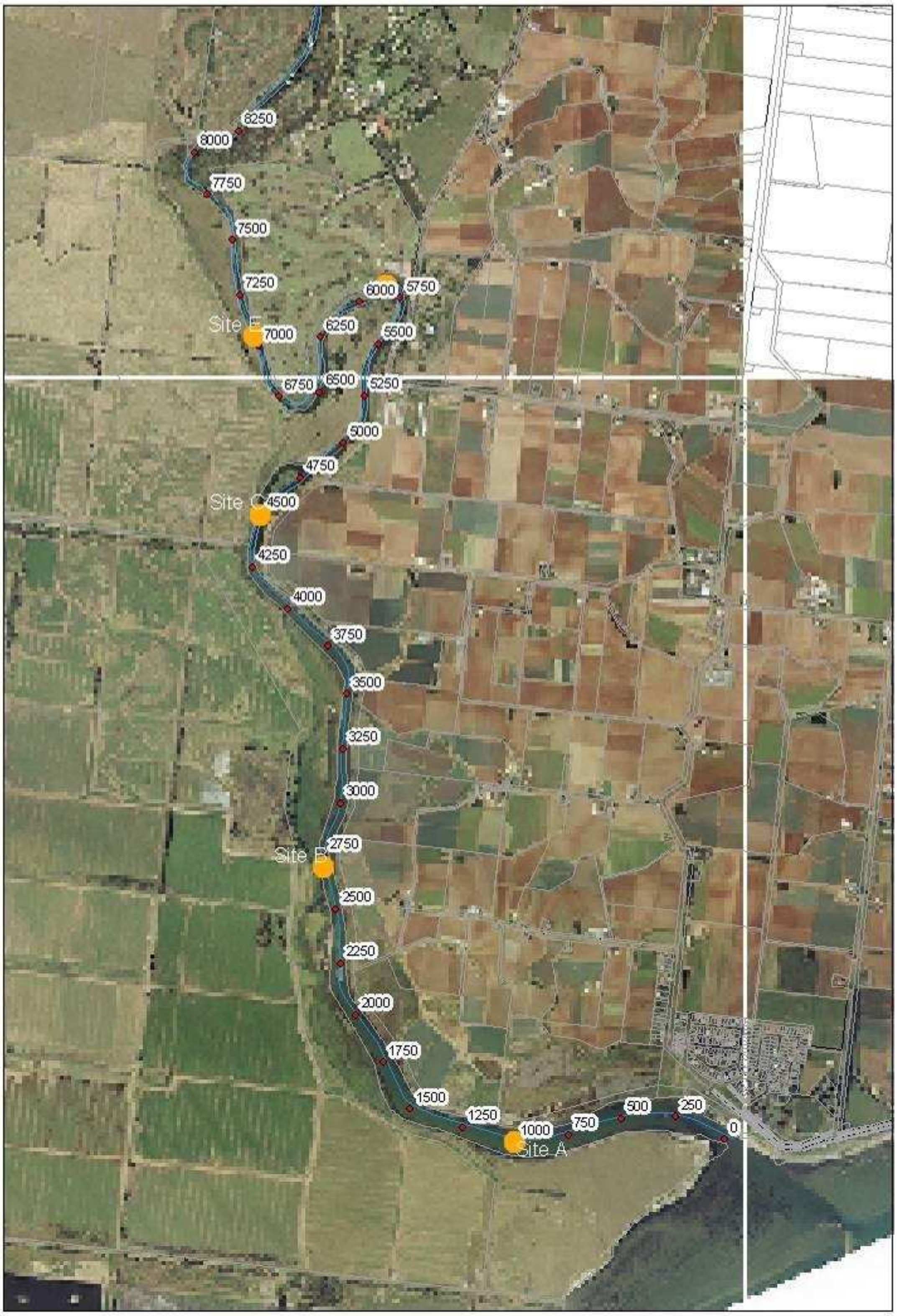

Figure 9-8. Map of the Werribee River Estuary showing the distance upstream of the entrance and the location of Sites A – E at which data was extracted from the Tide Model.

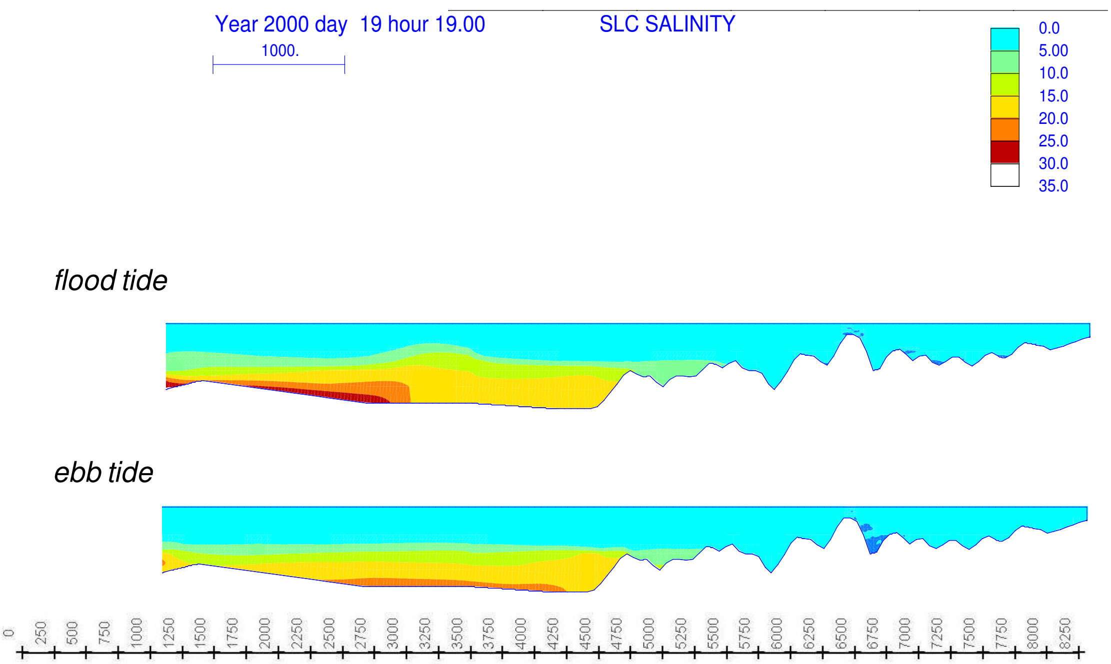

Figure 9-9 Longitudinal salinity profiles on an ebb and a flood tide with a constant freshwater inflow discharge of 100 ML/day.

Extent of Estuarine Conditions

During the Scientific Expert Panel workshop it became evident that it would be useful to divide the estuary into three zones according to the salinity of the water. The three zones and the associated salinity levels were:

- Marine: salinity > 30
- Estuarine: 5 < salinity < 30
- Fresh: salinity < 5

The length of the study region (i.e. the estuary) over which estuarine conditions was predicted was assessed using the longitudinal salinity distributions (e.g. Figure 9-5 to Figure 9-9). The results are summarised in terms of the absolute length over which estuarine conditions were found and the percentage of the estuary this represented (Table 9-2). These results show that moderate freshwater inflow discharges (20 – 50 ML/day) maximise the length over which estuarine conditions prevail.

Table 9-2.
Predicted length along the river that estuarine conditions can be found out of 8,250m total length (estuarine conditions = 5 > salinity > 30; somewhere in the vertical profile)

	Predicted Estuarine Length (m)	
Inflow Discharge	**Ebb**	**Flood**
1 ML/day	3000m (36%)	2000m (24%)
20 ML/day	6750m (82%)	6250m (76%)
50 ML/day	6250m (76%)	6500m (79%)
100 ML/day	5500m (67%)	5500m (67%)

9.3 Flood Model

The objective of simulation with the Flood Model was to estimate the inflow discharge required to cause various overbank water levels at different points along the estuary. A two-dimensional model was able to be developed using the LIDAR data (0.25 m contour surface) and was necessary given the complexity of the overland flow paths across the golf course and around the bend downstream of the golf course (Figure 9-10).

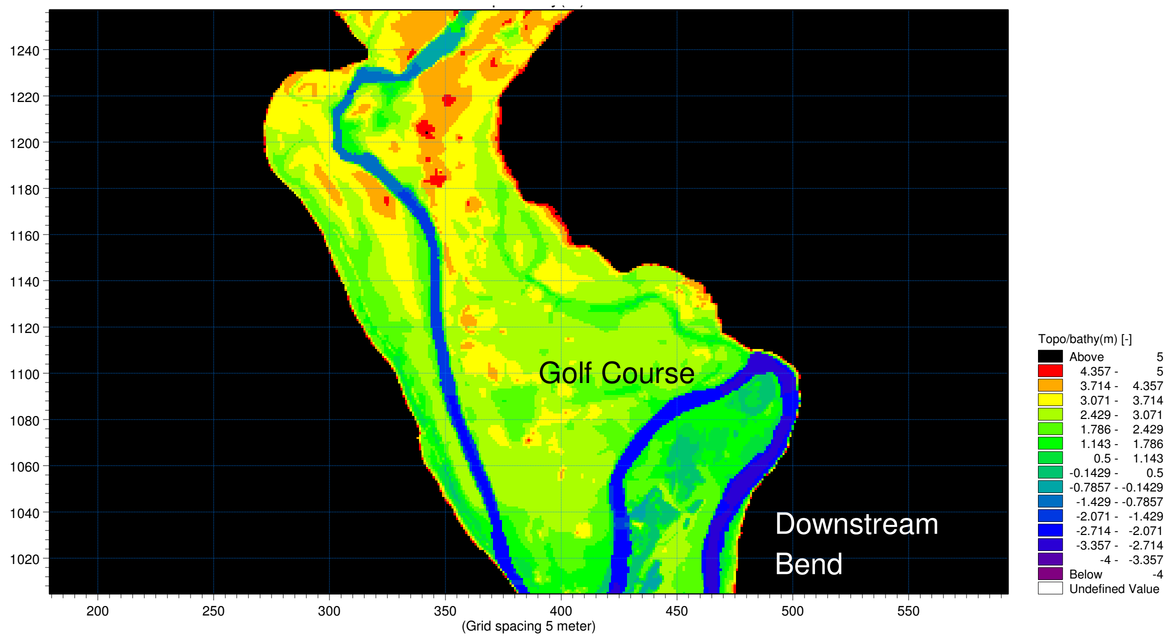

Figure 9-10. Detailed topography of the upstream section of the Werribee River estuary showing complexity across the golf course and around the downstream bend.

a) Model Development

Five key elements were required to define the Werribee Flood Model in MIKE21:

1. Channel and floodplain geometry – derived from existing LIDAR and survey data measured for this project.
2. Downstream boundary condition – reconstructed tidal water levels based on constituents published for Williamstown in the Australian National Tide Tables (Australian Hydrographic Service, 2004).
3. Upstream boundary condition – inflow discharge was the main variable used to define the test scenarios.
4. Atmospheric conditions – variations in wind and barometric pressure were outside the scope of the modelling; assumed zero wind speed and constant barometric pressure.
5. Hydraulic roughness of the channel and floodplain – initial roughness estimates were made with reference to published studies (see Section 9.2a) for details). Values for the channel were refined through calibration of the Tide Model (as per Section 9.2b)

The model was based on LIDAR data received from Melbourne Water Corporation[5], supplemented by field survey of the channel bed (Figure 9-11). The LIDAR was used to create a 5 m MIKE21 grid, with the River channel excavated to represent the bed level from the field survey. A 5 m grid was thought to be sufficiently detailed to represent flows down the Werribee River channel as the river is typically 25 m wide in the upper reach to 150 m wide in the lower reach.

Note:

It is important to emphasize that the flood modelling completed for this project is strictly only a first approximation. There was no scope for considering the complex interaction of catchment hydrology, tides, atmospheric pressure and wind generated storm surge, let alone the potential for sea level changes likely to occur due to climate changes or shifts. Consequently, flood levels were established under the following simplifying assumptions:

- no storm surge, no wind effects and standard atmospheric pressure; and
- a constant downstream water surface elevation equal to Mean High Water (MHW[6]) of 0.5 mAHD.

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[5] LIDAR data prepared for the Western Treatment Plant Flood Mapping Project (flown on 31 October 2002, data provided by Melbourne Water)

[6] Mean High Water is defined as the average of all high waters observed over a sufficiently long period (definition from the Australia Hydrographic Office Tidal Glossary adopted by the Permanent Committee on Tides and Mean Sea Level: http://www.icsm.gov.au/icsm/tides/tidal_interface.html)

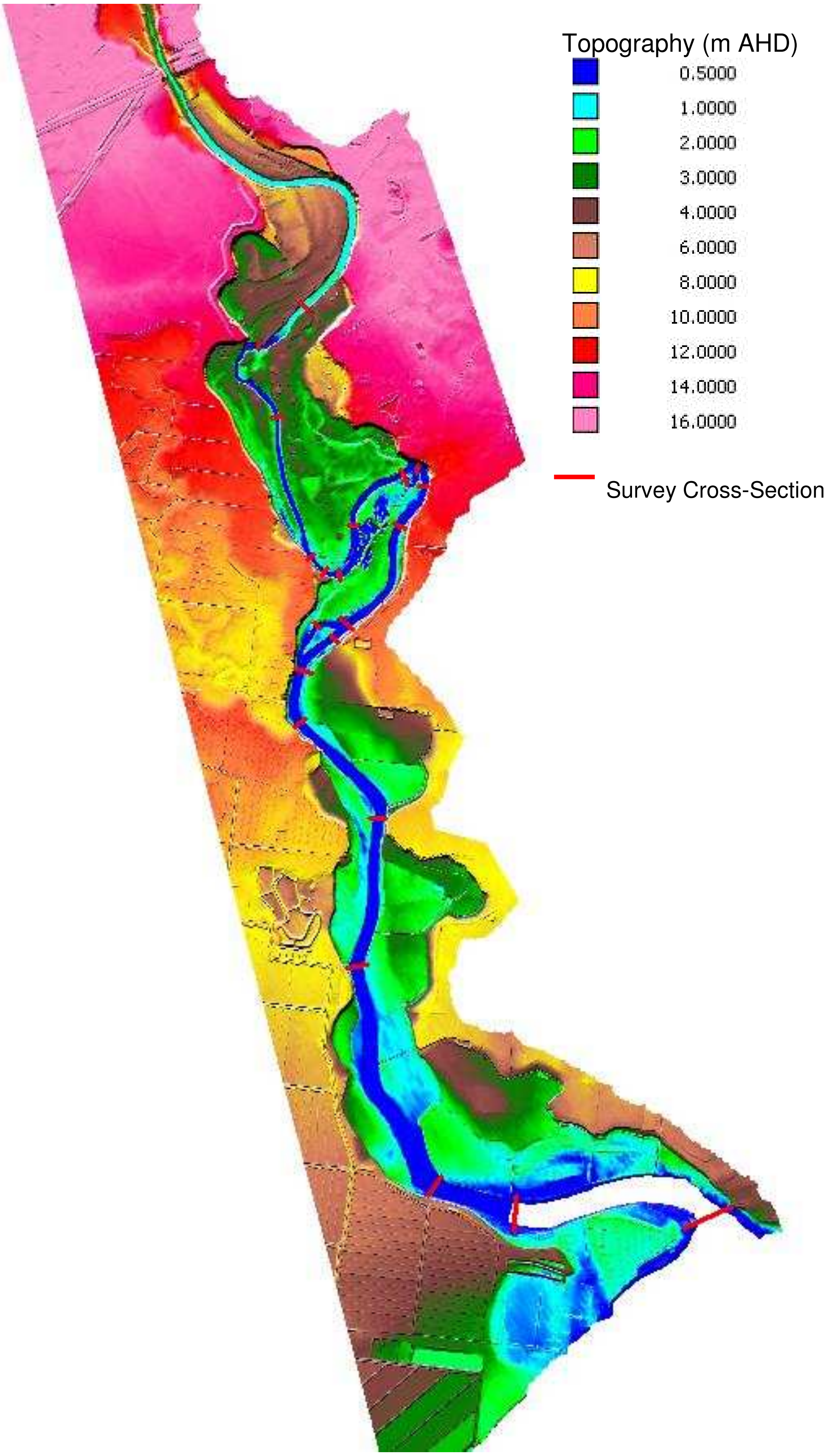

Figure 9-11. Flood Model topographic base data

b) Model Calibration

The model was calibrated to the 2005 flood event which peaked at just over 16,500 ML/d (Figure 9-12). Anecdotal evidence and photographs of the Golf Course during the 2005 flood extent was available for calibration (Figure 9-13).

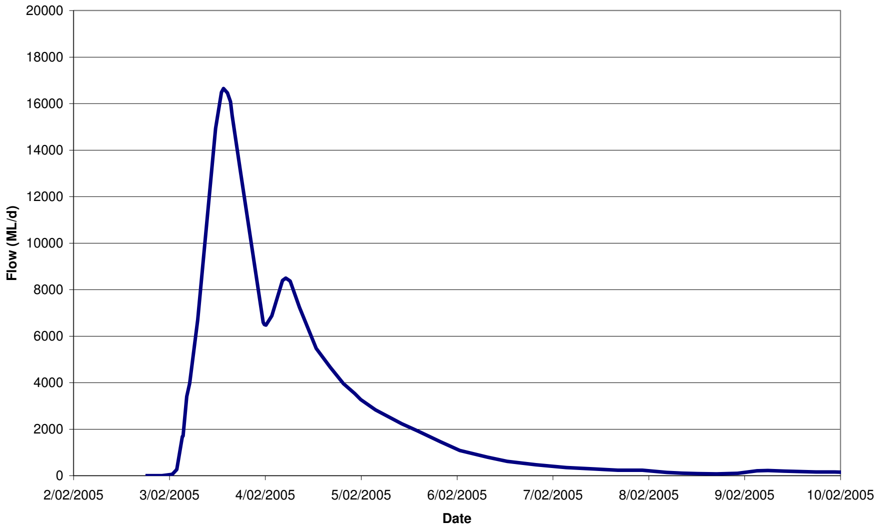

Figure 9-12. Event hydrograph for calibration: February 2005

The roughness values in the channel and on the floodplain were altered so as to achieve a similar level of inundation across the Golf Course as observed in 2005. The main aim of this exercise was to ensure that the model predicted out-of-bank flooding. Gauged flood levels and extents were not available, consequently the calibration relied on a qualitative comparison of the photographic evidence and eye witness accounts with model results (Figure 9-14).

At the flood peak the model results show flood water inundating approximately half of the golf course. The key positive indications of calibration were the activation of two overland flow paths (as indicated).

c) Sample Model Results

The ramp simulation predicts the approximate relationship between the extent of inundation (or water level) and the peak discharge of a flood. That is, it was assumed that the ramp inflow was gradual enough that inflow discharge at a particular time could be equated to peak flood discharge). Based on this assumption, charts were produced to estimate the peak flood discharge required to attain a given inundation extents at key locations along the estuary.

Figure 9-13. Photographs of inundation near the peak of the February 2005 flood event.

Snapshots of the inundation at different points through the ramp simulation (Figure 9-15) show:

- 8,500 ML/day = approx. 25% of area inundated with two flow paths actively bypassing the bend.
- 10,000 ML/day = approx. 50% of area inundated with most of the northeast corner under water (area opposite Red Cliff).
- 14,000 ML/day = general inundation of bend area, only higher ground in the middle of the bend and at the downstream end (adjacent to the island) remain dry.

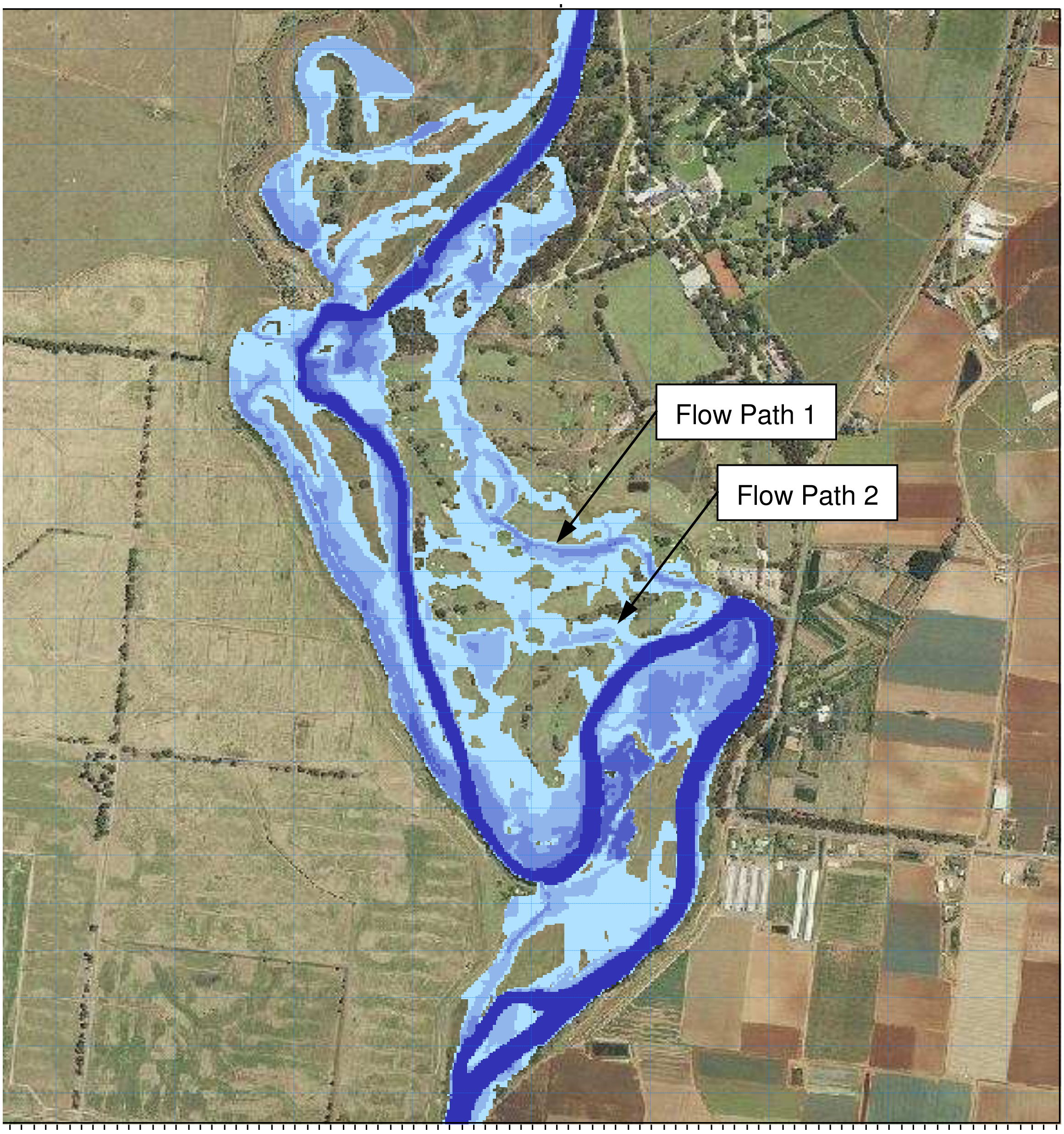

Figure 9-14. Calibrated model inundation at the peak of the February 2005 flood event over the Golf Course and the downstream bend.

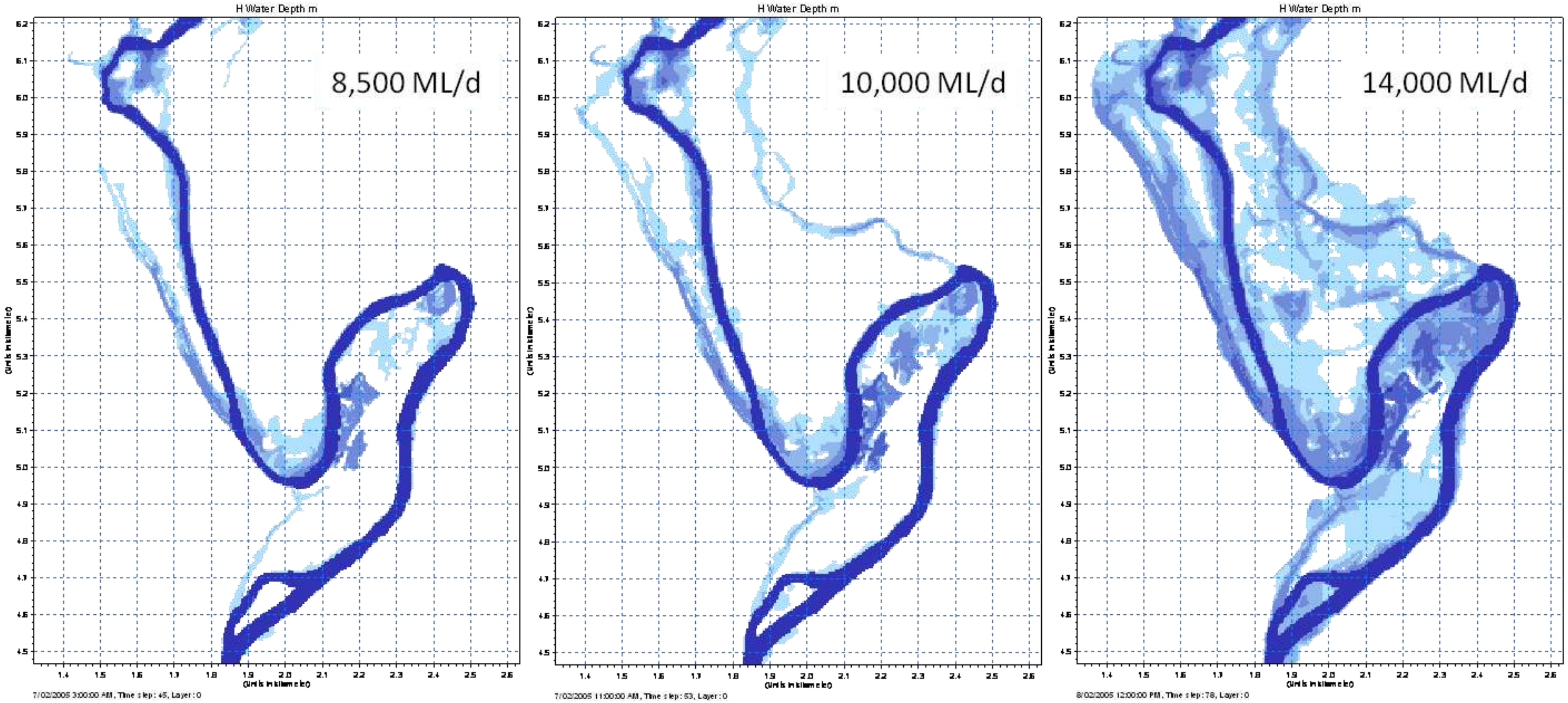

Figure 9-15. Snapshots of inundation of the top half of the estuary at three different points through the discharge ramp.

Sediment Transport Analysis

- A rational analysis of sediment transport potential was undertaken using mean channel velocities predicted by Flood Model simulation results. A threshold velocity approach was employed based on Hjulstrom curves (Gordon et al., 2004, p.192). The discharge required to entrain various grades of sediment at Sites A – D are shown in Figure 9-16.
- The key results shown are that medium to coarse sands may be moved by:
- inflow of around 2000 ML/day at Red Cliffs (Site D)
- inflow of around 5500 ML/day in the lower estuary below the island (Site C) and above the last bend (Site B); and
- inflow of around 8100 ML/day near the estuary entrance

Fine sands and silts require larger discharges to initiate entrainment.

Note that sediment transport methods are recognised as approximations – especially in estuarine locations where flocculation processes are important and cohesive sediments can be dominant bed and bank substrates. The sediment transport analysis employed assumes non-cohesive substrates. A more detailed examination of estuarine sediment transport was beyond the scope of this work. Further investigation is warranted to establish a method to estimate flushing flows from estuarine sea grass beds. Any method should consider cohesive floccs and also the discharge required to penetrate sea grass beds.

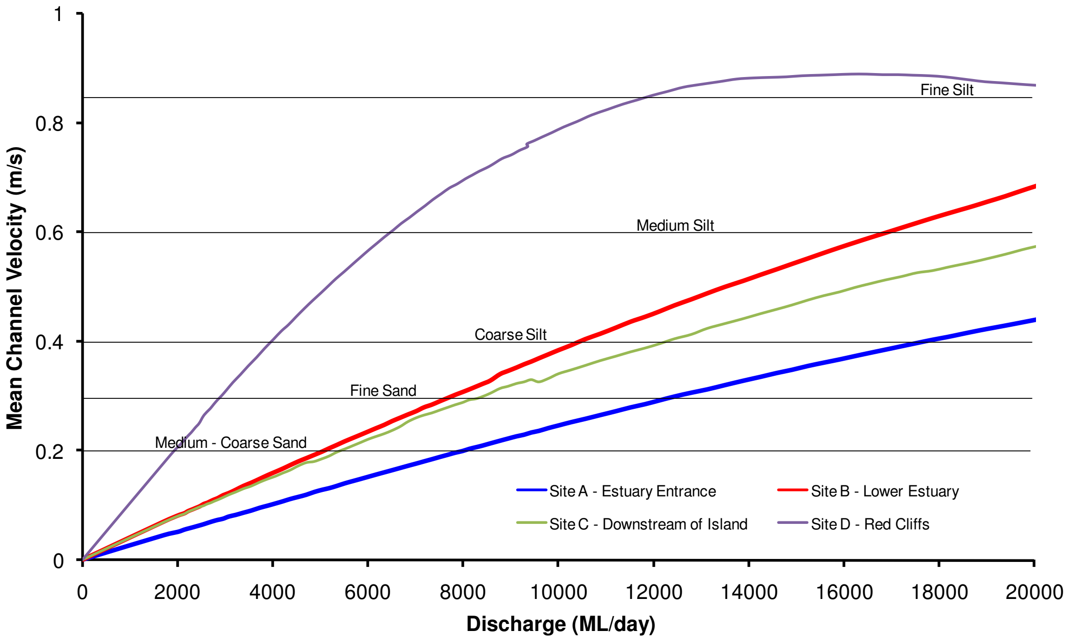

Figure 9-16. Inflow discharge versus mean channel velocity at various locations along the Werribee River Estuary. Horizontal lines indicate velocity thresholds required to move sediment of a particular grade based on Hjulstrom curves (Gordon et al., 2004, p.192).