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Environmental Water Requirements of the Gellibrand Estuary

Final Estuary FLOWs Report

by:

Lloyd Environmental

ecological associates pty ltd

FLUVIAL SYSTEMS

WATER TECHNOLOGY

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Final Draft
11th September 2008
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- FINAL ESTUARY FLOWS REPORT

for Corangamite Catchment Management Authority

by Lloyd Environmental Pty Ltd

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1 INTRODUCTION

Environmental flow 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 (Hardie, Lloyd and Sherwood 2006) has been developed based on an extension of the FLOWS methodology (NRE 2002). “FLOWS” is the accepted state-wide method for the determination of environmental water requirements (EWR) for rivers. It is an objective-based, multi-disciplinary, rigorous approach that can be broadly extended to estuaries. However, the methodology required pilot testing. This Gellibrand River project is a pilot test of the draft method and also includes considerable upgrading of the modelling approach and refinement of the ecological conceptual models and knowledge requirements.

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

1.1 The Gellibrand Estuary FLOWS Project

The upper reaches of the Gellibrand River are in good condition. Its condition declines in the lower reaches, although it improves through the estuary reach. The Central Region Sustainable Water Strategy (DSE 2006) aims to protect the ecological integrity of the Gellibrand River by ensuring that any development is consistent with environmental needs. Environmental flow determinations of the river and its estuary are required to allow Government to protect the flows of the Gellibrand River, before new entitlements or licences to extract additional water are issued. Results from the recent FLOWS study (EarthTech 2006) primarily considered needs of the freshwater reaches and therefore an estuary specific assessment was required.

The Gellibrand River rises in the Otway Ranges and flows to the sea near the township of Princetown. The estuary has a significant tributary, the Latrobe Creek, which joins the Gellibrand from the west, 1.25 km above the mouth. There are significant wetlands covering an area of 320 ha surrounding the Latrobe Creek and Gellibrand River, with parts of this area listed as Wetlands of National Importance (Environment Australia, 2001). The estuary, with its tidal and seawater influence, has a maximum extent of 10.7 km upstream (Sherwood, 1983) although a tidal signal was measured as far as 13.5 km upstream (at the Great Ocean Rd bridge) as part of this study. The estuary opens to the sea across a wide sandbar with a relatively narrow channel. Typically the channel has a maximum width of 25 - 30 m and a depth of 1 to 1.5 m, but it is frequently smaller than this. Upstream of the mouth, the estuary broadens to up to 50 m wide and 3 m deep, with occasional deeper (6 – 8 m) scour holes at bends, and with wide floodplains. The upper part of the estuary narrows at approximately 3.5 km from the mouth, becoming 6 to 20 m wide and 5 to 7 m deep, and with narrow floodplains, and levee banks beside the channel.

A large body of work exists on the Gellibrand River and estuary from the early 1980s (Sherwood, 1983 and 1984; Breen, 1982; Earl and Bennett, 1986; Koehn, 1984; Tunbridge and Glenane, 1988). This was associated with a major investigation by the State Rivers and Water Supply Commission into the environmental consequences of increased water diversion of the Gellibrand

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to supply southwestern district towns and Geelong (NREC, 1989). There has also been recent research by Kelly (2000) and McKay (2000), which formed a basis for the development of an estuary and wetland management plan (O'May and Wallace, 2001). More recently, a review was undertaken for Parks Victoria by Barton and Sherwood (2004).

1.2 Project Objectives

The major objectives of this project were to:

- identify freshwater-inflow dependant environmental and social values within the estuary;
- gauge the current health of the estuary assets;
- 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 was also to test the effectiveness of the methods and techniques of the current steps of the draft method.

1.3 The Pilot Methodology

The pilot methodology to determine environmental flow requirements of estuaries in Victoria was developed by Hardie, Lloyd and Sherwood (2006) for the Corangamite CMA and DSE and is being applied and refined in the current project.

The methodology has 3 stages, as outlined in Figure 1. 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 includes 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, but in estuaries with little biological information, 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 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 step, which is the review and updating of the Estuary FLOWS Method.
1.4 The Scientific Panel

The Scientific Panel for this project consisted of:

- Mr 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;

Mr John Leonard (John Leonard Consulting Services), hydrogeologist and environmental scientist;

Dr Phillip Macumber (Phillip Macumber Consulting Services), hydrogeologist, and,

Dr Danny Rogers, waterbird specialist.

1.5 Objectives of Final Estuary Flows Report

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

- Present refined biodiversity and hydrological objectives for the Gellibrand 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

The Estuary FLOWS methodology to determine environmental flow requirements of estuaries in Victoria was developed by Hardie, Lloyd and Sherwood (2006) for the Corangamite CMA and DSE. In determining flow requirements, the method seeks to identify flow components, undertake detailed hydraulic modelling and hydrological analysis, hold a scientific panel workshop to discuss the results of the modelling and hydrological analysis in relation to the previously identified ecological objectives. This section details the methodology as applied to the Gellibrand River Estuary. Ecology – Flow relationships could only be developed for fish and vegetation assemblages as quantification of wetland bird species was not possible with the available scientific information (Dr Danny Rogers pers. comm.).

2.1 Flow Components

The freshwater FLOWS method requires recommendations to be made for each river reach for a number of different flow components (Table 1). Each flow component has a known or assumed important environmental function. 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, the same flow components are generally used. One important additional flow component relates to the river discharge necessary to maintain an open estuary entrance. 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.

Table 1. Hydrological description of the generic FLOWS flow components

<table>
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<tr>
<th>FLOWS flow component</th>
<th>Hydrological description</th>
<th>Relevant season</th>
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<tr>
<td>Cease-to-Flow (also called “zero flows”)</td>
<td>Cease-to-flow is defined as periods where no flows are recorded in the channel.</td>
<td>Not present in some streams, nearly always occurs in Summer, but can occur in Winter</td>
</tr>
<tr>
<td>Low Flows</td>
<td>Low flows are the natural summer/autumn baseflows that maintain water flowing through the channel, keeping in-stream habitats wet and pools full.</td>
<td>Summer</td>
</tr>
<tr>
<td>Low Flow Freshes</td>
<td>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.</td>
<td>Summer</td>
</tr>
<tr>
<td>High Baseflows</td>
<td>High baseflows refer to the persistent increase in baseflow that occurs with the onset of the wet season.</td>
<td>Winter</td>
</tr>
<tr>
<td>High Flow Freshes</td>
<td>High flow freshes refer to sustained increases in flow during the high flow period as a result of sustained or heavy rainfall events.</td>
<td>Winter</td>
</tr>
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### FLOWS flow component

<table>
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<th>FLOWS flow component</th>
<th>Hydrological description</th>
<th>Relevant season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankfull Flows</td>
<td>Bankfull flows fill the channel, but do not spill onto the floodplain.</td>
<td>More common in Winter, but occur in Summer</td>
</tr>
<tr>
<td>Overbank Flows</td>
<td>Overbank flows are higher and less frequent than bankfull flows, and spill out of the channel onto the floodplain.</td>
<td>More common in Winter, but occur in Summer</td>
</tr>
</tbody>
</table>

### 2.2 Workshop and final flow recommendations

A workshop was convened in Werribee on 18th and 19th of 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.

### 2.3 Hydraulic Analyses

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.

For this pilot study a detailed topographic / hydrographic survey was commissioned; including 14 cross-sections along the Gellibrand River and 3 cross-sections along Latrobe Creek (see Sections 9 and 10 for survey specification and results respectively). In addition, water level variations at four sites along the estuary were measured with automatic logging tide gauges.

Using the field data and existing knowledge of the Gellibrand River estuary (e.g. hydraulic data review in Section 11.1), 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.

### 2.3.1 Investigations with the Tide Model

A series of standard scenarios were run with the calibrated Tide Model. The scenarios examined the sensitivity to river discharge of water level fluctuations and the salinity structure. The model was run for three different river discharges: 100, 300 and 900 ML/day. These were chosen by inspection of the hydrological data as representing summer baseflow (100 ML/day), winter...
baseflow (300 ML/day) and bankfull flow (900 ML/day). A moderate estuary entrance area was assumed (15 m$^2$ – as per tide gauging) and the downstream boundary was defined by a repeating spring-neap tidal cycle (based on constituents for Port Campbell from: Australian Hydrographic Service, 2004). The neap-spring cycle chosen was 15 days in length.

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 river 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.
- Saline recovery rates were qualitatively observed via animations of the salinity profile. The rate of development in the initial 4 weeks of simulation (that started with the estuary completely fresh) was compared to equilibrium salinity profiles through weeks 5 and 6.

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 11.3.

### 2.3.2 Investigations with the Flood Model

The objective of the Flood Model simulations was to estimate the river discharge required to cause various overbank water levels at different points along the estuary. The model allowed two flooding mechanisms to be examined:

- Freshwater Flood – simulation of overbank conditions caused by catchment flooding. A ramped freshwater inflow hydrograph starting at 100 ML/day and finishing at a maximum discharge of 20,000 ML/day was simulated.
- Entrance Closure – overbank conditions caused by build up of water behind a sandbar at the river mouth. Constant freshwater inflow discharges were assumed for the
Gellibrand River (50 ML/day) and Latrobe Creek (0.1 ML/day). The downstream boundary condition was set to approximate a sand bar with a leakage flow.

Simulation results generated for freshwater flood (first mechanism) were also used to estimate flows required to scour sediments from the estuary lagoon and the entrance (see Section 11.4.3c for a full description).

2.3.3 Estuary Entrance Dynamics

In this estuary field measurements at the estuary entrance have shown an approximately linear relationship between entrance cross-sectional area and river discharge (Sherwood, 2006). Given the complexity of modelling entrance conditions it may be necessary to make similar field measurements over a range of flow conditions on intermittently closed/open estuaries for which environmental flow studies are desired. Water level loggers installed in the estuary can show whether the estuary is tidal (i.e. open entrance) or ponded (i.e. entrance closed). A series of field surveys (say 4 to 6) could measure cross-sectional area at the entrance under different flow states. This task could be included in the estuary field trips to measure longitudinal profiles of temperature, salinity and dissolved oxygen.

The importance of this information should not be under-estimated. Increased incidence and duration of estuary entrance closure has a wide range of environmental, social and economic effects. These are documented in the Estuary Entrance Management Support System (EEMSS) project (Arundel, 2006).

2.4 Hydrological Analysis

Consideration by the Panel of the required ecological and geomorphological objectives resulted in a number of flow components being defined in terms of magnitude (upper or lower threshold), required 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 Gellibrand opens naturally, and is also artificially opened. After it has opened, it begins a trajectory towards closing. As the mouth gets narrower the hydraulics of the estuary change, so the hydraulic model that relates hydraulic conditions to a particular river discharge assumes certain (open) conditions at the entrance. In reality, the relationships describing estuary hydraulics as a function of freshwater inflows are variable (Sherwood, 2006). It has proved difficult to model the estuary opening and closing process, because of the unpredictable nature of marine influences in closing the bar.

The Panel decided that at this stage, while it would be technically possible to build a water balance model of the estuary that made predictions about when flow overtopped the entrance bar, such a model would not be constructed because marine processes influencing sediment dynamics would confound the model predictions. Certain assumptions would need to be made concerning the bathymetry of the estuary, especially around the entrance, as this is not fully described. If these issues can be overcome, then such a water balance model may be able to
provide reasonable predictions of when the river would naturally scour an opening at the mouth. This would allow predictions to be made about the time series of hydraulic conditions under a cycle of mouth opening and closing. For now, the assumption is made that the hydraulic conditions in the estuary are an unvarying function of inflows.

The frequency of the specified flow components was calculated using spells analysis. Unconventionally, independence criteria were not applied to the events, so every instance of the flow exceeding or falling below the threshold (as required by the recommendation) was counted as an event (provided it satisfied the season and duration requirements). Event independence criteria were not applied because the Panel supplied no such criteria, and in reality these criteria may vary between components (which is why a single set of criteria for all components was not assumed). The impact of this assumption of each event being independent was to overestimate event frequency and underestimate event duration, compared to if constraints had been placed on event independence.

The spells analysis was undertaken for the three available flow scenarios: natural, current and full development. Thirty-six flow components were analysed. 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. The spells program then calculated:

- Mean frequency of events per year
- Percentage of years on record with at least one event
- Central tendency and dispersion of duration of events (duration exceeded 25%, 50% and 75% of events)

This statistical description of the flow components provided a “reality check” of the frequency and duration of the required events, which assisted the Panel to make final recommendations on the flow components.

### 2.5 Flow-ecology relationships

#### 2.5.1 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.

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. In the Gellibrand estuary the conditions suitable for
Phragmites australis occur extensively across the floodplain whereas the conditions suitable for Juncus kraussii occur in a relatively narrow zone at the edge of the estuary channel. Nevertheless 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 Gellibrand 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 Gellibrand this assessment was assisted by Dr John Sherwood who has a detailed familiarity with the estuary and could describe the spread of water under flood conditions and estuary closure. 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 was 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 (particularly Breen 1982) 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 Ecological Vegetation Classes previously defined for the Warrnambool Plains Bioregion. 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 was 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 and estuary entrance closure.

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 Swamp Greenhood (Taylor 2006) and Leptospermum lanigerum (Ecological Associates 2006)

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 Gellibrand 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 is expected that gradients in groundwater level and salinity influence the distribution of plant associations, but no local data was 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. In other cases, local data was available to describe habitat conditions quite specifically. For example previous monitoring of water quality in floodplain depressions allowed the plant assemblages to be related to salinity directly.

Even when data was 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, estuary closure and sea 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 was 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.

### 2.5.2 Fish

Flow recommendations were developed for the fish fauna of the estuary. 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 Gellibrand 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.

The habitat requirements of fish was reviewed to identify the behaviours and habitat requirements of fish in the estuary. Three main groups 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 Gellibrand 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 Gellibrand 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 Gellibrand.

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 a 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 author (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 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 (“bio-stabilization”) or factoring against it (“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.

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 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 al., 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 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. It has been estimated that a flow of 100 ML/d will maintain the estuary mouth in an open state. This is the minimum baseflow required year round.

Sediment dynamics are greatly altered when the mouth closes. The flow required to open or enlarge the estuary entrance has previously been associated with a ‘flushing flow’ sequence of at least 2 days at ≥1,500 ML/d followed by at least 2 days at ≥500 ML/d. A rational analysis of sediment transport potential undertaken with one of the hydraulic models developed for this project (the ‘Flood Model’ – see Section 11) supports the magnitude of these flushing flows. Using a threshold velocity approach, the discharge required to entrain coarse to medium sands was found to lie between 1000 and 2000 ML/day (refer to Section 11.4.3c). Consequently, it was assumed that the flushing flow (as defined) will achieve this objective; although adaptive management is recommended to confirm the success or otherwise of this component.

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 were:

- **Winter period (Jun – Nov)** ≥100 ML/d baseflow to maintain the salt wedge dynamics to:
  - Maintain bank stability in the upper estuary
  - Maintain suspended sediment dynamics in the middle estuary

- **Summer period (Dec – May)** ≥100 ML/d baseflow maintained to minimise probability of mouth closure to:
  - Maintain suspended sediment dynamics in the middle estuary

- **High (morphological bankfull) flow** for at least 1 day any time of year to:
  - Maintain the channel and floodplain morphology of all parts of the estuary, including scour of the sandy delta at the entrance.

### 3.2 Vegetation

The Gellibrand estuary is part of the Heytesbury Zone of the Warrnambool Plains Bioregion (Ingeme, Duffy and Lowe 2002). The Warrnambool Plains (also known as the Coastal Plain) extends along the coast from Portland to Moonlight Head and covers an area of over 230,000 ha. The majority of the bioregion is bounded by the Glenelg Plain to the west, Victorian Volcanic Plain to the north and the Otways Plain to the west. The Warrnambool Plains Bioregion has nutrient deficient soils over low calcareous dune formations and a cliffed coastline. Areas of swamplands are characterised by highly fertile peats and seasonal inundation.

The estuary comprises a low-relief floodplain, into which the river channel is set, surrounded by high sandy and limestone country. Groundwater discharge at the foot of the surrounding slopes provides habitat for dense shrubby vegetation (Swamp Scrub) and frequently inundated, low lying areas of the floodplain near the estuary entrance support extensive *Phragmites australis* beds (Estuarine Reedbed). The floodplain further upstream is flooded less frequently and generally by less saline water. These areas have been extensively cleared for pasture but support remnants of Woolly Tea Tree. Woodland vegetation occurs on the floodplain near the upper limit of the estuary. Depressions on the floodplain capture water when estuary levels are high and support salt tolerant herbland communities (Coastal Saltmarsh and Estuarine Sedgeland).

Terrestrial vegetation and some wetland vegetation has been mapped, but generally to a coarse scale. Ecological Vegetation Classes have been attributed to the estuary in this report on the basis of vegetation mapping (DSE), a detailed vegetation survey by Breen (1982), observations from local naturalists and field observations by the author (Marcus Cooling) in the course of this project.
3.2.1 Representative Objective – Estuarine Reedbed (EVC 952)

Estuarine Reedbed has a 'rare' conservation status in the Warrnambool Plains bioregion.

Estuarine Reedbed occupies extensive areas of the floodplain approximately 1 to 3 km from the estuary entrance. It lies above the level of the daily high tide and is flooded only when estuary levels are particularly high (Arundel, 2006). This may result from closure of the entrance, unusually high tides, flood flows or a combination of these factors. Estuarine Reedbed occurs in freely draining areas which do not retain water when estuary levels recede. Flooding events will usually last several days to weeks and will be separated by periods of several days to weeks.

Flood water will tend to be brackish or fresh. The lower salinities reported from backwater ponds (Table 3) range between 2,700 and 17,000 EC and indicate salinities during general floodplain inundation. The floodplain is underlain by shallow groundwater which will have a lower and less variable salinity. It is likely that groundwater sustains the growth of deep-rooted aquatic macrophytes in the Estuarine Reedbed.

Estuarine Reedbed is dominated by *Phragmites australis* which forms dense and sometimes impenetrable beds. *Phragmites australis* tends to be most dense, tallest and particularly dominant on local rises on the floodplain such as the levees along the river bank. This species is favoured by inundation from late winter to late summer, reaching maximum canopy biomass in mid-late summer, although it responds to floods at other times (Hocking 1989a, 1989b).

Conditions become suboptimal within 1 km of the estuary entrance where surface water and groundwater salinities are likely to be higher. In this area *Juncus kraussii* is the dominant species and occurs with *Scheonoplectus pungens*, *Poa poiformis*, *Baumea juncea* and *Triglochin striata* (Breen 1982).

Conditions are also suboptimal for *Phragmites australis* in deeper floodplain areas within the Estuarine Reedbed. This may be because the depth of flooding is too great or because there is potential for water to pool and become too saline for *P. australis* through evaporation. These areas support a diverse community which includes the graminoids *Juncus kraussii*, *Isolepis nodosa* and *Poa poiformis* and a herb layer of *Cotula coronopifolia*, *C. reptans*, *Triglochin striata*, *Suaeda australis*, *Selliera radicans* and *Samolus reptans* (Breen 1982). *Sarcocornia quinquelora* can also be present (pers. obs. M. Cooling). When subject to regular or sustained flooding, presumably in spring, Estuarine Reedbed can include *Chara* sp., *Nitella* sp. and *Ruppia maritima*. Areas flooded with fresher water can include *Rumex bidens*, *Calystegia sepium* and *Lotus hispidus* (Breen 1982). Ecological and hydrological requirements are shown in Table 2 and Figure 2.
Plant assemblages:

A On rises and higher ground in the floodplain, inundated by winter freshes - *Phragmites australis*

B On lower points in the floodplain, inundated to a greater depth by winter freshes and subject to evaporative concentrations of salts from estuary water - diverse community including: *Juncus kraussii, Isolepis nodosa, Poa poiformis, Cotula spp., Triglochin striata, Suaeda australis, Sarcocornia*

C At the edge of the main estuary channel *Juncus krassii*, is present beneath and adjacent to *Phragmites*

Figure 2: Conceptual Model of *Phragmites* grassland ecological and hydrological objectives
### Table 2. Ecological and Hydrological Objectives for *Phragmites australis* Grassland

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a Brackish flood water</td>
<td>Promote salt-tolerant charophytes, herbs, grasses and forbs Exclude emergent macrophytes</td>
<td><strong>1a.1</strong> Flooding by brackish water in summer and autumn for sufficient durations to exclude emergent macrophytes and to provide reliable growing conditions for salt-tolerant aquatic herbs.</td>
<td>Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS10 of 5 to 10 in summer and autumn Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS10 of 2 to 5 in winter and spring</td>
<td>Median salinity of water &lt;1 m deep downstream of XS10 on seasonal basis.</td>
</tr>
<tr>
<td>1b Shallow low salinity groundwater</td>
<td>Maintain plant growth between inundation events. Provide a source of low salinity water if inundated by saline water</td>
<td>Groundwater salinity predicted to be less than 3 Depth to water table predicted to be less than 0.2m at all times</td>
<td>No assessment possible</td>
<td></td>
</tr>
<tr>
<td>1c Frequent and prolonged flooding in winter and spring</td>
<td>Maintain dominance of <em>Phragmites australis</em> in dense, closed stands</td>
<td><em>Phragmites</em> habitat inundated to a depth of 0.25 to 0.5 m for a quarter of the time in winter and spring.</td>
<td>River level must exceed 1.25 to 1.5 m AHD at XS10 25% of the time between June and December with a maximum interval between events of 4 weeks.</td>
<td>Water level regime in winter - percent time water level exceeds 1, 1.25 or 1.5 m AHD at XS10 - median interval between events</td>
</tr>
<tr>
<td>1d Intermittent flooding in summer and autumn</td>
<td>Maintain dominance of <em>Phragmites australis</em> in dense, closed stands</td>
<td><em>Phragmites</em> habitat intermittently inundated to a depth of 0.25 to 0.5 m during summer. Years with no events may occur 1 year in 3</td>
<td>River level must exceed 1.25 to 1.5 m AHD at XS10 25% of the time between December and June with a maximum interval between events of 4 weeks. Years with no events may occur 1 year in 3.</td>
<td>Water level regime in summer - percent time water level exceeds 1, 1.25 or 1.5 m AHD at XS10 - % of years when water level does not exceed 1, 1.25 or 1.5 m AHD at XS10</td>
</tr>
</tbody>
</table>
3.2.2 Representative Objective – Coastal Saltmarsh (EVC 009)

Coastal Saltmarsh has not been mapped in Warrnambool Bioregion and therefore has no conservation rating.

Coastal Saltmarsh occupies shallow depressions at the outer edge of the floodplain. It occurs within 4 km of the estuary entrance on parts of the floodplain that are regularly inundated by high water levels. In the lower part of the estuary flood water is influenced by marine water and is more likely to be saline.

The depressions fill when estuary levels are high and the floodplain is inundated. This may be due to closure of the entrance, unusually high tides or flood flows. In contrast to the Estuarine Reedbed where water drains off the floodplain, water is captured in the depressions providing persistent flooding. There is little scope for seepage on the floodplain where the water table is shallow. Most water is therefore lost to evaporation and already brackish water will become more saline over time. The water filling the lagoons is most likely to be fresh in winter and spring when river flows cause flood events but is more likely to be saline in summer and autumn when high estuary levels will be caused by closure of the entrance and estuary salinities are generally higher. High flows in the following winter flush salts from the depressions to some degree.

The depressions therefore have a somewhat unpredictable water level and salinity regime. They are generally flooded in spring by brackish water and are generally muddy in summer when very high salinities will occur. Salinities tend to be higher near the estuary entrance where the marine influence is greatest (Table 3).

<table>
<thead>
<tr>
<th>Site (distance from estuary entrance)</th>
<th>Sampling Event</th>
<th>Salinity (EC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latrobe Creek (1 km)</td>
<td>September, December, February 1999 / 2000</td>
<td>17,000 to 21,000</td>
</tr>
<tr>
<td>Latrobe Creek (1 km)</td>
<td>May, August 2000</td>
<td>3,300 to 10,000</td>
</tr>
<tr>
<td>Wildlife Refuge (2 km)</td>
<td>September, December, February 1999 / 2000</td>
<td>7,000 to 10,000</td>
</tr>
<tr>
<td>Wildlife Refuge (2 km)</td>
<td>May, August 2000</td>
<td>2,700 to 3,300</td>
</tr>
<tr>
<td>Football Oval (2 km)</td>
<td>September, December, February 1999 / 2000</td>
<td>6,500 to 8,000</td>
</tr>
<tr>
<td>Football Oval (2 km)</td>
<td>May, August 2000</td>
<td>4,200 to 5,000</td>
</tr>
<tr>
<td>Northern Floodplain (9 km)</td>
<td>September, December 1999 (dry February)</td>
<td>500 to 1000</td>
</tr>
<tr>
<td>Northern Floodplain (9 km)</td>
<td>August 2000 (dry May)</td>
<td>600</td>
</tr>
</tbody>
</table>

The retention level of the depressions appears to be approximately 1 m above the wetland bed. However the depressions are broad and generally less than 0.5 m deep.
During spring the depressions support a diverse community of salt-tolerant wetland plants. When flooded in winter and spring a range of soft-leaved aquatic plants will be present including *Ruppia maritima*, *Potamogeton pectinatus* and the charophytes *Chara* sp., and *Nitella* sp. as well as filamentous algae (Breen 1982). Lower water levels in early summer will favour a range of herbland species, some of which will have initiated growth when flooded more deeply in spring. These species include *Cotula coronopifolia*, *C. reptans*, *Selliera radicans*, *Triglochin striata*, *Mimulus repens* and *Distichlis distichophylla* (Breen 1982). *Schoenoplectus validus* is a salt tolerant sedge which will also grow in this community in late spring and early summer.

*Sarcocornia quinqueflora* is also present in this community and is indicative of very high salinities. A comparative survey of groundwater dependent vegetation in the South East of South Australia found this species in areas with the shallowest groundwater (approximately 0.4 m below the surface – although sites subject to regular flooding were excluded from this study) and the highest salinities (average 64,000 EC) (Ecological Associates 2006). *Sarcocornia* is likely to continue to grow actively in summer and autumn after other species in this community become dormant due to high salinities. Species that become dormant during this period retreat to below-ground storage tissues and other resting stages.

Coastal Saltmarsh provides a contrasting habitat for fauna to the fringing Estuarine Wetlands and Estuarine Sedgelands because of the dominance of submerged aquatic macrophytes and forbs and the paucity of emergent macrophytes. Emergent species are excluded by the relatively higher salinities.

Coastal Saltmarsh species are adapted to variable flooding depths and will be relatively tolerant of prolonged closure of the estuary entrance (Table 3). Ecological and hydrological requirements are shown in Table 4 and Figure 3.
**Figure 3: Conceptual Model of Coastal Salt Marsh ecological and hydrological objectives**

**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*

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*Lloyd Environmental*
### Table 4. Ecological and Hydrological Objectives for Coastal Salt Marsh

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a</td>
<td>Depth and extent of floodplain depressions</td>
<td>Retain water from high estuary levels, local rainfall.</td>
<td>Geomorphic processes to maintain depression depth of approximately 0.5 m and current extent</td>
<td><strong>Possible Assessment Approaches</strong></td>
</tr>
<tr>
<td>2b</td>
<td>Flooding by saline water in summer and autumn</td>
<td>Promote salt-tolerant charaphytes, herbs, grasses and forbs Exclude emergent macrophytes</td>
<td>Peak salinity (between refreshing events) of 7.5 to 20 in summer and autumn in depressions</td>
<td>Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS10 exceeds 5 in summer and autumn.</td>
</tr>
<tr>
<td>2c</td>
<td>Flooding by brackish water in winter and spring</td>
<td>Promote salt-tolerant charaphytes, herbs, grasses and forbs Exclude emergent macrophytes</td>
<td>Peak salinity (between refreshing events) of 5 in winter and spring in depressions</td>
<td>Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS10 exceeds 3 in winter and spring</td>
</tr>
<tr>
<td>2d</td>
<td>Persistent flooding in winter and spring by fresh / brackish water</td>
<td>Promote salt-tolerant charaphytes and submerged vascular macrophytes Exclude emergent macrophytes</td>
<td>Persistent flooding to depth of 0.25 to 0.5 m (predominantly 0.5 m) from May to October</td>
<td>Median interval between events where water level at XS10 exceeds 1.0 m AHD is 2 weeks in May to October</td>
</tr>
<tr>
<td>2e</td>
<td>Shallow flooding in late spring / early summer</td>
<td>Provide habitat for salt-tolerant grasses, sedges, herbs and forbs</td>
<td>Average water level from November to December is 50% of average water level from August to September</td>
<td>Median interval between events where water level at XS10 exceeds 1 m AHD is 3 weeks in summer and autumn</td>
</tr>
<tr>
<td>2f</td>
<td>Intermittent flooding in summer and autumn</td>
<td>Maintain <em>Sarcocornia quinquelora</em></td>
<td>Depressions less than 20% of maximum depth 80% of the time over summer autumn</td>
<td>Median interval between events where water level at XS10 exceeds 1 m AHD is 8 weeks in summer and autumn</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------------------------</td>
<td>-----------------------------</td>
<td>--------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>2g Waterlogging by saline groundwater in summer and autumn</td>
<td>Maintain <em>Sarcocornia quinqueflora</em></td>
<td>Groundwater depth less than 0.4 m to maintain evaporative concentration of salts in surface soil</td>
<td>Groundwater salinity 10 to 60</td>
<td>No assessment possible</td>
</tr>
</tbody>
</table>
3.2.3 Representative Objective – Estuarine Scrub (EVC 953)

Estuarine Scrub is not documented in the Warrnambool Plains Bioregion.

Estuarine Scrub habitat is interpreted to occur on the broad flats of the floodplain upstream of the current Estuarine Reedbed extent. Estuarine Scrub habitat therefore commences 3 km from the estuary entrance and extends 5.5 km, where it meets the Riparian Forest. These areas are subject to waterlogging throughout winter, spring and early summer and localised flooding where runoff from the surrounding hillslopes discharges to the watercourse. They are subject to inundation when estuary levels are high, particularly in winter and spring, in events which may last several days. This area is also affected by high estuary levels when the entrance is closed.

Vegetation has been almost entirely cleared from this area to provide pasture for stock. Drains have been dug to direct runoff from the local hillslopes more directly to the estuary channel and to minimise floodplain inundation. Remnant vegetation occurs in a narrow strip along the watercourse, providing an indication of the likely vegetation elsewhere. Species which have been observed are identified below by (o); those which are interpreted to have occurred are marked (i).

The dominant vegetation type would have been a tussock sedgeland of Gahnia species (o), most likely Gahnia filum (i) and Gahnia trifida (i). Leptospermum lanigerum (o) would have formed a very open overstorey but may have been present more densely on local rises. Leptospermum lanigerum remains on the natural levee adjacent to the channel and at the foot of the hill slopes surrounding the floodplain. Within the tussock sedgland would have been a variety of waterlogging-tolerant and salt-tolerant species: Scheonoplectus validus (o), Poa poiformis (o), P. labillardieri (i), Distichlis distichophylla (o), Triglochin striata (i) and Bolboschoenus caldwellii (o).

Deeper areas, particularly those subject to regular flushing and inundation from freshwater runoff would support Baumea species such as B. arthrophylla (i) and B. articulata (o) and a variety of aquatic plants: Phragmites australis (o), Persicaria descipients (o), Scheonoplectus validus (o) and Triglochin procera (o).

Gahnia filum and Gahnia trifida typically occur in areas subject to seasonal waterlogging (Brownlow 1997) and rare inundation. This is similar to to the habitat requirements of Leptospermum lanigerum, although typically more saline. Baumea articulata is found in mildly saline wetlands with reported salinities of 250 to 650 EC at Kulicup Swamp and 1900 to 5800 EC at Noobijup Swamp in Western Australia (Ogden and Froend 1998).

While a relatively minor component of this area, the presence of Leptospermum lanigerum indicates that this area is not subject to prolonged or frequent inundation. This species typically occurs above the normal high water level in wetlands (Taylor 2006). Ecological and hydrological requirements are shown in Table 5 and Figure 4.
Plant assemblages:

A On seasonally waterlogged floodplain - *Ghania* tussock sedgeland (*Schoenoplectus validus*, *Poa spp.*, *Bolboschoenus*) with overstorey of *Leptospermum lanigerum* on higher ground; groundwater dependant

B On lower points in the floodplain, inundated to a greater depth by winter freshes - community includes: *Baumea spp.*, *Persicaria decipens*, *Phragmites australis*, *Triglochin procera*, *Schoenoplectus validus*

![Diagram of Conceptual Model of Estuarine Scrub ecological and hydrological objectives](image)

Figure 4: Conceptual Model of Estuarine Scrub ecological and hydrological objectives
### Table 5. Ecological and Hydrological Objectives for Estuarine Scrub

<table>
<thead>
<tr>
<th>Physical Component</th>
<th>Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Approaches Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a Seasonal waterlogging</td>
<td>Maintain <em>Gahnia</em> tussock sedgeland and <em>Leptospermum lanigerum</em></td>
<td>Groundwater less than 0.2m deep for 4 to 8 months of the year</td>
<td></td>
<td></td>
<td>No assessment possible</td>
</tr>
<tr>
<td>3b Low salinity groundwater</td>
<td>Maintain growth and health of <em>L. lanigerum</em> and <em>Gahnia</em> tussock sedgeland</td>
<td>Groundwater salinity less than 3000 EC</td>
<td></td>
<td></td>
<td>No assessment possible</td>
</tr>
<tr>
<td>3c Infrequent inundation</td>
<td>Maintain <em>Gahnia</em> tussock sedgeland and <em>Leptospermum lanigerum</em>. Prevent invasion by <em>Phragmites australis</em>.</td>
<td>Less than 10 inundation events per year. No single inundation event longer than 10 days duration</td>
<td>Median duration of events where water level exceeds 1.5m AHD at XS9 is 1 to 2 weeks. Frequency of events where water level exceeds 1.5 m at XS9 is 5 per year.</td>
<td>Median duration of events exceeding thresholds at XS9 Frequency of events exceeding thresholds at XS9</td>
<td></td>
</tr>
<tr>
<td>3d Inundation by brackish to fresh surface water</td>
<td>Maintain <em>Gahnia</em> tussock sedgeland and <em>Leptospermum lanigerum</em>. Prevent invasion by <em>Bolboschoenus caldwellii</em> and <em>Juncus kraussii</em>.</td>
<td>Median salinities in shallow (&lt;1m deep) estuary water downstream of XS9 is less than 3 in summer and autumn. Winter and spring salinities may be this salinity or fresher.</td>
<td>Median salinity of water &lt;1 m deep downstream of XS9 on seasonal basis.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2.4 **Representative Objective – Swamp Scrub (EVC 053)**

Swamp Scrub has an endangered conservation rating in the Warrnambool Plains Bioregion.

Swamp Scrub occupies the lower slopes of the hills and dunes surrounding the estuary. These areas are subject to perennial waterlogging due to groundwater discharge. They may be subject to rare, brief inundation when estuary levels are high.

The dominant overstorey plant species is *Leptospermum lanigerum* (Woolly Tea Tree) which generally forms a closed canopy with little other understorey vegetation. The canopy may be more open at the perimeter of the floodplain, particularly near the floodplain depressions. Where the canopy is more open the understorey includes *Distichlis distichophylla* (Emu Grass), *Poa* sp. (*P. poiformis* or *P. labillardieri*), *Bolboschoenus caldwellii*. The presence of these species, particularly *B. caldwellii*, is indicative of persistent inundation with brackish water during winter and spring. The sparse canopy in these areas suggests these conditions are sub-optimal for *L. lanigerum* and are at the wetter end of the habitat.

Dense sedgelands of *Gahnia* species (*G. trifida, G. sieberiana*) occur adjacent to the *L. lanigerum* woodland.

A survey of groundwater-dependent vegetation in the South East of South Australia included *L. lanigerum* woodlands (Ecological Associates 2006). The survey found that *L. lanigerum* woodlands occurred predominantly in soils with a high pH (more than 8.5) relative to other species assessed. The woodlands were subject to perennially or frequently waterlogged soils. Where the water table was less than 0.5 m deep groundwater salinities were less than 7,000 EC and soils tended to be rich in clay. However salinities as high as 8,000 EC were reported where the water table was more than 1 m deep in areas where soils tended to be sandier. The woodland did not occur in areas subject to regular inundation.

*Leptospermum lanigerum* woodlands provide habitat for a population of *Pterostylis tenuissima* (Swamp Greenhood) in the Gellibrand Estuary. This species is listed as Vulnerable under the Commonwealth Environment Protection and Biodiversity Conservation Act and is listed as Vulnerable in Victoria. The distribution of this species is restricted to Woolly Tea Tree woodlands in coastal areas from western Victoria to south-eastern South Australia. Ecological and hydrological requirements are shown in Table 6 and Figure 6.
A survey of 134 *P. tenuissima* individuals at Piccaninnie Ponds in South Australia found this species in *L. lanigerum* woodland surrounding wetlands (Taylor 2006). The plant was found above the elevation occupied by emergent macrophytes and outside areas subject to normal seasonal inundation. Approximately one third of the population occurred where the depth to groundwater was less than 0.35 m but none occurred in flooded areas (Figure 4). The groundwater salinity at this site is approximately 1000 EC (Ecological Associates unpublished data). *Pterostylis tenuissima* is almost certainly intolerant of extended or permanent inundation (Taylor 2006).
Plant assemblages:

A On higher ground - *Ghania* tussock sedgeland

B At break of slope - Closed canopy woodland of *Leptospermum lanigerum*, with understorey of *Distichlis, Poa spp.* and *Pterostylis tenuissima*

C Near floodplain depressions, inundated by winter freshes - *Distichlis, Poa spp.*, *Schoenoplectus pungens, Bolboschoenus caldwellii*

Figure 6: Conceptual Model of Swamp Scrub ecological and hydrological objectives
Table 6. Ecological and Hydrological Objectives for Swamp Scrub

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a Perennial waterlogging</td>
<td>Maintain dense <em>L. lanigerum</em> canopy and</td>
<td>Groundwater less than 0.2m deep at all times</td>
<td></td>
<td>No assessment possible</td>
</tr>
<tr>
<td>4b Low salinity groundwater</td>
<td>Maintain growth and health of <em>L. lanigerum, P. tenuissima</em></td>
<td>Groundwater salinity less than 1000 EC</td>
<td></td>
<td>No assessment possible</td>
</tr>
<tr>
<td>4c Brief and infrequent inundation</td>
<td>Exclude aquatic macrophytes from understorey. Prevent flood stress to <em>L. lanigerum, P. tenuissima.</em></td>
<td>Less than 5 inundation events per year. No single inundation event longer than 5 days duration</td>
<td></td>
<td>Median duration of events exceeding thresholds at XS10</td>
</tr>
</tbody>
</table>

Median duration of events where water level exceeds 2.0m AHD at XS10 is less than 1 week. Frequency of events where water level exceeds 2.0 m at XS10 is less than 5 per year. Zero events per year is acceptable.
3.2.5 Representative Objective – Herb-rich Foothill Forest (EVC 23)

Herb-rich Foothill Forest has a conservation rating of vulnerable in the Warrnambool Plains bioregion.

There is very little native vegetation in the upper part of the estuary to indicate the original plant communities present. The overstorey comprises *Acacia melanoxylon* and *Eucalyptus ovata* with a mid-storey of scattered *Leptospermum lanigerum*. Woody weeds are common and include *Prunus*, *Salix* sp. and *Rubus* sp. The understorey is grazed and is dominated by pasture grasses but includes *Poa tenua*, *Paspalum distichum*, *Persicaria descpiens* and *Gratiola peruviana*.

*Acacia melanoxylon* and *Eucalyptus ovata* are typically found in areas of shallow groundwater that are not subject to inundation (Forestry SA 2005).

This vegetation is most likely sustained by shallow, low salinity groundwater. It would not require flooding but would tolerate brief, rare flooding events. Ecological and hydrological requirements are shown in Table 7.
### Table 7. Ecological and Hydrological Objectives for Herb-rich Foothill Forest

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
</table>
| 5a Shallow low-salinity groundwater | Maintain *Acacia melanoxylon* and *Eucalyptus ovata* overstorey | Groundwater depth less than 2m at all times  
Groundwater salinity less than 1000 EC | No assessment possible |
| 5b Rare, brief flooding | Maintain *Acacia melanoxylon* and *Eucalyptus ovata* overstorey | Flooded to a maximum of 10 days per year. | Water level exceeds 3.0m AHD at XS2 for a total of less than 10 days per year (median). | Median days per year water level exceeds 3.0m AHD at XS2 |
3.2.6 Representative Objective – Sea-grass Meadow (EVC 845)

Sea-grass Meadow has not been mapped as an EVC in the Warrnambool Plain Bioregion and no bioregional conservation status has been assigned to it. 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.” and occurs in the lower estuary, up to 1 km from the entrance. It was observed in the shallow sands in this area but may occur in deeper water as well. The species growing in the Gellibrand Estuary have not been identified, but based on the seagrasses mapped in regional estuaries, the dominant species is expected to be Zostera muelleri although Heterozostera spp. (identified as H. tasmanica before a current taxonomic revision) and Ruppia spp. are also common both locally (Ierodiaconou & Laurenson, 2002; Pope, 2006) as well as in the minor inlets of eastern Victoria (Blake et al. 2000) and more generally in estuaries between Adelaide and southern NSW (Larkum et al., 1989). Ruppia is a key genus for another EVC - Saline Aquatic Meadow (EVC 842) and mixed beds – while not described as a separate EVC - are common in estuaries of the region.

Of the species likely to be present, H. tasmanica is generally subtidal and can only exist where it is exposed to the atmosphere for minimum periods (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). In contrast with the more stable distributions and large losses of Z. muelleri and H. tasmanica in bays and larger inlets, seagrasses in intermittently-open estuaries have been shown to have large positive and negative changes in extent in response to changes in inundation and salinity over interannual timeframes (Pope, 2006).

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).

Ruppia spp. frequently undergo large, often seasonal, changes in coverage and biomass and are capable of living in environments where inundation and salinity vary dramatically. For example, in Australia, Ruppia species are known to exist in environments that are inundated for as little as two months a year and across salinity ranges between 0 and 220/oo total dissolved solutes (Brock, 1985). Of the Ruppia species recorded in southern Australian estuaries, R.
polycarpa and *R. tuberosa* typically have ‘annual’ life cycles and are found primarily in temporary salt lakes, while *R. megacarpa* has a nominally more ‘perennial’ life history, although it has been consistently observed to have an ‘annual’ habit in ephemeral salt-lake systems (Brock, 1982b; Jacobs & Brock, 1982; Brock & Lane, 1983). Salinity is known to affect seed germination of two of the species in different ways; *R. megacarpa* is more likely to germinate in fresh water and *R. tuberosa* is more likely to germinate in hypersaline water (Brock, 1982a).

Seagrass meadows are found in water depths of up to 2.5m in estuaries of western Victoria and South Australia and often occurs as a fringing band around the edges of deeper lagoons (Shepherd & Robertson, 1989; Ierodiaconou & Laurenson, 2002). Seagrasses colonise mud, silt and sand, using their extensive rhizomes to anchor themselves. The leaves retard currents and increase sedimentation in their vicinity. 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 and are shown in Table 8 and Figure 7.
Figure 7: Conceptual Model of Seagrass ecological and hydrological objectives

- Flushing flows prevent sediment accumulation and decrease turbidity
- Light required for photosynthesis
- Turbidity affects euphotic depth
- Sediment resuspension
- Intertidal Zostera
- Subtidal Heterozostera

High Tide

Low Tide
### Table 8. Ecological and Hydrological Objectives for Sea-grass Meadow

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>6a Salinities</td>
<td>Seagrass meadows tolerate salinities above and below that of sea water</td>
<td>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 a salinity of 6) in the lowest kilometre. Freshwater pulses may be trigger for germination. Prolonged fresh conditions will remove <em>Heterozostera</em> and <em>Zostera</em>.</td>
<td>Flows required to extend salt upstream</td>
<td>Sea water enters the estuary at flows less than 465 ML/d (Sherwood, 1983 ). Prolonged events above this will result in fresh conditions. Events below this will result in saline condition in the lowest 1 km of estuary. Evaluate from Salt Wedge Model in terms of extent of salt. Evaluate events from hydrological analysis. This could determine the MAX baseflow.</td>
</tr>
<tr>
<td>6b Water Level</td>
<td><em>Zostera muelleri</em></td>
<td>Stable water levels but mostly inundated</td>
<td>Water level (within normal tidal range)</td>
<td>Water level monitoring</td>
</tr>
<tr>
<td>6c Turbidity</td>
<td>Poor light penetration can reduce seagrass photosynthesis and growth</td>
<td>Maintain euphotic conditions within 1 km of estuary entrance.</td>
<td>Flows required to extend salt upstream</td>
<td>See salinity method above</td>
</tr>
<tr>
<td>6d Sedimentation</td>
<td>Excessive sedimentation smothers seagrasses</td>
<td>Provide regular flushing flows to prevent excessive accumulation of sediment within 1 km of estuary entrance.</td>
<td>River flow (shear stress to move silt but not large enough to shift/disturb the seagrass (uproot the bed))</td>
<td>Sediment transport threshold based on hydraulic analysis Hydrological analysis of events</td>
</tr>
</tbody>
</table>
3.3 Fish and Aquatic Fauna

3.3.1 Introduction

The fish community of the Gellibrand estuary consist of 30 species (Table 9) which occupy a range of habitats within the estuary (O’May and Wallace 2001, EarthTech 2005, Barton and Sherwood 2004, DSE FIS Database, Koehn and O’Connor 1990).

Three broad zones can be recognised in the Gellibrand estuary:

**Marine-dominated zone** downstream of the recreation reserve bridge where marine water is at the surface, marine macrophytes (*Zostera, Heterozostera*) grow on the bed,.

The entrance to the Gellibrand River estuary is narrow and shallow, during inspection it was 6m wide and 0.5m deep. The substratum is clean sand, with little submerged aquatic vegetation. There is some drift algae and submerged woody debris in this area that provide fish with habitat. Inside the estuary there are extensive beds 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 when it is flooded.

There are some seagrass beds in the system. These do not cover a large area, but it is a significant habitat type. Rocky habitat and deep holes are a feature of this site as the river abuts a rock outcrop as it runs to the sea. There are undercut banks and the open water in the channel itself, which are also important fish habitats.

**Transitional zone**. At the Gellibrand, from marine zone (about Recreation Rd bridge) to the limit of the salt wedge (upstream of Bowker’s Bridge).

The channel narrows further upstream, and the water appears to become slightly turbid. There is a saltwedge structure in the middle region of the system, which is important to fish larvae and juvenile fish. This zone is flanked by large and extensive reedbed wetlands which are inundated in high spring tides, high flows and when the mouth is closed. Submerged aquatic vegetation beds (e.g. *Triglochin* and *Persicaria*) increase in size, frequency and diversity with increasing distance upstream within this zone.

**Freshwater zone**. Influenced by tide but not strongly saline. At the Gellibrand, this is from the tip of the salt wedge (upstream of Bowker’s Bridge) to the Great Ocean Rd.

Further upstream the riparian zone becomes dominated by trees and riparian shrubs which provides habitat as overhanging vegetation and woody debris. There is also some undercutting of banks which forms an important habitat structure for fish. There is significant aquatic submerged vegetation, reed beds, narrow instream benches and a wide shallow floodplain.
3.3.2  Fish Conservation Values of the Estuary

In the Gellibrand estuary only one species is listed as vulnerable, (Australian Grayling), (Table 9). There are however 16 species which are important either as a recreational or commercial fisheries species (Table 9).

3.3.3  Biology and Distribution of Fish

The fish within estuaries can be divided into 3 groups according to their biology and distribution (Figure 8). These groups include some species which live solely within the estuary or in freshwater and saline environments:

- Estuarine Residents
- Estuarine Dependent
- Estuarine Opportunists

**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 which they can tolerate for some-time (e.g. Black Bream).

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

**Marine derived** fish (some are Anadromous) are estuarine dependent species which mostly live in the sea but migrate into the estuary to breed or for recruitment (e.g. King George Whiting juveniles use estuaries as 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. Australian Grayling and Common, Spotted and Climbing galaxiids) or in the sea (*Anguilla australis*) 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 estuarine conditions 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 salinity. These species will be displaced from the estuary during high freshwater inflows.

Estuarine opportunist species from marine waters will be limited in their use of the estuary by the degree of entrance opening. The entrance to the Gellibrand estuary is often closed. Even when
open, the entrance is often shallow and narrow, and there can be some head loss across the entrance. These factors would restrict use of the system by many of the marine species. Despite this almost one third of the species within the estuary are regarded as estuarine opportunist species derived from the marine environment.

Many of the marine opportunist species would occur in the lower to middle sections of the estuary. The degree to which the species move upstream will depend on the flows in the system, and related reductions in salinity. During low flow periods, higher salinity waters may penetrate upstream, allowing marine species greater range of the estuary. Higher flows will reduce the salinities in the estuary, restricting the marine species to the lower reaches of the estuary. In very high flow periods, the whole estuary may be flushed, and marine species will likely exit the system.

Figure 8. Fish groups and their distribution in the Gellibrand Estuary
### Table 9. Fish groups in the Gellibrand Estuary (Barton and Sherwood 2004, DSE FIS Database, Koehn and O’Connor 1990)

<table>
<thead>
<tr>
<th>Estuary Fish Group</th>
<th>Sub-Types</th>
<th>Example Species present in Gellibrand</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Estuarine Residents</td>
<td>n/a</td>
<td>Estuary Perch C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Black Bream C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blue Spot Goby</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tamar Goby</td>
</tr>
<tr>
<td>B: Estuarine Dependent</td>
<td>Marine Derived (Anadromous)</td>
<td>Congolli (Tupong) C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>King George Whiting C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smallmouth Hardyhead</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elongate Hardyhead</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mulloway C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pouched Lamprey</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short-headed Lamprey</td>
</tr>
<tr>
<td></td>
<td>Freshwater Derived (Catadromous)</td>
<td>Short-finned Eel C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Australian Grayling#</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Common Jollytail</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Climbing Galaxias</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spotted Galaxias</td>
</tr>
<tr>
<td>C: Estuarine Opportunists</td>
<td>Marine Derived</td>
<td>Longsnout Flounder C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Australian Herring (tommy rough) C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Australian Salmon C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth Toadfish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sea Mullet C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yellow-Eyed Mullet C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long-snouted Flounder C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Luderick C,R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silver Trevally C,R</td>
</tr>
<tr>
<td></td>
<td>Freshwater Derived</td>
<td>Big-headed Gudgeons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Australian Smelt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown Trout R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>River Blackfish R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Southern Pigmy Perch</td>
</tr>
</tbody>
</table>

# Australian Graying is listed as vulnerable under the Victorian FFG Act and the Australian Government’s EPBC Act

C These species have commercial fisheries value

R These species have recreational fisheries value
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 Table 10 and Figure 9.

**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 ppt and 21 °C, 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 ppt (Ramm 1986). Nicholson *et al.* (2004) found that bream eggs are neutrally buoyant in salinities 16-20 ppt, and therefore float in the halocline. Eggs generally hatch two days after fertilisation, but embryos fail to develop in salinities below 5 ppt (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 ppt, Ramm (1986) suggests these lifestages tolerate a wide range of salinity (from 0 to 32 ppt). 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 impacted by 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 ppt. Some 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.
Freshwater flows are important to Black Bream moving upstream into freshwaters at times and retreating back downstream, if large flows occur. Black Bream move upstream in response to freshes in summer for feeding, parasite removal, etc.

Black Bream live their entire life cycle within estuaries. Mature Black Bream spawn in the salt wedge at salinities between 15 and 20.

Black Bream eggs remain suspended. Black Bream eggs hatch in 2 days and larvae settle into seagrass beds or Phragmites stands and then mature to begin cycle again.

Figure 9: Black Bream Conceptual Model ecological and hydrological objectives
### Table 10. Ecological and hydrological objectives for Black Bream

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
</table>
| 7a 1 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) | Report length of estuarine conditions for 3-4 baseflows? (steady state inflow over a spring/neap cycle). Refer to natural conditions for reality check.  
  Ignore interactions with flow peaks and length of estuarine conditions |
| 7b 2 Salt wedge            | Spawning/egg survival      | Salinity between 15 and 20 in middle reaches, where *Phragmites* stands largest  
DO >5 mg/L in bottom water during spawning season Sep to Dec  
Top (0.1 m) water salinity less than 10 AND bottom (0.5 m above bottom) salinity greater than 25.  
DO/residence time | Presence of halocline between 15 and 20  
Halocline present as described by longitudinal plots (2dv)  
Use residence time to approximate DO - set maximum residence time of 2 days anywhere in water below halocline. | Salinity of 20 no further down than XS11 (lowest Bridge) at the surface on the ebb of the spring tide  
Halocline present as described by longitudinal plots (2dv)  
Use residence time to approximate DO - set maximum residence time of 2 days anywhere in water below halocline. |
| 7c 3 Phragmites / seagrass | Refuge/feeding for settlement and post settlement juveniles | Inundated vegetation near salinity 15-20 | specify flow band which positions the halocline near the required vegetation type (seagrass or Phragmites) | Determine flow band to provide halocline less than XS3 for seagrass beds  
Determine flow band to provide halocline d/s Rivernook Bridge for Phragmites (pref XS9) |
Information for conceptual model for black bream – Life history in the small estuaries, with reference to freshwater flows and salt wedge dynamics

- The movement, spawning and recruitment of black bream are all likely to impacted by freshwater flows.

- Black bream are capable of withstanding low salinities, but can move extensively to avoid such conditions.

- High flow events that reduce the salinity in/of the system will probably force fish to retreat downstream until the flows subside.

- In summer, there is some evidence that fish will move upstream in response to freshwater flows - reasons unknown, but could related to feeding, removal of parasites etc.

- The salt wedge is critical habitat for spawning, with fish preferring water between 15 and 20 ppt.

- The salt wedge should be as extensive as possible - maximising areas with salinities 18 to 20 ppt.

- Salt wedge should also overlap in time and space with juvenile habitat - including Phragmites, woody debris and seagrass

- High flows during spawning probably flush eggs and larvae out of the system, and unclear what effects this has - but probably not positive.

- Some turbidity associated with the salt wedge may be important in providing shelter for larval and juvenile fish.

- As above, 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.

- Eggs and larvae have narrow range of salinities for development, so flow into the system should maximise area of estuary with salinities 15 to 22 ppt between August and November.
3.3.5 Representative Objective – King George whiting (Sillaginodes punctata) – Estuarine Dependent (Marine Derived)

Distribution and habitat

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). Juvenile fish prefer shallow vegetated habitats (especially seagrass) in sheltered estuaries and embayments, while older fish are common in deeper sandy patches among vegetation. Ecological and hydrological requirements are shown in Table 11 and Figure 10.

Reproduction and spawning

King George whiting from Victorian waters are spawned between May and July (Jenkins and May 1994). Fish do not use bays or inlets for spawning (Jenkins 1986), and the 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).

Information for conceptual model for King George whiting – Life history in the small estuaries, with reference to freshwater flows and salt wedge dynamics

- King George whiting are estuarine dependent species.
- The sheltered, highly productive environments of lower and mid estuaries are likely to be provide habitat for juvenile King George whiting.
- Larvae are likely to enter systems during strong flood tides, and then settle into sheltered habitats that provide food and refuge from predation (e.g. seagrass).
- Larger fish may enter the estuary periodically.

- Fish may remain in the estuary for significant periods of time, but are likely to move out during flood events.

- The lower salinities in the upper region of the estuary probably inhibit the movement of fish upstream.

- While flood events could certainly encourage fish to leave the estuary, it is unlikely that smaller changes in flow and salt wedge structure influence the distribution of fish in the lower estuary.

- There may be an indirect link between fish and flow through potential impacts of freshwater on seagrass health and distribution in the lower estuary.

- Flows will be important in flushing stagnant deoxygenated water from the system. This will help to ensure healthy benthic communities that are main dietary items.
King George Whiting are estuarine dependent species which breeds in marine waters and their larvae move into estuaries in August to October. Larvae recruit to seagrass and juveniles remain in protected areas but as they grow they inhabit more open waters. Sub-Adult fish move out of Estuary prior to reaching breeding age. High freshwater flows prevent fish moving up into the mid and upper Estuary and high flows are required to open mouth so larvae can migrate into Estuary.

Figure 10: King George Whiting Conceptual Model ecological and hydrological objectives
<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>8a 1 Entrance of larvae to estuary</td>
<td>Allow migration to estuary from the sea</td>
<td>Open Mouth August to late October</td>
<td>Mouth 30-50cm deep during period August to October (inclusive)</td>
<td>Empirical relationship derived using Sherwood (2006) research showing 100ML/d to keep mouth open. A specific tool will need to be developed for other estuaries possibly using geomorphology, hydrology and hydraulics. Estuary watch data might be used to calibrate above.</td>
</tr>
<tr>
<td>8b 2 Larval fish habitat in estuary</td>
<td>Provide habitat for larvae to survive and grow</td>
<td>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. Phragmites may provide habitats at high tide, or if they are permanently inundated, but no great evidence of this. KGW will prefer access to seagrass or other subtidal veg. Though there is some evidence that fish use un veg mud/sand in sheltered area – e.g. Corio Bay.</td>
<td>Salinity greater than 25 in bottom 1 m more than 80% of the time. KGW primarily marine species, so probably likely to be restricted to lower regions of estuary. Below XS12 (lowest Bridge). DO/residence time</td>
<td>A) Determine steady state conditions which create salinity greater than 25 in bottom 1m more than 80% of the time below XS12 (lowest Bridge) during spring and summer. B) Use residence time to approximate DO - set maximum residence time of 2 days below XS12 (lowest Bridge) in bottom 1m.</td>
</tr>
</tbody>
</table>
3.3.6 Representative Objective – Australian Grayling (*Prototroctes maraena*) - Estuarine Dependent (Freshwater Derived)

Australian Grayling are an important estuarine representative species as they spend the majority of their time in freshwater but are dependent upon estuaries and coastal zones for early larval development and the development and growth of juveniles returning from the sea. They also require access to the sea and therefore mouth opening and closures are important to these fish. In addition, the fish are regarded as vulnerable by the Victoria Flora and Fauna Guarantee Act (FFG Act) and the Australian Government’s Environment Protection and Biodiversity Act (EPBC ACT). Ecological and hydrological requirements are shown in Table 12 and Figure 11.

**Habitat**

Australian Grayling spend the majority of their adult life in freshwater, with the adults moving downstream to breed. Larvae are washed to the sea and return to mature in the estuary (Bishop & Bell 1978a &b; Bell et al. 1980; Berra and Cadwallader 1983; Hall & Harrington 1989). As adults Australian Grayling are found in clear, gravel-bottomed streams with alternating pools and riffles, rocky streams and muddy-bottomed habitats. Grayling require a well oxygenated stream, which is promoted by flowing water.

**Movement**

Grayling migrate between freshwater streams, the estuary and the ocean (Bishop & Bell 1978a). Adults move downstream in February to May to spawn in freshwater (mostly May in Victoria), triggered by a high flow event and then juveniles return at the end of their first year to spend time in the estuary (May to Oct) before migrating upstream as they grow in October to December for up to 3 years until they mature (Bishop & Bell 1978a &b; Bell et al. 1980; Berra and Cadwallader 1983; Hall & Harrington 1989). Grayling can swim up riffles having flows of 2-4m/s, have sustained swimming at 0.6m/sec but their preferred flow is 0.2 to 0.35 m/s.

**Reproduction**

Grayling require a high flow event, possibly also associated with a drop in water temperature (to 13.5 - 12°C), and a full moon to last quarter lunar phase for breeding (Jackson and Koehn 1988; Hall and Harrington 1989; O’Connor and Mahoney 2000). The eggs are classified as demersal non-adhesive eggs which are scattered in the water column and develop in freshwater. Fry are slender and buoyant and are washed out to sea (mostly May – July) (Berra 1982; Bishop and Bell 1978b; Crook et al 2006). Normally eggs require freshwater (below 5 ppt) to develop, however, larvae can withstand salinities up to sea water. Juveniles return at the end of their first year to spend time in the estuary (May to Oct) before migrating upstream as they grow (Oct to Dec) for up to 3 years until they mature (Bishop and Bell 1978a and b; Bell et al. 1980; Berra and Cadwallader 1983; Hall and Harrington 1989).
Information for conceptual model for Australian Grayling

- Maintain permanent deep pools of minimum depth 3 m
- Provide breeding trigger and recruitment in freshwater above estuary.
- High flow fresh to create salt-wedge and mixing in estuary between February to May and to inundate vegetation beds and instream benches
- Provide flows to allow longitudinal connection in channel for adult grayling movement
- Provide flows to open mouth to allow downstream migration of larvae between May and July
- Provide flows to open mouth to allow juveniles to migrate upstream from sea between October and December
A Freshwater flows provide for longitudinal connections and breeding triggers for adult Australian Grayling. These freshwater fish which use estuaries as juveniles and breed in freshwaters in May. Larvae are washed out to sea in May to July and juveniles begin to mature at sea in August. In May to October sub-adult fish spend time in the estuary before upstream migrations into freshwaters in October to December. High freshwater flows allow mouth opening to allow larvae to move out to sea in May to July and upstream into the estuary and upstream between October to December.

Figure 11: Australian Grayling Conceptual Model ecological and hydrological objectives
Table 12. Ecological and hydrological objectives for Australian Grayling

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>9a</td>
<td>1 Flow Fresh</td>
<td>Adults spawning</td>
<td>Flow fresh in late autumn</td>
<td>Occurs in water below 1-2 Salinity – therefore top section of estuary or lowest freshwater reach</td>
</tr>
<tr>
<td>9b</td>
<td>2 Freshwater in upper estuary</td>
<td>Egg development</td>
<td>Larvae take 14 + days to develop, they require freshes, required for a few days to develop in &lt;5 salinity High O₂ in pools to allow survival</td>
<td>Flow event Salinity concentration &lt;5 O₂ concentration &gt;5 mg/L Autumn or Winter</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
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<td>--------------------------------</td>
</tr>
<tr>
<td>9c 3 Estuary Mouth State</td>
<td>Marine Migration by larvae</td>
<td>High Flow Fresh</td>
<td>Require open mouth during May to July, salinity is not critical so up to 35 is OK for periods of up to 7 days with 2-3 events during the season</td>
<td>Determine flow required to cause/sustain a mouth opening event using the empirical data of Sherwood (2006). Estimates range from high end at 100ML/d (Sherwood 2006) to low end estimate of EarthTech FLOW Study &gt;260ML/d (4f5 = Dec – May 4 times per year, also April – May 4f5 – low flow fresh = Grayling breeding trigger overridden by disturbance flow)</td>
</tr>
<tr>
<td>9d 4 Estuary Mouth State</td>
<td>Migratory cue to return to estuary</td>
<td>uncertain</td>
<td>Met by flows required to provide passage?</td>
<td>No assessment required</td>
</tr>
<tr>
<td>9e 5 Estuary Mouth State</td>
<td>Freshwater Migration to estuary from sea by juveniles</td>
<td>30-50cm deep river mouth</td>
<td>Require open mouth, 30-50cm deep, during Oct-Dec, salinity not material, duration should be for up to 7 days with 2-3 events during the season</td>
<td>Oct-Dec, min duration of mouth opening of 3 days min 2 events per season</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
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</tbody>
</table>
| 9f 6 Low Flow fresh | Migration from estuary to freshwater reaches by juveniles | flow cue to migrate upstream | Require access to upstream reaches over riffles - Upstream riffle depth at least 0.3m  
 At least 2 events in spring (to provide 2 opportunities)  
 At the site of the riffle/rock bar (which has not been surveyed to date)  
 Dec – May, min 4 events | Thalweg depth at upstream bar/riffle >30cm |
3.3.7 Representative Objective – Common Jollytail (*Galaxias maculatus*) -
Estuarine Dependent (Freshwater Derived)

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 Gondwanian distribution. They are a significant species in the ecosystem as a food source for other fish and birds and are a significant invertebrate predator (Koehn and O'Connor 1990; McDowall 1996; Merrick and Schmida 1984). Ecological and hydrological requirements are shown in Table 13 and Figure 12.

**Habitat**

Common jollytails are able to utilise a wide range of habitats and have a preference for still or slow moving waters. They are capable of withstanding 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**

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

**Reproduction**

Common jollytails spawn 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 & Backhouse 1983).

**Information for conceptual model for Common Jollytail**

- Provide flows to allow longitudinal connection in the channel for adult jollytail movement down to the estuary in January to March
- Provide flows to open mouth to allow downstream migration of larvae in autumn
- Provide flows to open mouth to allow juveniles to migrate upstream from sea between July and December
- Provide flow freshes to inundate vegetation beds and instream benches to stimulate invertebrate production for fish condition
Freshwater flows provides longitudinal connection for Common Galaxias to move down to the estuary from freshwater habitats in January to March. Larger flows allow the river mouth to open. Common Galaxias lay their eggs in samphire and wetlands in estuary. Common Galaxias larvae hatch and are washed out to sea by mouth opening flows in autumn to mature before returning to the estuary in July to December.

Figure 12: Common Galaxias Conceptual Model ecological and hydrological objectives
Table 13. Ecological and hydrological objectives for Common Jollytail (*Galaxias maculatus*)

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>10a High Flow Fresh</td>
<td>Migration to estuary in autumn before spring tides</td>
<td>Flow cue to migrate downstream</td>
<td>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)</td>
<td>No physical data to decide appropriate fresh in the estuary, therefore rely on estimate based on assumed riffle dimensions, slope and friction coefficient. Also refer to requirement for high flow freshes in the upstream freshwater reach. 2 events of min 3 days.</td>
</tr>
<tr>
<td>10b Flooded samphire or estuarine floodplain vegetation</td>
<td>Adults spawning</td>
<td>Spring tide in autumn following migration event</td>
<td>Inundation of emergent vegetation or samphire at the upper extent of the intertidal zone (once every two weeks based on the tidal regime)</td>
<td>Requires mouth to be open with mean daily tidal range equal to or greater than 0.2 m at lower bridge (XS10). <em>This ensures sufficient tidal variation to provide opportunity for fish to find locations to spawn.</em></td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
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<td>---------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>10c 3 Estuary Mouth State</td>
<td>Marine Migration by larvae</td>
<td>30-50cm deep mouth</td>
<td>Require open mouth during May to July, salinity is not critical so up to 35 is OK for periods of up to a 7 days with 2-3 events during the season</td>
<td>Determine flow required to cause/sustain a mouth opening event using the empirical data of Sherwood (2006).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mouth open during May to July (downstream movement)</td>
<td></td>
<td>See 9c.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity sufficient to create flow sufficient to move silt downstream</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity sufficient to take larvae 4 days to get down to an already open mouth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10d 4 Estuary Mouth State</td>
<td>Migratory cue to return to estuary</td>
<td>uncertain</td>
<td>met by flows required to provide passage?</td>
<td>No assessment required</td>
</tr>
<tr>
<td>10e 5 Estuary Mouth State</td>
<td>Freshwater Migration to estuary from sea by juveniles</td>
<td>30-50cm deep river mouth</td>
<td>Require open mouth, 30-50cm deep, during Oct-Dec, salinity not material, duration should be for up to 7 days with 2-3 events during the season</td>
<td>Oct-Dec, min duration of mouth opening of 3 days min 2 events per season</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mouth open during July to December (upstream migration)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10f 6 Riffles, stream bars, flow freshes</td>
<td>Migration from estuary to freshwater reaches by juveniles</td>
<td>flow cue to migrate upstream – probably flow freshes (low and high)</td>
<td>Require access to upstream reaches over riffles - Upstream riffle depth at least 0.3m min</td>
<td>Thalweg depth at upstream bar/riffle &gt;30cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>At least 2 events in spring (to provide 2 opportunities)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>At the site of the riffle/rock bar (which has not been surveyed to date)</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Summary of Hydraulic Analyses

This section describes the targeted field data collection program, development of the two numerical simulations of the Gellibrand River estuary (Tide Model and Flood Model) and presents some sample results. A full description of the hydraulic modelling work and a presentation of more detailed results can be found in Appendices 1 - 3 (Sections 9 - 11).

3.4.1 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.

A fuller description and discussion of the field measurement exercise is presented in Section 11.

a) Survey

Fourteen cross-sections were designated along the Gellibrand River and three along Latrobe Creek (Figure 13). Cross-sections were located to capture key morphological changes along the length of the estuary channel and to allow a good approximation of floodplain storage (see Section 9 for details of the survey specification and location of the cross-sections). Reed and Reed Surveying completed the survey and provided a detailed report (Section 10). The collected survey data and photographs taken during the work are included on the Data DVD that accompanies this report.
Figure 13  Map of the study area bounded by the 10 m contour. Latrobe Creek is shown flowing from the North into the lower Gellibrand River estuary just prior to the coast. Two sets of cross-sections are shown: red lines indicate sections that were surveyed for this project; green lines indicate additional sections constructed to aid model development.
b) Tide Gauging

Five Onset HOBO pressure/temperature loggers (Model U20-001-04-Ti) were deployed along the Gellibrand estuary. Four loggers were mounted below the water surface at the following bridges along the estuary:

- Lower Bridge (Murray Park, 1.3 km upstream of estuary entrance);
- Rivernook Bridge (5.4 km upstream of estuary entrance);
- Theo’s Bridge (8.6 km upstream of estuary entrance); and
- Great Ocean Road Bridge (13.7 km upstream of estuary entrance).

The fifth logger was deployed on land near the lower bridge (at Murray Park) to measure atmospheric pressure.

The loggers were deployed on 3rd September and retrieved on 10th September. 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.

Tide gauge positions were not surveyed. Consequently the water level results could only be approximately reduced to Australian Height Datum. The method used to do this is detailed in Section 11. The tide gauge records resulting from this analysis are plotted in Figure 14. The inflow discharge from the nearest upstream gauge on the Gellibrand River (Gellibrand Rv @ Burrapa) measured over the deployment period is shown in Figure 15.

Measured water surface elevation increases in an upstream direction (from the Lower Bridge to Great Ocean Rd) along the 13.7 km reach. Note that truncation of the Great Ocean Rd record occurred as readings were taken every 15 seconds filling the memory of the logger prematurely. Also, the dashed line indicates the predicted tide outside the estuary based on Port Campbell tidal constituents published in the Australian National Tide Tables (Australian Hydrographic Service, 2004).

The gauges were installed just prior to the peak of a minor fresh (Figure 11-3) that had a maximum discharge on 4th September of 367 ML/day. Water levels slowly declined over the period of record with the water levels at the two downstream sites declining more rapidly than the upstream sites. Variation with the tide is also greater at the two downstream gauges, with water level variation at the upstream gauges driven more by the inflow hydrograph. However, it should be noted that tidal variation at Theo’s Bridge became far more pronounced around 7th September when the inflow discharge dropped below 300 ML/day. This observation suggested that a flow of around 300 ML/day limits upstream progression of the tidal wave to around Theo’s Bridge - based on prevailing conditions at the time, especially mouth cross-sectional area which was measured pre- and post-tide gauge deployment as approximately 15 m².
Figure 14. Measured tide gauge data at four sites corrected approximately to Australian Height Datum with predicted tides for Port Campbell shown for reference. Note Great Ocean Rd record is short due to incorrect logging interval being set.

Figure 15. Hydrograph measured by the Burrupa gauging station (freshwater inflow discharge to the estuary) over the period of tide gauge deployment.
3.4.2 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 Gellibrand Estuary is long (13.7km) and flows within a relatively narrow channel with banks topped in many places by natural levees. This morphology makes the estuary 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.

2. Downstream boundary condition – reconstructed tidal water levels based on constituents published for Port Campbell in the Australian National Tide Tables (Australian Hydrographic Service, 2004).

3. Upstream boundary condition – a freshwater inflow hydrograph was defined by discharge recorded by the nearest upstream gauge (Gellibrand River@Burrapa, #235 224) 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 (see Section 11.4.1 for details), these were refined during the calibration process.

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 (especially the level of the invert and hydraulic roughness). The level of calibration achieved is shown by Figure 16.
Figure 16  Results of model calibration at the four tide gauging stations showing measured water levels (solid line) and predicted (modelled) water levels (dashed line).

The Tide Model was able to reproduce to an acceptable level the water level dynamics observed along the Gellibrand River estuary. Water level variation over the first part of the record could not be reproduced with sensible parameter values, suggesting that uncontrolled boundary conditions (e.g. barometric pressure) may have significantly influenced the measured data. Calibration effort therefore focussed on results at the end of the gauging period (Sept. 7 – 10). Ultimately, good agreement in tidal range and timing was achieved at the two downstream bridges (Rivernook and Lower). The results at the upstream bridges (Theo’s and Great Ocean Rd) were not as good. However most ecological interest focussed on the downstream section of the estuary and hence further work to improve model performance at these sites was not done.

A more detailed discussion of calibration is presented in Section 11.3.2. Discrepancies between the measured and modelled results demonstrate the complexity of estuarine hydrodynamics. While the calibration achieved was deemed acceptable for the purpose of this pilot study, it is recommended for future studies that tide gauge deployments provide a minimum of 30 days data (ideally 60 days) to more completely describe estuary water level dynamics.
c) Modelled Scenarios

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 salinity structure. The model was run for three different freshwater inflow discharges: 100, 300 and 900 ML/day. These were chosen by inspection of the hydrological data as representing summer baseflow (100 ML/day), winter baseflow (300 ML/day) and bankfull flow (900 ML/day). A moderate estuary entrance area was assumed (15 m² – as per tide gauging) and the downstream boundary was defined by a repeating spring-neap tidal cycle (based on constituents for Port Campbell from: Australian Hydrographic Service, 2004). The neap-spring cycle chosen was 15 days in length.

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.
- Saline recovery rates were qualitatively observed via animations of the salinity profile. The rate of development in the initial 4 weeks of simulation (that started with the estuary completely fresh) was compared to equilibrium salinity profiles through weeks 5 and 6.

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.

Two sets of plots were prepared for each of the three test inflow cases:
- time series of the variation of the simulated water (e.g. Figure 17); and
- salinity profiles at the ebb and flood tides at neap and spring tides (e.g. Figure 18).

![Figure 17](image)

**Figure 17** Water level variation with 100 ML/day inflow at Lower Bridge highlighting times at which snapshots of the salinity distribution were taken.

![Salinity distributions](image)

**Figure 18** Salinity distributions at four times through the tidal cycle with 100ML/day inflow discharge. Note the scale mark below the year indicates distance in metres.
3.4.3 Flood Model

A MIKE 11 hydraulic model was developed to simulate overbank flow behaviour in the Gellibrand River estuary. The objective of the simulations was to estimate the inflow discharge required to cause various overbank water levels at different points along the estuary. The model allowed two flooding mechanisms to be examined:

- Freshwater Flood – simulation of overbank conditions caused by catchment flooding.
- Entrance Closure – overbank conditions caused by build up of water behind a sandbar at the river mouth.

Simulation results generated for freshwater flooding (first mechanism) were also used to estimate flows required to scour sediments from the estuary lagoon and the entrance.

a) Model Development

Five key elements were required to define the Gellibrand Flood Model in MIKE11:

1. Channel and floodplain geometry – derived from survey data measured for this project. To adequately represent the floodplain storage in large floods a number of additional cross-sections were constructed based on the survey and also 10 m contours and ortho-photographs of the floodplain. A combination of the surveyed and constructed cross-sections was utilised for the model schematization (Figure 13).

2. Downstream boundary condition – reconstructed tidal water levels based on constituents published for Port Campbell 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 11.4.1 for details). Values for the channel were refined through calibration of the Tide Model (as per Section 3.4.2b).

b) Model Calibration

No model calibration was possible as no quantifiable observations of prior flood levels were available to the authors at the time this work was completed.

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 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 0.5 mAHD.

c) Sample Model Results

Freshwater Flood

The ramped flow progressively inundates the floodplains of the estuary from the upstream end down toward the mouth. Water backs up behind each of the bridges at higher flows, especially Theo’s Bridge (Figure 19). This model behaviour is consistent with observations by local residents.

The ramp simulation predicted 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 water surface elevation at particular locations along the estuary. For example, Figure 20 shows stage height versus discharge curves at two key locations along the Gellibrand estuary: just upstream of the entrance, and 2 km further upstream (at XS10). The chart highlights the discharge required to attain water levels of 1.0, 1.25, 1.50 and 2.0 mAHD at XS10, which are relevant to some of the flow-ecology relationships.

\(^1\) 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_interf___html)
Figure 19  Water surface profile (blue zone – top is water surface, bottom is bed) for Gellibrand River with 10,000 ML/day freshwater inflow. Vertical arrows indicate the location of the key structures along the reach.

Figure 20  Inflow discharge versus water surface level predicted just upstream of the estuary entrance and at cross-section 10. The line annotations cross-reference the discharge predicted to achieve different water surface levels at cross-section 10.
Entrance Closure

The second set of scenarios was designed to mimic closure of the estuary entrance by a sandbar. The sandbar was modelled with a leakage flow that varied with water level behind the bar. A simple Darcy’s Law (Sturm, 2001) formulation was used to define a downstream stage-discharge relationship (with a constant mean sea level of 0.0 mAHD assumed).

The model was run twice with different downstream boundary conditions, assuming different hydraulic conductivity ($k$) estimates for the sandbar of 10 and 100 based on low and high conductivity estimates for fine and coarse sand respectively (Gordon et al., 2004). The difference between the two leakage coefficients was negligible.

Simulation results showed that the estuary filled from the downstream end with zero water surface slope up to the extent of ponding. The relationship between water surface elevation and volume stored in the estuary is listed in Table 14. The rate at which a given volume will accumulate (i.e. number of days after mouth closure) depends on the inflow discharge rate (integrated over time).

Table 14 Water surface elevation just upstream of sandbar compared with estimate of the volume of water stored in the estuary.

<table>
<thead>
<tr>
<th>Elevation (m AHD)</th>
<th>Volume Stored in Estuary (GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.52</td>
</tr>
<tr>
<td>0.25</td>
<td>0.62</td>
</tr>
<tr>
<td>0.50</td>
<td>0.75</td>
</tr>
<tr>
<td>0.75</td>
<td>0.95</td>
</tr>
<tr>
<td>1.00</td>
<td>1.32</td>
</tr>
<tr>
<td>1.25</td>
<td>2.03</td>
</tr>
<tr>
<td>1.50</td>
<td>2.93</td>
</tr>
<tr>
<td>1.75</td>
<td>4.00</td>
</tr>
<tr>
<td>2.00</td>
<td>5.18</td>
</tr>
<tr>
<td>2.25</td>
<td>6.46</td>
</tr>
<tr>
<td>2.50</td>
<td>7.82</td>
</tr>
</tbody>
</table>
3.5 Summary of Hydrological Analysis

The hydrological analysis was undertaken for the purpose of guiding the Panel in making their deliberations on the specification of flow components. The analysis was limited to calculation of simple statistics to describe frequency and duration of events specified only in terms of threshold magnitude and season of occurrence; a minimum duration or frequency was not specified, and no restrictions were placed on event independence. In practice, flow components must be specified in more detail, taking into account minimum event duration, minimum events per year, and minimum number of years in a sequence when the flow component should be present.

There was very little difference or no difference between the Natural, Current and Full Development scenarios for frequency of flow components involving a threshold being exceeded. However, there were marked differences in frequency between scenarios for components involving flows less than the threshold (unless the threshold was 1,800 ML/d, in which case there was minimal difference). The greatest difference between scenarios was for the component - summer flows <50 ML/d. Under the Natural scenario this event occurred in only 3% of years, while under the Current scenario it occurred in 49% and under the Full Development scenario it occurred in 57% of years. Thus, in general, the occurrence of the high flow components in the Current and Full Development scenarios have strong compliance with their occurrence in the Natural regime, but the low flow components do not.

For some components involving a threshold being exceeded there were differences in mean number of events per year, but not in terms of percentage of years with the event. For those components with a difference (spring, and summer periods, for thresholds >100, >240 and >300 ML/d) the natural scenario was different to the Current and Full Development scenarios (which were similar). The difference in mean frequency was also reflected in an expected difference in duration statistics (when duration was longer, frequency was lower, and vice-versa).

In general, most flow components had highly variable duration. This means that delivery of environmental flow components at fixed durations would not mimic the natural variability. It was also the case that flow components had variable frequency. While all components had a long-term average frequency of >1 event per year (except for summer low flows <50 ML/d in the Natural scenario), for only half of the components did the component occur in every year of the series. This is explained by the occurrence of wet years (when the component occurs frequently) and dry years (when the component does not occur at all).

Caution is required in interpreting the calculated frequency of occurrence of freshes and higher magnitude events. For example, the Bankfull Flow component >7,000 ML/d (any month) occurred with an average frequency of around 1.3 events per year (Natural scenario), but it occurred in only 60 percent of years. Thus, while the average frequency value suggests that this is an annual event (at least), the percent of years value is a better indicator of the true frequency, which is less than annual. The frequency of large events such as this is more correctly determined by flood frequency analysis. For the Natural scenario, a partial series...
(extracting 70 events from 35 years of record), with a polynomial fitted to the data, predicted the 1 in 1 year ARI event was 5,400 ML/d and the 1 in 2 year ARI event was 7,500 ML/d. The component >7,000 ML/d had a frequency of 1.7 years ARI, and the High Flow Fresh (Gahnia) component >3,900 ML/d had a flow frequency of 0.52 years ARI (Natural scenario). However, it is important to realise that while the average frequency of occurrence of the High Flow Fresh (Gahnia) component >3,900 ML/d was twice per year, this component did not occur in 11% of years of the 35-year time series. The spells analysis indicated an average frequency of occurrence of nearly 4 events per year, which is clearly an unrealistic annual target. A flow of 3,900 ML/d was exceeded 4 times or more per year in only 51 percent of years (Natural scenario). The occurrence of these events is very sensitive to duration. For example, including the constraint of minimum duration of 2 days, such an event was exceeded 4 times or more per year in only 29 percent of years. There was no theoretical reason why the duration had to exceed 1 day to meet the objectives of this component. Thus, for the High Flow Fresh (Gahnia) component, the recommended frequency was 1 event per year, with a minimum duration of 1 day. For compliance, the requirement was that the event should occur in 8 of every 10-year sequence. This specification had 100 percent compliance in the Natural scenario.

An important consideration in specifying flow components was that the flow series available for analysis was based on a daily time-step. All of the flow components specified here were for a duration of at least one day. This minimum duration was largely set by the minimum time thought to be required for the physical and/or ecological processes to be completed, but the 1-day time-step was also a factor. It is possible that some processes may not need to be sustained for a full 24 hours in order to achieve the desired objectives, but insufficient information was available to recommend durations of less than 1 day.
4  FLOW RECOMMENDATIONS

Flow recommendations are summarised in the Table 15 and are based on the flow-ecology relationships which could be quantified (vegetation and fish) and the hydraulic and hydrological analysis results shown in Appendix 1 and 2 respectively.

Eleven flow components have been identified and nine have detailed flow specifications made. Cease to flows events do not occur in the Estuary and are not required (and in fact would be detrimental) for the Estuary. A summer low flow and two low flow freshes are required to meet specific requirements for fish ecology. While no specific winter base flow is identified at this stage, without current base flow levels high flow freshes are unlikely to occur and as default the natural quantities, timing and duration of base flows should be provided to ensure general ecological requirements are met. Six high flow freshes have been identified to meet important processes for a range of fish and vegetation requirements. An overbank event is recommended to briefly inundate riparian trees and shrubs once a year. Details of these recommendations are found in Table 15 and the subsequent sections, 4.1 to 4.11.
Table 15: Summary of Flow Recommendations

<table>
<thead>
<tr>
<th>Event/Condition</th>
<th>Magnitude (ML/day)</th>
<th>Frequency (events per season)</th>
<th>Duration (days)</th>
<th>Season</th>
<th>Salinity (or Halocline Present?)</th>
<th>Water Column Position (Depth) for Salinity</th>
<th>Location</th>
<th>Mouth Status</th>
<th>Objective ID</th>
<th>Supporting Objective ID</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summer-Autumn</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cease to Flow</td>
<td></td>
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<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Low Flow</td>
<td>100 ML/day</td>
<td></td>
<td></td>
<td>Summer-Autumn</td>
<td>Salinity range of 5 to 30</td>
<td>&lt; 1m</td>
<td>XS10</td>
<td>-</td>
<td>7a-c, 8b, 9a</td>
<td>2b, 2e, 2f</td>
</tr>
<tr>
<td>Low Flow Fresh (Fish Migration)</td>
<td>240 ML/day</td>
<td>at least 4</td>
<td>3</td>
<td>Summer-Autumn</td>
<td>Median salinity between 5 and 10</td>
<td>0.3m - 1m</td>
<td>XS12</td>
<td>-</td>
<td>9f, 10a</td>
<td>1a.1</td>
</tr>
<tr>
<td>Low Flow Fresh (Galaxiid Spawning)</td>
<td>600 ML/day</td>
<td>2</td>
<td>3</td>
<td>Autumn (March – May)</td>
<td>-</td>
<td>-</td>
<td>XS10</td>
<td>-</td>
<td>10b</td>
<td>3d</td>
</tr>
<tr>
<td><strong>Winter-Spring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Base Flow</td>
<td></td>
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<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>High Flow Fresh (Estuarine Conditions)</td>
<td>300ML/day</td>
<td>3</td>
<td>11</td>
<td>Winter-Spring</td>
<td>Median salinity between 15 - 35 Salinity</td>
<td>&gt;0.3 - 1m</td>
<td>XS12</td>
<td>-</td>
<td>3d</td>
<td>1a.2, 2c, 2d, 2e, 6c, 9f, 10f</td>
</tr>
<tr>
<td>High Flow Fresh (Seagrass)</td>
<td>900ML/day</td>
<td>4</td>
<td>4</td>
<td>May - July</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6a, 9b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event/Condition</td>
<td>Magnitude (ML/day)</td>
<td>Frequency (events per season)</td>
<td>Duration (days)</td>
<td>Season</td>
<td>Salinity (or Halocline Present?)</td>
<td>Water Column Position (Depth) for Salinity</td>
<td>Location</td>
<td>Mouth Status</td>
<td>Objective ID</td>
<td>Supporting Objective ID</td>
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</tr>
<tr>
<td>High Flow Fresh (Salt Flushing Flows)</td>
<td>1500/500 ML/day</td>
<td>1-2</td>
<td>4 - 6</td>
<td>Winter-Spring</td>
<td>-</td>
<td>0.3 to 0.5m</td>
<td>XS12</td>
<td>Open</td>
<td>8a, 9c, 9e, 10c, 10e</td>
<td></td>
</tr>
<tr>
<td>High Flow Fresh (Phragmites)</td>
<td>1800 ML/day</td>
<td>7-8</td>
<td>3</td>
<td>Winter-Spring</td>
<td>-</td>
<td>0.25 to 0.5m</td>
<td>XS10</td>
<td>Open</td>
<td>1c</td>
<td>1d</td>
</tr>
<tr>
<td></td>
<td>200 ML/day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Closed (4 days)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Flow Fresh (Gahnia)</td>
<td>3900 ML/day</td>
<td>4</td>
<td>2</td>
<td>Any month</td>
<td>-</td>
<td></td>
<td>XS 9</td>
<td>Open</td>
<td>3c</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ML/day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Closed (12 days)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Overbank</td>
<td>7000 ML/day</td>
<td>1</td>
<td>1</td>
<td>Any month</td>
<td>-</td>
<td></td>
<td>XS 2 &amp; XS10</td>
<td>Open</td>
<td>5b</td>
<td>4c</td>
</tr>
</tbody>
</table>
4.1 Cease-to-flow

Cease-to-flows are not a component of the hydrology of this estuary nor are they required or desirable for ecological or physical objectives set and therefore they are not recommended for the Gellibrand estuary.

4.2 Summer Low Flow

A summer low flow of at least 100 ML/day is required effectively all of summer and autumn to maintain the maximum extent of the estuarine salt wedge and to keep the mouth open. Maximising the extent of the salt wedge will support habitat for Black Bream and other estuarine resident fish (7a-c), estuarine habitats for King George Whiting (Estuarine Dependent – Marine Derived; 8b), and spawning of estuarine dependent (freshwater dependent) fish such as Australian Grayling (10a) in the upper estuary or upstream freshwater reaches. These flows also promote salt-tolerant charaphytes, herbs, grasses and forbs by flooding with saline water in summer and autumn (2b, 2e) and maintaining samphire (e.g. Sarcocornia quinqueflora) by flooding in summer and autumn.

4.3 Low Flow Fresh (Fish Migration)

A low flow fresh of 240 ML/day is required 5 times in the season for at least 3 days each to reduce salinities to 5 – 10. This flow component will allow migration of Australian Grayling juveniles from estuary to freshwater reaches (9f) and allow migration of Common Jollytails to the estuary in autumn before spring tides (10a). Flooding by brackish water in summer and autumn for sufficient durations will exclude emergent macrophytes and to provide reliable growing conditions for salt-tolerant aquatic herbs (1a.1).

4.4 Low Flow Fresh (Galaxiid Spawning)

A low flow fresh of 600 ML/day is required 2 times per year for at least 3 days each to flood samphire or estuarine floodplain vegetation to trigger Galaxiid spawning. Fish will lay their eggs in samphire or estuarine floodplain vegetation. These hatch in two weeks and are distributed via subsequent flows.

4.5 Baseflow

No specific requirement for winter baseflows have been identified by the ecological objectives but obviously a baseflow will be a feature of the hydrology of the estuary and will allow high flow freshes to occur. As default the natural quantities, timing and duration of base flows should be provided to ensure general ecological requirements are met.
4.6 High Flow Fresh (Estuarine Conditions)

A high flow fresh of 300ML/day is required 3 times in Winter-Spring for 11 days to maintain the median salinity between 15 - 35 in surface waters at the estuary mouth. These flows will maintain Gahnia tussock sedgeland and Leptospermum lanigerum and prevent invasion by Bolboschoenus caldwelli and Juncus kraussii (3d) by inundation of brackish to fresh surface water. The flows will also support Phragmites australis grassland (1a.2) and promote salt-tolerant charophytes, herbs, grasses and forbs (2c, 2d, 2e). These freshes will provide a flow cue for fish juveniles (Common Jollytail and other estuarine dependent-marine fish) to migrate upstream from estuary to freshwater reaches. (10f). They will also maintain euphotic conditions within 1 km of estuary entrance (6c).

4.7 High Flow Fresh (Seagrass)

A high flow fresh of 900ML/day is required 4 times per season for at least 4 days in the winter/spring period as these freshwater pulses may be a trigger for germination but prolonged fresh conditions will remove Heterozostera seagrass (6a). In the upper estuary or freshwater reaches above estuary these flows will support larval development of grayling (9b).

4.8 High Flow Fresh (Salt Flushing Flows)

A high flow fresh sufficient to remove all salt water from the estuary should occur for 4 to 6 days approximately monthly during winter-spring. Each fresh will require an initial flushing flow of 1500 ML/day for 2 – 3 days and thereafter flows of 500 ML/day for 2 – 3 days will prevent re-entry of salt water into the estuary. One or two events a season will meet the objectives listed and allow migration of larvae and juveniles to the estuary from the sea of King George Whiting (8a), Australian Grayling (9e), and Common Jollytail (10e). It will also create opportunities for Australia Grayling larvae (9c) and Common Jollytail larvae (10c) to be washed from the estuary to the sea.

4.9 High Flow Fresh (Phragmites)

A large high flow fresh of 1800 ML/day for about 3 days about 7-8 times when the mouth is open will ensure frequent and prolonged flooding in winter and spring and maintain the dominance of Phragmites australis in dense, closed stands (1c, 1d). If the mouth is closed then only 200 ML/day is required for as little as 4 days.

4.10 High Flow Fresh (Gahnia)

A very high flow fresh of 3900 ML/day is required 4 times each year for 2 days at anytime of the year under open mouth conditions. This will create the infrequent inundation which is required to maintain Gahnia tussock sedgeland and Leptospermum lanigerum and prevent invasion by Phragmites australis (3c). The same inundation under closed mouth conditions will occur at flows of 200 ML/day (for at least 12 days).
4.11 Moderate Overbank Flow

A bankfull flow of 7000 ML/day is required once per year in any month throughout the estuary to create brief and infrequent inundation to maintain the *Acacia melanoxylon* and *Eucalyptus ovata* overstorey (5b), exclude aquatic macrophytes from the understorey and prevent flood stress to *L. lanigerum*, and *P. tenuissima* (4c).
5 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.

Eleven important flow components have been identified and for nine of these detailed flow specifications have been made for the Gellibrand Estuary. Cease to flows events do not occur in the Gellibrand Estuary and are not required (and in fact would be detrimental) for it. A summer low flow and two low flow freshes are required to meet specific requirements for fish ecology. While no specific winter base flow is identified at this stage, without current base flow levels high flow freshes are unlikely to occur and as default the natural quantities, timing and duration of base flows should be provided to ensure general ecological requirements are met. Six high flow freshes have been identified to meet important processes for a range of fish and vegetation requirements. An overbank event is recommended to briefly inundate riparian trees and shrubs once a year.

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.”
6 REFERENCES


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## APPENDIX 1 – HYDRAULIC RESULTS

### Table 7-1. Ecological and Hydrological Objectives for *Phragmites australis* Grassland together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Brackish flood water</td>
<td>Promote salt-tolerant charophytes, herbs, grasses and forbs Exclude emergent macrophytes</td>
<td>Flooding by brackish water in summer and autumn for sufficient durations to exclude emergent macrophytes and to provide reliable growing conditions for salt-tolerant aquatic herbs. Flooding by fresher water in spring to support growth of Phragmites and less salt-tolerant species.</td>
<td>1a.1 Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS 10 of 5 to 10 in summer and autumn 1a.2 Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS 10 2 to 5 in winter and spring</td>
<td>Median salinity of water &lt;1 m deep downstream of XS 10 on seasonal basis.</td>
</tr>
<tr>
<td>1a.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1a.2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>1b Shallow low salinity groundwater</td>
<td>Maintain plant growth between inundation events. Provide a source of low salinity water if inundated by saline water</td>
<td>Groundwater salinity predicted to be less than 3</td>
<td>Groundwater depth predicted to be less than 0.2 m deep at all times</td>
<td>No assessment possible</td>
<td>Not required.</td>
</tr>
</tbody>
</table>
| 1c | Frequent and prolonged flooding in winter and spring | Maintain dominance of *Phragmites australis* in dense, closed stands | River level must exceed 1.25 to 1.5 m AHD at XS10 25% of the time between June and December with a maximum interval between events of 4 weeks. | Water level regime in winter
- percent time water level exceeds 1, 1.25 or 1.5 m AHD at XS10
- median interval between events | When the mouth of the estuary is open, the water level will remain within the banks of XS10 with a freshwater inflow of up to approximately 900 ML/day. The water depth at XS10 will exceed 1.0, 1.25 or 1.5 m AHD in the following cases:

<table>
<thead>
<tr>
<th>Level</th>
<th>Events</th>
</tr>
</thead>
</table>
| > 1.0 m | 1. Inflow of ~1800 ML/day 
2. 1 in 2 year Storm surge in Bass Strait (adds 0.20m to water levels) with a freshwater inflow of at least 900 ML/day 
3. Bar closure of at least 4 days (with a mean inflow discharge of 200 ML/day). |
| > 1.25 m | 1. Inflow of ~2600 ML/day 
2. 1 in 2 year Storm surge in Bass Strait (adds 0.20m) with a freshwater inflow of at least 1900 ML/day. 
3. Bar closure of at least 7.5 days (with a mean inflow discharge of 200 ML/day). |
| > 1.50 m | 1. Inflow of ~3900 ML/day 
2. 1 in 2 year Storm surge in Bass Strait (adds 0.20m) with a freshwater inflow of at least 2900 ML/day. 
3. Bar closure of at least 12 days (with a mean inflow discharge of 200 ML/day). |
<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
</table>

Hydraulic Recommendation:
CRITICAL NOTE: The present protocol for river mouth opening recommends consideration be given to artificial bar breaching if the water level reaches 1.136 mAH (O’May and Wallace, 2001).

I suggest that consideration only be given to flow cases that cause the water level to exceed 1.0 mAH. Hydrologic analysis is required to attempt to estimate the frequency (or the median interval between events).

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2 Data as per Figure 5, based on flood model (Mike 11) prediction for cross-section 10.

3 As a first order approximation the elevation of the storm surge will translate into an equivalent depth in the estuary in small volume estuaries such as the Gellibrand.

4 As per Table 2.

5 Figure 3 (bottom left) and Figure 4 indicate that 900 ML/day produces a minimum water level around 0.8 mAH. Note also that the hydrologic analysis presented in the Issues Paper shows that the median flow in the Gellibrand exceeds 900 ML/day in July - September; therefore a storm surge in these months will achieve the required water level (1.00 mAH).

6 As per Figure 7 (determined from the data underlying this figure).

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1d</td>
<td>Intermittent flooding in summer and autumn</td>
<td>Maintain dominance of Phragmites australis in dense, closed stands</td>
<td>River level must exceed 1.25 to 1.5 m AHD at XS 10 25% of the time between June and December with a maximum interval between events of 4 weeks. Years with no events may occur 1 year in 3.</td>
<td>Water level regime in summer - percent time water level exceeds 1, 1.25 or 1.5 m AHD at XS 10 - % of years when water level does not exceed 1, 1.25 or 1.5 m AHD at XS10</td>
<td>As per 1c APPLY 1.0 M AHD THRESHOLD</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>2a Depth and extent of floodplain depressions</td>
<td>Retain water from high estuary levels, local rainfall.</td>
<td>Geomorphic processes to maintain depression depth of approximately 0.5 m and current extent</td>
<td>CHRIS</td>
<td>CHRIS</td>
<td>Not required.</td>
</tr>
<tr>
<td>2b Flooding by saline water in summer and autumn</td>
<td>Promote salt-tolerant charophytes, herbs, grasses and forbs. Exclude emergent macrophytes</td>
<td>Peak salinity (between refreshing events) of 7.5 to 20 in summer and autumn in depressions</td>
<td>Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS10 exceeds 5 in summer and autumn. (assume salinisation of water detained in floodplain depressions by evaporation) Median salinity of water &lt;1 m deep downstream of XS10 on seasonal basis.</td>
<td>Median salinity in the surface layer at XS10 with 100 ML/day inflow is 5.7 dropping to 0.57 when the inflow is doubled to 100 ML/day. Median salinity in the surface layer at XS12 (downstream) with 50 ML/day inflow is 7.6 dropping to 1.5 when the inflow is doubled to 100 ML/day. <strong>Hydraulic Recommendation:</strong> For median salinity to exceed 5 in the surface waters (&lt;1m) at XS10 and downstream of this point, the maximum inflow should be 50 ML/day.</td>
<td></td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>2c Flooding by brackish water in winter and spring</td>
<td>Promote salt-tolerant charaphytes, herbs, grasses and forbs</td>
<td>Peak salinity (between refreshing events) of 5 in winter and spring in depressions</td>
<td>Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS10 exceeds 3 in winter and spring</td>
<td>(assume salinisation of water detained in floodplain depressions by evaporation) Median salinity of water &lt;1 m deep downstream of XS 10 on seasonal basis.</td>
<td>Median salinity in the surface layer at XS10 with 50 ML/day inflow is 5.7 dropping to 0.57 when the inflow is increased to 300 ML/day. Median salinity in the surface layer at XS12 (downstream) with 100 ML/day inflow is 7.6 dropping to 1.5 when the inflow is increased to 300 ML/day. Therefore, for salinity to exceed 3 at XS12, the maximum inflow should be less than 300 ML/day. Based on linear interpolation, an inflow of 240 ML/day would lead to a salinity of around 3 in the surface waters at XS12 (and a salinity of around 2 in the surface waters of XS10 itself). <strong>Hydraulic Recommendation:</strong> For median salinity to exceed 3 in the surface waters (&lt;1m) downstream of XS10, the <strong>maximum</strong> inflow should be 240 ML/day. <strong>Note that by specifying the minimum median salinity this places quite a restrictive upper limit on the winter inflow - one that the hydrology may show to be unrealistic.</strong></td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>Persistent flooding in winter and spring by fresh / brackish water</td>
<td>Promote salt-tolerant charaphytes and submerged vascular macrophytes Exclude emergent macrophytes</td>
<td>Persistent flooding to depth of 0.25 to 1.0 m (predominantly 0.5 m) from May to October</td>
<td>Median interval between events exceeding thresholds at XS 10, seasonally split</td>
<td>Median interval between events exceeding thresholds at XS 10, seasonally split</td>
<td>As per 2c. 2c does not refer to event interval?</td>
</tr>
<tr>
<td>Shallow flooding in late spring / early summer</td>
<td>Provide habitat for salt-tolerant grasses, sedges, herbs and forbs</td>
<td>Average water level from November to December is 50% of average water level from August to September</td>
<td>Median interval between events exceeding thresholds at XS 10, seasonally split</td>
<td>Median interval between events exceeding thresholds at XS 10, seasonally split</td>
<td>As per 2b, c.</td>
</tr>
<tr>
<td>Intermittent flooding in summer and autumn</td>
<td>Maintain <em>Sarcocornia quinqueflora</em></td>
<td>Depressions less than 20% of maximum depth 80% of the time over summer autumn</td>
<td>Median interval between events exceeding thresholds at XS 10, seasonally split</td>
<td>Median interval between events exceeding thresholds at XS 10, seasonally split</td>
<td>As per 2b.</td>
</tr>
<tr>
<td>Waterlogging by saline groundwater in summer and autumn</td>
<td>Maintain <em>Sarcocornia quinqueflora</em></td>
<td>Groundwater depth less than 0.4 m to maintain evaporative concentration of salts in surface soil Groundwater salinity 10 to 60</td>
<td>No assessment possible</td>
<td>No assessment possible</td>
<td>Not required.</td>
</tr>
</tbody>
</table>
### Table 7-3. Ecological and Hydrological Objectives for Estuarine Scrub together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a Seasonal waterlogging</td>
<td>Maintain <em>Gahnia</em> tussock sedgeland and <em>Leptospermum lanigerum</em></td>
<td>Groundwater less than 0.2 m deep for 4 to 8 months of the year</td>
<td>No assessment possible</td>
<td>Not required.</td>
<td></td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>3b Low salinity groundwater</td>
<td>Maintain growth and health of <em>L. lanigerum</em> and <em>Gahnia</em> tussock sedgeland</td>
<td>Groundwater salinity less than 3000 EC</td>
<td>No assessment possible</td>
<td>Not required.</td>
<td></td>
</tr>
<tr>
<td>3c Infrequent inundation</td>
<td>Maintain <em>Gahnia</em> tussock sedgeland and <em>Leptospermum lanigerum</em>. Prevent invasion by <em>Phragmites australis</em>.</td>
<td>Less than 10 inundation events per year. No single inundation event longer than 10 days duration</td>
<td>Median duration of events where water level exceeds 1.5 m AHD at XS 9 is 1 to 2 weeks. Frequency of events where water level exceeds 1.5 m at XS9 is 5 per year.</td>
<td>Median duration of events exceeding thresholds at XS 9 Frequency of events exceeding thresholds at XS 9</td>
<td>When the mouth of the estuary is open, the water depth at XS9 will equal 1.5 m AHD in the following cases (as for XS10, see 1c): &gt; 1.50 m 1. Inflow of ~3900 ML/day(^8) 2. 1 in 2 year Storm surge(^{9}) in Bass Strait (adds 0.20m(^{10})) with a freshwater inflow of at least 2900 ML/day(^{11}). 3. Bar closure of at least 12 days(^{12}) (with a mean inflow discharge of 200 ML/day). <strong>Hydraulic Recommendation:</strong> CRITICAL NOTE: The present protocol for river mouth opening recommends consideration be given to artificial bar breaching if the water level reaches 1.136 m AHD (O’May and Wallace, 2001)(^{13}). The bar closure condition is unlikely to ever be allowed to occur given the present threshold for artificial opening is 1.136 m AHD. Hence, only the first two cases are likely to provide conditions that will lead to flooding at 1.5 m AHD. Hydrologic assessment is required to determine frequency. It looks like hydrologic assessment for condition 1 and 2 is all that is required. I expect this objective will be easily met.</td>
</tr>
</tbody>
</table>

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\(^8\) Data as per Figure 5, based on flood model (Mike 11) prediction for cross-section 10 (no significant difference at cross-section 9).
As a first order approximation the elevation of the storm surge will translate into an equivalent depth in the estuary in small volume estuaries such as the Gellibrand.

As per Table 2.

Data as per Figure 5, based on flood model (Mike 11) prediction for cross-section 10 (no significant difference at cross-section 9).

As per Figure 7 (determined from the data underlying this figure).

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3d</td>
<td>Inundation by brackish to fresh surface water</td>
<td>Maintain Gahnia tussock sedgeland and Leptospermum lanigerum. Prevent invasion by Bolboschoenus caldwelli and Juncus kraussii.</td>
<td>Median salinities in shallow (&lt;1 m deep) estuary water downstream of XS 9 is less than 3 in summer and autumn. Winter and spring salinities may this salinity or fresher.</td>
<td>Median salinity of water &lt;1 m deep downstream of XS 9 on seasonal basis.</td>
<td>Relevant Results: Salinity data at cross-sections 10 and 12 were assessed (both downstream of XS9). Median salinity in the surface layer at XS10 with 100 ML/day inflow is 5.7 dropping to 0.57 when the inflow is increased to 300 ML/day. Median salinity in the surface layer at XS12 (downstream) with 100 ML/day inflow is 7.6 dropping to 1.5 when the inflow is increased to 300 ML/day. Therefore, for salinity to exceed 3 downstream of XS9, the maximum inflow should be less than 300 ML/day. Based on linear interpolation, an inflow of 240 ML/day would lead to a salinity of around 3 in the surface waters at XS12 (and a salinity of around 2 in the surface waters of XS10 itself). Hydraulic Recommendation: Summer-Autumn For median salinity to exceed 3 in the surface waters (&lt; 1m) at least at XS12, the maximum inflow should be 240 ML/day. ** Note that by specifying the minimum median salinity this places quite a restrictive upper limit on the summer/autumn inflow - is this reasonable or does there need to be a duration associated with it? (e.g. 1 month in summer, 1 month in autumn) Winter-Spring The models suggest that freshwater inflow discharges greater than 240 ML/day are predicted to keep median salinity equal to or less than 3 in surface waters at both XS10 and XS12.</td>
</tr>
</tbody>
</table>
### Table 7-4. Ecological and Hydrological Objectives for Swamp Scrub together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a</td>
<td>Perennial waterlogging</td>
<td>Maintain dense <em>L. lanigerum</em> canopy and Groundwater less than 0.2 m deep at all times</td>
<td>No assessment possible</td>
<td>Not required.</td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td>Low salinity groundwater</td>
<td>Maintain growth and health of <em>L. lanigerum, P. tenuissima</em> Groundwater salinity less than 1000 EC</td>
<td>No assessment possible</td>
<td>Not required.</td>
<td></td>
</tr>
<tr>
<td>4c</td>
<td>Brief and infrequent inundation</td>
<td>Exclude aquatic macrophytes from understorey. Prevent flood stress to <em>L. lanigerum, P. tenuissima</em>. Less than 5 inundation events per year. No single inundation event longer than 5 days duration</td>
<td>Median duration of events where water level exceeds 2.0 m AHD at XS 10 is less than 1 week. Frequency of events where water level exceeds 2.0 m at XS 10 is less than 5 per year. Zero events per year is acceptable.</td>
<td>Median duration of events exceeding thresholds at XS 10 Frequency of events exceeding thresholds at XS 10</td>
<td>Relevant Results: A water level of 2.0 mAHD or greater at cross-section 10 is attained under a flood with a peak around 7000 ML/day. It is possible that the flood could coincide with a storm surge, although this is far less likely than a flood by itself (e.g. 3900 ML/day flow gives 1.50 mAHD would need to be coupled with a 20 ARI storm surge providing +0.48 m). Hydraulic Recommendation: The annual flood of 7000 ML/day will achieve this objective according to the model. NOTE: The locals would know whether this is a realistic result. Does an annual flood inundate the bottom of the estuary to this depth?</td>
</tr>
</tbody>
</table>
### Table 7-5. Ecological and Hydrological Objectives for Herb-rich Foothill Forest together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a Shallow low-salinity groundwater</td>
<td>Maintain <em>Acacia melanoxylon</em> and <em>Eucalyptus ovata</em> overstorey</td>
<td>Groundwater depth less than 2 m at all times</td>
<td>Groundwater salinity less than 1000 EC</td>
<td>No assessment possible</td>
<td>Not required.</td>
</tr>
<tr>
<td>5b Rare, brief flooding</td>
<td>Maintain <em>Acacia melanoxylon</em> and <em>Eucalyptus ovata</em> overstorey</td>
<td>Flooded to a maximum of 10 days per year.</td>
<td>Water level exceeds 3.0 m AHD at XS 2 for a total of less than 10 days per year (median).</td>
<td>Median days per year water level exceeds 3.0 m AHD at XS 2</td>
<td>Relevant Results: A flood discharge is required to produce an elevation of 3.0 m AHD at the inland end of the reach. The stage-discharge relationship predicts that an inflow discharge of 6000 ML/day is required.</td>
</tr>
</tbody>
</table>
Table 7-6. Ecological and Hydrological Objectives for Sea-grass Meadow together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>General Conditions Required</th>
<th>Specific Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>6a Salinities</td>
<td>Seagrass meadows tolerate salinities above and below sea water</td>
<td>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 Heterozostera.</td>
<td>Flows required to extend salt upstream</td>
<td>Sea water enters the estuary at flows less than 465 ML/d (John’s 1983 report). Prolonged events above this will result in fresh conditions. Events below this will result in saline conditions. In lowest 1 km of estuary. Evaluate from Salt Wedge Model in terms of extent of salt. Evaluate events from hydrological analysis. This could determine the MAX baseflow.</td>
<td>Relevant Results: Examination of the salinity variation over a full tidal cycle shows that for the majority of the 15 days salinity varies between 10 and 20 in the 2 bottom layers at XS12 with an inflow of 300 ML/day. This should be sufficient to sustain Heterozostera. However, the transition to a fresh regime is predicted between an inflow of 300 and 900 ML/day. Salinity was evaluated at cross-section 12 to determine the inflow discharge that results in median salinity of a) 6 and b) 15 in the 2nd bottom layer of the water column. a) Freshwater inflow of 300 ML/day provides a median salinity of 10.3 at XS12. b) Freshwater inflow of 200 ML/day (based on interpolating results) should provide a median salinity of around 15 at XS12. Hydraulic Recommendation: 6a.1 The salt wedge model suggests that salt will penetrate the estuary at freshwater inflow discharges less than 300 ML/day. 6a.2 – 900ML/day for triggering breeding</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>General Conditions Required</td>
<td>Specific Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>6b Water Level</td>
<td>Zostera muelleri</td>
<td>Stable water levels but mostly inundated</td>
<td>Water level (within normal tidal range)</td>
<td></td>
<td>(Hydrology)</td>
</tr>
<tr>
<td>6c Turbidity</td>
<td>Poor light penetration can reduce seagrass photosynthesis and growth</td>
<td>Maintain euphotic conditions within 1 km of estuary entrance.</td>
<td>Flows required to extend salt upstream</td>
<td>See salinity method above</td>
<td>See 6a above.</td>
</tr>
</tbody>
</table>
| 6d Sedimentation          | Excessive sedimentation smothers seagrasses | Provide regular flushing flows to prevent excessive accumulation of sediment within 1 km of estuary entrance. | River flow (shear stress to move silt but not large enough to shift/disturb the seagrass (uproot the bed)) | Sediment transport threshold based on hydraulic analysis Hydrological analysis of events | Relevant Results:
Near-bed velocities were evaluated at both cross-section 10 and 12 for discharges 100, 300 and 900. The results showed that velocities were an order of magnitude or more smaller than the velocities the Hjulstrom curves predict are required to move even the most mobile of silts and sands. Indeed, the results suggest that velocities are an order of magnitude greater in the confined channel section (XS10) than the Gellibrand lagoon (XS12). Hence the lagoon is likely to be a depositional environment due to both:
- the comparatively low velocity (and low shear stress) environment; and
- the more frequent presence of saline waters that will tend to flocculate suspended materials.
Hydraulic Recommendation:
The sea-grass is located in a depositional environment. Do not set a specific flow recommendation to provide flushing of silt.
### Table 7-7. Ecological and hydrological objectives for Black Bream together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>7a</td>
<td>1 Adult fish habitat</td>
<td>Maintain estuarine salinities</td>
<td>Salinity range of 5 to 30 present over at least 50% of longitudinal section 80% of the time</td>
<td>Freshwater inflows to create estuarine conditions (5 to 30 salinity)</td>
<td>Relevant Results: The model results show that estuarine conditions are present over 5.8 km for a 100 ML/day inflow and that this length is reasonably stable. However, at 300 ML/day, salt is able to penetrate up the estuary only for part of the tidal cycle and then occupies only the lower part of the water column. At this inflow, only the entrance lagoon is predicted to have brackish surface waters. With a flow of 900 ML/day the model predicts that very little salt will enter the estuary at all. These results are in broad agreement with measured data presented by Sherwood (2006). He reports measurements of the length of the salt wedge (which equates to ‘estuarine length’ in the Gellibrand River Estuary). This data (reproduced as Figure 10) indicates that the toe of the salt wedge can be found at around 6km (Rivernook Bridge) at flows up to 300 ML/day.</td>
</tr>
</tbody>
</table>

Hydraulic Recommendation: Estuarine conditions will be present over extended distances (> 1000m) when the freshwater inflow discharge is low (≤ 300 ML/day). At higher discharges (and lower entrance cross-sectional areas) brackish or saline conditions are only likely to be found in the lagoon behind the entrance up to Murray Park Bridge, and then mainly in the bottom waters.
<p>| | | | | |</p>
<table>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>7b</strong> 2 Salt wedge</td>
<td><strong>Spawning/egg survival</strong></td>
<td>Salinity between 15 and 20 in middle reaches, where Phragmites stands largest. DO &gt;5 mg/L in bottom water during spawning season Sep to Dec</td>
<td>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. DO/residence time</td>
<td>Salinity of 20 no further down than XS 11 (lowest Bridge) at the surface on the ebb of the spring tide. Halocline present as described by longitudinal plots (2dv). Use residence time to approximate DO - set maximum residence time of 2 days anywhere in water below halocline.</td>
</tr>
<tr>
<td><strong>Relevant Results:</strong></td>
<td></td>
<td></td>
<td></td>
<td>The model results suggest that a strong halocline will develop at lower inflow discharges (&lt;300 ML/day) and during spring tides. Plots of the spring flood and ebb tides at 100 ML/day give the best example of a well established halocline extending over a long reach (&gt;1000 m). At 300 ML/day the spring flood is only barely able to establish a halocline, and then only in the bottom waters (i.e. lower 50% of the water column).</td>
</tr>
<tr>
<td><strong>Hydraulic Recommendation:</strong></td>
<td></td>
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<td></td>
<td>In order to establish a persistent halocline low freshwater inflow discharge is required (&lt;300 ML/day) coupled with larger amplitude tides. Based on the model runs completed, a halocline will be established for around 50% of the standard tidal cycle (amplitude of 0.3m) with inflow discharges less than 100 ML/day.</td>
</tr>
<tr>
<td><strong>7c</strong> 3 Phragmites/seagrass</td>
<td><strong>Refuge/feeding for settlement and post settlement juveniles</strong></td>
<td>Inundated vegetation near salinity 15-20</td>
<td>specify flow band which positions the (former) halocline near the required vegetation type (seagrass or Phrag)</td>
<td>Determine flow band to provide halocline less than xs 3 for seagrass beds. Determine flow band to provide halocline d/s Rivernook Bridge for Phragmites (pref XS 9)</td>
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<td>See results for 7b (above)</td>
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</tbody>
</table>
### Table 7-8. Ecological and hydrological objectives for King George Whiting together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>8a</td>
<td>Entrance of larvae to estuary</td>
<td>Allow migration to estuary from the sea</td>
<td>Open Mouth August to late October</td>
<td>Mouth 30-50cm deep during period August to October (inclusive)</td>
<td>Empirical relationship derived by JS/BA (≥100ML to keep open JS graph) This won’t be apply to other estuaries – CG has possible method using geomorph, hydrology and hydraulics Estuary watch data might be used to calibrate above</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>8b 2 Larval fish habitat in estuary</td>
<td>Provide habitat for larval to survive and grow</td>
<td>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 veg. Though there is some evidence that fish use unveg mud/sand in sheltered area – e.g. Corio bay.</td>
<td>Salinity greater than 25 in bottom 1 m more than 80% of the time. KGW primarily marine species, so probably likely to be restricted to lower regions of estuary. Below XS 12 (lowest Bridge). DO/residence time</td>
<td>A) Determine steady state conditions which create salinity greater than 25 in bottom 1 m more than 80% of the time below XS 12 (lowest Bridge) during spring and summer. B) Use residence time to approximate DO - set maximum residence time of 2 days below XS 12 (lowest Bridge) in bottom 1 m.</td>
<td>Relevant Results: A) The model results suggest that highly saline bottom waters will develop at lower inflow discharges (&lt;=300 ML/day) and during spring tides. At 300 ML/day the spring flood pushes high salinity water into the lagoon behind the entrance, although this is flushed by the ebb tide. Hydraulic Recommendation: An inflow discharge of 100 ML/day will guarantee highly saline waters downstream of the Murray Park Bridge. B) The tracer study results suggest that the e-folding time at cross-section 12 (Murray Park Bridge) will be less than or equal to 2 days for flows greater than 100 ML/day. Hydraulic Recommendation: An inflow discharge of 100 ML/day is sufficient.</td>
</tr>
</tbody>
</table>
### Table 7-9. Ecological and hydrological objectives for Grayling together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
</table>
| 9a 1 Flow Fresh             | Adults spawning           | Flow fresh in late autumn | Occurs in water below 1-2 Salinity – therefore top section of estuary or lowest freshwater reach | Flow event which creates these conditions – max Salinity of 2 at 9,600m (third bridge) (top section of estuary or just upstream) – throughout water column in autumn. | Relevant Results:
The model results suggest that saline water progresses around 6 km up the Gellibrand River estuary under low flow conditions (100 ML/day). Sherwood’s compilation of measured data indicates that the toe of the salt wedge may migrate up to the third bridge (9.6km) at such low inflows. The physical requirement to meet this ecological requirement is that the toe of the salt wedge be pushed downstream of the third bridge. Based on Sherwood’s data (Figure 10), this will occur for inflow discharges greater than 120 ML/day.  

Hydraulic Recommendation:
An inflow discharge of 120 ML/day will keep the salt wedge below the third bridge (under most circumstances, e.g. excluding storm surge events). |

<table>
<thead>
<tr>
<th>Relevant Results:</th>
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</thead>
<tbody>
<tr>
<td>The model results suggest that saline water progresses around 6 km up the Gellibrand River estuary under low flow conditions (100 ML/day). Sherwood’s compilation of measured data indicates that the toe of the salt wedge may migrate up to the third bridge (9.6km) at such low inflows. The physical requirement to meet this ecological requirement is that the toe of the salt wedge be pushed downstream of the third bridge. Based on Sherwood’s data (Figure 10), this will occur for inflow discharges greater than 120 ML/day.</td>
</tr>
<tr>
<td>Hydraulic Recommendation:</td>
</tr>
<tr>
<td>An inflow discharge of 120 ML/day will keep the salt wedge below the third bridge (under most circumstances, e.g. excluding storm surge events).</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
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<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>9b 2 Freshwater in upper estuary</td>
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</table>

Relevant Results:
A) As per above. The models and data are not of sufficiently high calibration to distinguish between salinity < 5 and salinity < 2. However, in autumn and winter baseflow discharge (unimpaired flow series) is more than sufficient to keep the toe of the salt wedge well downstream of the third bridge.

Hydraulic Recommendation:
An inflow discharge of 120 ML/day will keep the salt wedge below the third bridge (under most circumstances, e.g. excluding storm surge events).

B) The tracer study results indicates that the e-folding time at cross-section 4 (Third Bridge) will be less than or equal to 2 days for flows of around 900 ML/day.

Hydraulic Recommendation:
An inflow discharge of 900 ML/day is required to keep the residence time below 2 days. Is this for the freshwater inflow? Salt water residence time is not relevant to this species.
<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>9c</td>
<td>3 Estuary Mouth State</td>
<td>High Flow Fresh</td>
<td>Require open mouth during May to July, salinity is not critical so up to 35 is OK for periods of up to 7 days with 2-3 events during the season</td>
<td>Determine flow required to cause/sustain a mouth opening event using the empirical data of Sherwood.</td>
<td>Relevant Results: As per discussion for criteria 8a.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mouth open during May to July (downstream movement)</td>
<td></td>
<td></td>
<td>Hydraulic Recommendation: Recommend an early (i.e. in July) winter fresh to open the mouth, or an artificial opening, if the mouth has been closed during May and June.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity create flow after the mouth open (flow sufficient to move silt downstream)</td>
<td></td>
<td></td>
<td>Winter fresh magnitude as per existing recommendations for opening and flushing the estuary:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity sufficient to take larvae 4 days to get down to an already open mouth (from GOR Bridge – with a small mouth open) “large estimate” John estimates 100ML/d</td>
<td></td>
<td></td>
<td>Flow sufficient to remove all salt water from the estuary should occur for 4 to 6 days at least monthly during the period July to October. For each episode initial flushing will require flows of 1500 – 2000 ML/day for 2 – 3 days. Thereafter flows of 500 – 750 ML/day for 2 – 3 days will prevent re-entry of salt water into the estuary. (Sherwood, 2006, Section 4.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ET FLOW Study = 4f5 = Dec – May &gt;260MLd 4 times per year</td>
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<td>April – May 4f5 – low flow fresh = Grayling breeding trigger overridden by disturbance flow</td>
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<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>9d 4 Estuary Mouth State</td>
<td>Migratory cue to return to estuary</td>
<td>uncertain</td>
<td>met by flows required to provide passage?</td>
<td>No assessment required</td>
<td>No assessment required.</td>
</tr>
<tr>
<td>9e 5 Estuary Mouth State</td>
<td>Freshwater Migration to estuary from sea by juveniles</td>
<td>30-50cm deep river mouth, Mouth open during Oct – Dec (upstream migration)</td>
<td>require open mouth, 30-50cm deep, during Oct-Dec, salinity not material, duration should be for up to 7 days with 2-3 events during the season</td>
<td>Oct-Dec, min duration of mouth opening of 3 days, min 2 events per season</td>
<td>Relevant Results: As per discussion for criteria 8a. Hydraulic Recommendation: Recommend the existing recommendation for late winter – early spring freshes be endorsed: Flow sufficient to remove all salt water from the estuary should occur for 4 to 6 days at least monthly during the period July to October. For each episode initial flushing will require flows of 1500 – 2000 ML/day for 2 – 3 days. Thereafter flows of 500 – 750 ML/day for 2 – 3 days will prevent re-entry of salt water into the estuary. (Sherwood, 2006, Section 4.2)</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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</tr>
<tr>
<td>9f</td>
<td>6 Low Flow fresh</td>
<td>Migration from estuary to freshwater reaches by juveniles</td>
<td>flow cue to migrate upstream</td>
<td>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) At the site of the riffle/rock bar (which has not been surveyed to date) Dec – May, min 4 events</td>
<td>thalweg depth at upstream bar/riffle &gt;30cm</td>
</tr>
</tbody>
</table>

**Relevant Results:**
Water level spot heights recorded during the survey indicate that there is a riffle somewhere between cross-section 1 (Great Ocean Road bridge) and cross-section 2 (2.7 km downstream).
Without any specific information it is **not possible** to determine the required discharge. An indicative discharge of 80 ML/day provides 30 cm flow depth over a rectangular channel 15 m wide (based on surveyed widths of upstream cross-sections) assuming a water surface slope of 1:5000 (as per field survey, Figure 9: XS1 to XS2) and Manning’s n of 0.03.

**Hydraulic Recommendation:**

i) The riffle should be found and surveyed.
ii) Until that time a discharge of 240 ML/day is recommended (with a margin of safety of 3 based on the simple analysis given above).

Note: This is a similar discharge to the ‘high flow’ recommendation for Reach 4 (Gellibrand River Mid Reach) of 260 ML/day.
Table 7-10. Ecological and hydrological objectives for Common Jollytail (*Galaxias maculatus*) together with Hydraulic Assessment Results

<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>10a 1 High Flow Fresh</td>
<td>Migration to estuary in autumn before spring tides</td>
<td>flow cue to migrate downstream</td>
<td>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)</td>
<td>No physical data to decide appropriate fresh in the estuary, therefore rely on estimate based on assumed riffle dimensions, slope and friction coefficient. Also refer to requirement for high flow freshes in the upstream freshwater reach. 2 events of min 3 days.</td>
<td>Relevant Results: As per 9f. Hydraulic Recommendation: i) The riffle should be found and surveyed. ii) Until that time a discharge of 240 ML/day is recommended (with a margin of safety of 3 based on the simple analysis given above). Note: This is a similar discharge to the ‘high flow’ recommendation for Reach 4 (Gellibrand River Mid Reach) of 260 ML/day.</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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<tr>
<td>10b 2 Flooded samphire or estuarine floodplain vegetation</td>
<td>Adults spawning</td>
<td>Spring tide in autumn following migration event</td>
<td>Inundation of emergent vegetation or samphire at the upper extent of the intertidal zone (once every two weeks based on the tidal regime)</td>
<td>Requires mouth to be open with mean daily tidal range equal to or greater than 0.2 m at lower bridge (XS10). This ensures sufficient tidal variation to provide opportunity for fish to find locations to spawn.</td>
<td>Relevant Results: The tidal amplitude declines as inflow discharge increases. Tidal amplitude will also be greater when the cross-sectional area at the mouth is larger (model results are for a moderate opening of 15 m²). In order to provide spawning opportunity the mouth of the estuary must therefore be open. The model suggests that an inflow discharge of 900 ML/day will damp the daily tidal variation to less than 0.10 m much, whereas at 300 ML/day the mean daily tidal range is almost 0.3 m. Thus a maximum inflow discharge of 600 ML/day</td>
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</tbody>
</table>

Hydraulic Recommendation:
<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>10c 3 Estuary Mouth State</td>
<td>Marine Migration by larvae</td>
<td>30-50cm deep mouth</td>
<td>Require open mouth during May to July, salinity is not critical so up to 35 is OK for periods of up to a 7 days with 2-3 events during the season</td>
<td>Determine flow required to cause/sustain a mouth opening event using the empirical data of Sherwood.</td>
<td>As per 9c.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mouth open during May to July (downstream movement)</td>
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<td>Velocity create flow after the mouth open (== flow sufficient to move silt downstream)</td>
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<tr>
<td></td>
<td></td>
<td>Velocity sufficient to take larvae 4 days to get down to an already open mouth (from GOR Bridge – with a small mouth open) “large estimate” John estimates 100ML/d</td>
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<tr>
<td>10d 4 Estuary Mouth State</td>
<td>Migratory cue to return to estuary</td>
<td>uncertain</td>
<td>met by flows required to provide passage?</td>
<td>No assessment required</td>
<td>No assessment required</td>
</tr>
</tbody>
</table>

Z:\Documents\LE Projects\0717 Estuaries Method Stage 2\Gellibrand Final Recommendations Paper 110908apedv3.doc
<table>
<thead>
<tr>
<th>Physical Habitat Component</th>
<th>Role of Habitat Component</th>
<th>Conditions Required</th>
<th>Physical Factors</th>
<th>Possible Assessment Approaches</th>
<th>Hydraulic Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>10e 5 Estuary Mouth State</td>
<td>Freshwater Migration to estuary from sea by juveniles</td>
<td>30-50cm deep rivermouth Mouth open during July to December (upstream migration)</td>
<td>require open mouth, 30-50cm deep, during Oct-Dec, salinity not material, duration should be for up to 7 days with 2-3 events during the season</td>
<td>Oct-Dec, min duration of mouth opening of 3 days min 2 events per season</td>
<td>As per 9e.</td>
</tr>
<tr>
<td>Physical Habitat Component</td>
<td>Role of Habitat Component</td>
<td>Conditions Required</td>
<td>Physical Factors</td>
<td>Possible Assessment Approaches</td>
<td>Hydraulic Assessment</td>
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<td>---------------------------</td>
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<td>-----------------</td>
<td>--------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>10f</td>
<td>6 Riffles, stream bars, flow freshes</td>
<td>Migration from estuary to freshwater reaches by juveniles</td>
<td>flow cue to migrate upstream – probably flow freshes (low and high)</td>
<td>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) At the site of the riffle/rock bar (which has not been surveyed to date)</td>
<td>thalweg depth at upstream bar/riffle &gt;30cm</td>
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</table>

**Relevant Results:**
Water level spot heights recorded during the survey indicate that there is a riffle somewhere between cross-section 1 (Great Ocean Road bridge) and cross-section 2 (2.7 km downstream).
Without any specific information it is not possible to determine the required discharge. An indicative discharge of 80 ML/day provides 30 cm flow depth over a rectangular channel 15 m wide (based on surveyed widths of upstream cross-sections) assuming a water surface slope of 1:5000 (as per field survey, Figure 9: XS1 to XS2) and Manning's n of 0.03.

**Hydraulic Recommendation:**
1) The riffle should be found and surveyed.  
2) Until that time a discharge of 240 ML/day is recommended (with a margin of safety of 3 based on the simple analysis given above).

Note: This is a similar discharge to the 'high flow' recommendation for Reach 4 (Gellibrand River Mid Reach) of 260 ML/day.
## 8 APPENDIX 2 – HYDROLOGICAL ANALYSIS RESULTS

### Table 8-1. Gellibrand River analysis of discharge series for estuary thresholds

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Scenario</th>
<th>Threshold</th>
<th>Greater/Less than</th>
<th>Months</th>
<th>Per year Mean Freq</th>
<th>% Years with event</th>
<th>Days</th>
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<td></td>
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<td></td>
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<td></td>
<td>Duration (Q25)</td>
</tr>
<tr>
<td>1a</td>
<td>Full devel</td>
<td>100</td>
<td>Less than</td>
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<td>3.89</td>
<td>89%</td>
<td>14</td>
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<tr>
<td>1a</td>
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<td>100</td>
<td>Less than</td>
<td>12.1 - 5</td>
<td>3.89</td>
<td>89%</td>
<td>14</td>
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<td>43%</td>
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<td>8a, 9c</td>
<td>Full devel</td>
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<td>100%</td>
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<td>100%</td>
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<td>Months</td>
<td>Per year</td>
<td>% Years with event</td>
<td>Days</td>
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<td>97%</td>
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<td>5-7</td>
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<td>10-12</td>
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<td>7</td>
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<td>1.89</td>
<td>83%</td>
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<td>83%</td>
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</tr>
<tr>
<td>10b</td>
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<td>600</td>
<td>Greater than</td>
<td>3-5</td>
<td>1.97</td>
<td>86%</td>
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</table>

**Threshold**
- Q25: exceeded 25% of time
- Q50: median
- Q75: exceeded 75% of time
9 APPENDIX 3 – TOPOGRAPHIC SURVEY

Topographic survey was undertaken by Reed and Reed Surveyors in August and September 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.

9.1 Site locations

Seventeen cross-sections were specified to provide sufficient information on which to develop both hydraulic models. The locations were specified to capture key changes along the length of the estuary channel and to approximate floodplain storage. Fourteen cross-sections were designated along the Gellibrand River (Figure 9-1 and Figure 9-2) and three along Latrobe Creek (Figure 9-3).

9.2 Specification

The following specification was provided to guide the work of the surveyor.

- Survey cross-sections at locations indicated on accompanying maps.
- Surveys to provide sufficient detail to characterise the detailed morphology of the channel and levees (at the top of the bank), and to generally characterise the floodplains.
- 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.
- Surveys to include water surface elevation on the day of the survey (indicating the time of day when the survey as made) at each cross-section where water is present.
- As a minimum, the data must be provided in text file format (either comma separated values, .csv, or tab delimited, .txt). Data in GIS format would also be useful.
- Hard copy plans are NOT required but soft copy report is required including: identification of projections, height controls, and statement of positional and level accuracy/precision; and plans of survey data.

The attached plans show the location of seventeen cross-sections. Each cross-section is labelled showing the coordinates of the end points of each transect (UTM coordinates projected in GDA 94). These coordinates are not intended to be prescriptive, but indicative of the location (and bearing) of the transect.

In addition each cross-section has been labelled (in yellow) with an approximate distance (metres) upstream of the estuary mouth. In the case of the three cross-sections on Latrobe Creek (plan 3), which enters the Gellibrand from the northwest, the distances are from the junction with the Gellibrand River with a ‘99’ pre-pended.

The survey of the Gellibrand includes transects at three bridges (1100, 5400 and 8600). At each of these locations please survey a transect across the top of the bridge and along the top of any road embankment that blocks the floodplain. Please also survey the channel cross-section 1-5 m upstream of the bridge (from top-of-bank to top-of-bank). At the two locations higher up the reach, a second transect is required to indicate the morphology of the floodplain away from the roadway.

The cross-section highest up the river (13500 m) is to be measured immediately upstream of the highway bridge (Great Ocean Road). The cross-section at the mouth of the estuary may be difficult to locate exactly. The mouth is dynamic and the estuary may be open or closed.
Figure 9-1. Definition of cross-section locations near the mouth of the Gellibrand River Estuary
Figure 9-2. Definition of cross-section locations at the upper end of the Gellibrand River Estuary
Figure 9-3. Definition of cross-section locations on Latrobe Creek (tributary to the northwest of Gellibrand River)
10 APPENDIX 4 - SURVEYORS NOTES

The following report was prepared by Harry Reed to accompany his survey data. The format has been slightly modified for presentation in this report.

10.1 Introduction

15 sections have been surveyed along the Gellibrand River and 3 along the Latrobe Creek. Section 1A (just downstream of the Great Ocean Road bridge section 1) was not in the original specification, but was added at our discretion, as the change in section was considered to be significant. Sections are numbered from upstream to downstream, beginning with 1 at the GOR bridge and ending with sec. 14 at the entrance. Latrobe Creek sections are 15, 16 & 17. All sections were surveyed after the river broke through the entrance bar. There are tidal variations in water levels that will be hard to quantify – but observation indicates that the range is no more than 0.3m. Water levels for sections 3-14 & 16 & 17 are affected to some degree by tide, but there is a time lag of course.

Flow conditions in July were too vigorous for safe survey, and early August was very windy, so the survey presented was conducted between mid August and 9th September. River flow conditions were moderate (mid-August) tapering to low in September. Survey in mid August was concentrated in the wide river sections near the mouth where flow variations have little effect compared to tide, so the variations in river flow have been minimized in their effect.

Section co-ordinates supplied were always considered, but the surveyed sections were often varied a little due to local factors (as is always the case). The variations retain the perceived integrity of the section decision. Survey was primarily done by survey accuracy GPS across the wetlands; supplemented by crossline depthing by leadline in the river, and EDM [electronic distance measurement – ed] for GPS hostile environs (under trees and steep cliffs). Our CAD distinguishes GPS values as black crosses, leadline as cyan and EDM as magenta.

We have re-numbered the shots that are relevant to each section in ascending order from the extreme left bank shot. A shot number of 321 indicates a section 3 shot - a shot number 1123 indicates section 11 and so on. The text file forwarded contains only these shots along the section. There are other shots that are relevant, such as top of bridge and culvert inverts. They are in the SHAPE file but not the text file. We hope this expedites processing at your end.

3 photos (across – upstream – downstream) have been taken at each section and will be forwarded later (we are prioritizing delivery of the survey data).

THE RIVERBED was firm and clear of obstructions for all sections. The margins varied with local conditions but the bed was always firm (clay or sand).

LEVEL DATUM is AHD. GRID is Zone 54 MGA.94
10.2 Gellibrand River Estuary Sections

SECTION 1
Runs along the shoulder of the Great Ocean Road, but dips down into the floodways and river bed. SHOTS 101 –150 apply
Water level was 1.96 on 26/8/07 at 1100hrs. Flow was moderate – tide not known. ( shots 121 & 136 are water level)
Deepest bed –0.86 AHD ( shot 129)

SECTION 1A
Not requested but run on our discretion as section is different.
Section follows floodplain ( lightly wooded with wetlands on left bank – grassed pasture on right)
SHOTS 151 –195 apply
Water level 1.95 at 26/8/07 @ 1400hrs ( 167 & 182 )
Deepest bed –1.27AHD (shot 171, 172)

SECTION 2
High ground on left bank ( narrow wetland) – wide wetland on right bank – no significant vegetation.
SHOTS 201 –263 apply
Deepest bed –2.20 AHD ( 226)

SECTION 3
Run 20m upstream of Ferrari/Barlow bridge. Wetland on left bank. Narrower wetland on right bank then a spur ridge ( section follows crest of ridge )
SHOTS 301 –375 apply
Water level 0.64 at 1100hrs on 9/9/07 ( lowish tide and low flow) ( 327 & 345)
Deepest bed –2.06 AHD( 333 ).

SECTION 4
Run along upstream edge of Ferrari-Barlow bridge. Wetland on left bank. Road embankment on right bank.
SHOTS 401-465 apply
Bridge girders obstruct flows between RLs 2.8 & 3.8
NOTE 6 off 750mm dia. Culvert pipes are placed through road embankment one at invert 0.95 – the rest at 1.5 ( shots 5501-5506 )
Water level 0.64 as above
Deepest bed is –1.50AHD ( 436)

SECTION 5
Across Barlows corner beside Coes block. River runs in formed drain here, but readily floods wetlands on both sides.
SHOTS 501-558 apply
WL was 0.68 on 8/9 @1530hrs and 0.60 on 9/9 @ 1330hrs ( low flow –tide??)
Deepest bed is –2.22 ( 529 )

SECTION 6
80m upstream of Ferrari-Kangaroobie bridge. Wetlands on left bank – road embankment on right bank.
SHOTS 601 –645 apply
WL. 0.35 AHD at 1400hrs on 5/9/07 ( 624 & 635 )
Deepest bed –3.35 ( 630)
SECTION 7

Along upstream face of Ferrari-Kangaroobie bridge. Along road embankment on both sides.
SHOTS 701-753 apply.
NOTE 1 A concrete floodway (ford) has been constructed on left bank road as shown.
NOTE 2 Two 900mm culvert pipes lead through the left bank road at shots 7701 & 7702.
NOTE 3 Bridge beams obstruct flows between RLs 1.4 & 2.3
Water level 0.35 @ 1300hrs on 5/9/07 (low flow & lowish tide)
Deepest bed –4.63 (732).

SECTION 8

At Kangaroobie – at upstream edge of fringing sand dunes (left bank). Left bank is sand hill. Right bank is wetlands/floodplain. Upstream end of wide river section.
SHOTS 801 – 853 apply
Water level 0.33 1000 on 8/9/07 (809 & 830)
Deepest bed –3.92 (821)

SECTION 9

At Kangaroobie. Left bank has narrow floodplain under dense vegetation (melaleuca etc) Right bank is open with sandy high ground near river and floodway further back. River is wide
SHOTS 901-980 apply
Water level 0.38 1230 on 8/9/07 (low flow but rising tide) (908 & 952)
Deepest bed –2.52AHD (941)
NOTE 1 Sandy high ground on near right bank at RL 2.8+ has old dairy sort of standing – which indicates it is above normal flood level.

SECTION 10

Section across low lying phragmites/rush wetlands on both banks. River is wide.
SHOTS 1001-1077 apply
WL 0.40 on 27/8/07 @ 1200 (mid tide and middling flow) (1033 & 1051)
Deepest bed –2.90 AHD (1040).

SECTION 11

A very long section from the sand dunes, across the sports ground through the phragmites/rush swamp on the left bank. Right bank rises quickly.
SHOTS 1101-1181 apply
WL 0.42 1400hrs 28/8/07 (1152 & 1172)
Deepest bed –1.95AHD (1164)

SECTION 12

Downstream edge of bridge to Rec Reserve. Section follows road embankment both sides.
SHOTS 1201-1243 apply
Bridge beams obstruct flows between RLs 1.5 & 1.65
WL 0.45
Deepest bed –3.23 (1223)

SECTION 13

Widest part of estuary with shallow sand banks uncovering at low tide (right bank) Right bank is steep cliff, left bank is undulating sand hills.
SHOTS 1301-1375
Water level is tide dependant while estuary is open (range 0.3m+)
Deepest bed –1.63AHD (1318)
SECTION 14
Upstream start of exit race to ocean. Sandy bed is dynamic and changes from tide to tide. Undulating sand hills on left bank. High sheer cliff on right bank.
SHOTS 1400-1447 apply
WL 0.35 at low tide – but hard to estimate due to wave surges.
 Deepest bed – 1.85
NOTE: current varies with wave surges from strongly out to gently in.

10.3  Latrobe Creek Sections

SECTION 15
Upstream creek section. Dry at time of survey. Open pasture land. Rises steeply on both sides.
SHOTS 1501-1522 apply
Drain bed RL 3.17 (1510,1511)

SECTION 16
Mid section.  Phragmites/rush wetlands on both banks with frequent open pools of water (duck holes). Creek is tidal.
SHOTS 1601 – 1685 apply
Water level 0.56 (low tide & low flow) (1623 & 1634)
Lowest bed is – 0.94AHD (1626)

SECTION 17
Lower reach just before junction with Gellibrand. Phragmites wetland with open pools on right bank.
Narrow floodplain with Melaleuca & sword grass on left bank. Creek is tidal
W.L. 0.415 (1711 & 1723 )
Deepest bed – 2.06 AHD (1717)

10.4 Other Field Notes

The extent of tidal influence surprised me, as did the existence of deep holes well below zero AHD along the entire length (anecdotally there are even deeper holes in reaches not surveyed).
As zero AHD is mean ocean water level this indicates these pools can never drain and must rely on flood flushing.

The whole estuary changes dramatically once the ocean bar breaks through. Just how you model that I cannot imagine – but there are a lot of things computers can do that are beyond my ken.

Harry Reed

12/9/07
11 APPENDIX 5 – 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.

11.1 Review of existing data

11.1.1 Tides and other factors causing sea level variation

The tides along the Otway coast are semi-diurnal with a tidal range of approximately 0.8 m during spring tides and 0.6 m during neap tides. During the summer spring tides, the greater tidal difference occurs during the night. However, the reverse is the case in winter with the greater difference during the day. The sill/sand barrier at the mouth of the estuary further attenuates the tidal influence in the estuary.

Atmospheric pressure leads to sea-level variations, by what is known as the inverse barometer effect (Beer 1983). Based on measurements made by Hamon (1966, in Barton and Sherwood, 2002) Barton and Sherwood (2002) calculate that sea levels may vary by up to 50 cm as a result of the passage of pressure systems.

In western Victoria, on-shore winds from the west and southwest are common in all months and may reach speeds up to 30 knots. Such strong winds are often associated with low pressure and cold fronts and therefore can enhance pressure-based sea level superelevation (Watterson et al., 2007).

The coastline into which the Gellibrand River enters has very high wave energy from the prevailing southwesterly ocean swell and storm waves arriving through deep water over a narrow section of the Australian continental shelf (Bird, 1993). Large waves generated by Southern Ocean storms may arrive at the coast any time and do not necessarily synchronise with the local weather system. However, such waves have been known to overtop sand bars at
the entrance to west Victorian estuaries and add significant volumes of sea water. For example, in April 1994 the Hopkins estuary level rose 10 cm in 6 hours due to this effect (Rouse, 1998).

Storm surge and the associated wave setup are important factors that can cause floods in estuaries. A succinct explanation of these phenomena by Watterson et al. (2007) is reproduced in Figure 11-1. Simulation results presented herein are based on present sea surface levels and take no account of storm surge.

**Box 5.2 Contributions to coastal sea level from tides, storm surge and wave processes**

A storm surge is a region of elevated sea level at the coast caused by the combined effect of falling atmospheric pressure and intense winds of severe weather events such as tropical cyclones. The rise in sea level due to falling pressure is about 1 cm per hectopascal fall in pressure (the so-called inverse barometer effect) although the larger contribution is due to wind, which pushes the water against the coast. Factors influencing the impact of winds on the storm surge include its strength, direction relative to the coast and the way in which the storm moves in relation to the coast.

For example, a tropical cyclone-induced storm surge would be most intense over the region of strongest onshore winds as the cyclone makes landfall. The shape of the sea floor and the proximity to bays, headlands and islands also affect the storm surge height.

Wide and gently sloping continental shelves amplify the storm surge, and bays and channels can funnel and increase the storm surge height. Storm systems such as tropical cyclones and mid-latitude storms and their associated cold fronts are the main cause of storm surges. Storm surges can interact with other ocean processes such as tides and waves to further increase coastal sea levels and flooding. A storm surge will have maximum impact if it coincides with high tide. Breaking waves at the coast can also produce an increase in coastal sea levels, known as wave setup.

![Figure 11-1 Storm surge, wave setup and wave runup (after Watterson et al., 2007, p.94)](image-url)
11.1.2 Tides and other factors causing sea level variation

Water Technology analysed the tidal records at Portland to estimate the 100 year combined tide and storm surge level for the South Warrnambool Flood Study (J118, 2007). It was assumed that tide and surge were independent and that any given peak astronomical tide may coincide with the peak in a surge event. Since the peak levels of a surge event typically have a duration of many hours, this assumption is reasonable and results in slightly conservative (over) estimate of 100 year tide plus surge levels. The estimated peak tide plus surge levels are summarised in Table 11-2.

Table 11-1 Annual exceedance probability (AEP) and annual recurrence intervals (ARI) of sea levels based on tide plus storm surge calculated for Portland

<table>
<thead>
<tr>
<th>Portland Level (m AHD)</th>
<th>Est. Gellibrand Level (mAHD)</th>
<th>Increase in level over simulated case (m)</th>
<th>AEP (%)</th>
<th>ARI (1 in Yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>0.60</td>
<td>0.20</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>0.85</td>
<td>0.75</td>
<td>0.25</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>0.93</td>
<td>0.83</td>
<td>0.43</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>0.98</td>
<td>0.88</td>
<td>0.48</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>1.03</td>
<td>0.93</td>
<td>0.53</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>1.07</td>
<td>0.97</td>
<td>0.57</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

The above analysis was based on available data from Portland. Tidal amplitudes at the mouth of the Gellibrand River are less than at Portland with peak tide levels 0.10 m lower (peak at 0.5mAHD compared with 0.6mAHD at Portland). Thus, a discount of 0.10 m was applied to the Portland storm surge levels in order to estimate the equivalent levels at the Gellibrand River.
11.2 Field Measurements

A series of field investigations were undertaken to provide input data to configure and calibrate the hydrodynamic models. Funding was provided for topographic/hydrographic survey of the estuary channel and floodplains and automatic tide gauges were deployed along the reach.

11.2.1 Topographic / Hydrographic Survey

Reed and Reed Surveying were commissioned to survey seventeen cross-sections that formed the basis for development of both the Tide Model and the Flood Model. Cross-sections were located to capture key changes along the length of the estuary channel and to approximate floodplain storage (see Section 9 for full details). Fourteen cross-sections were designated along the Gellibrand River and three along Latrobe Creek.

Survey was primarily achieved using survey-accuracy GPS across the wetlands. The GPS was supplemented by cross-line depthing using a leadline in the river, and electronic distance measurement in other GPS hostile environments (i.e. under trees and steep cliffs).

The surveyor provided:

- vertical levels reduced to Australian Height Datum (AHD);
- reported positions using the grid: Zone 54, MGA.94
- all measurements in a text file as well as ESRI shape files;
- the water level on the day of the survey at each cross-section;
- three photographs at each cross-section (across the stream, upstream, downstream); and
- size, position and invert level of culverts through levees on the floodplain crossings.

A more detailed report on the survey is presented in Section 10. The survey data and photographs are included on the Data DVD that accompanies this report.

11.2.2 Tide Gauging

Five Onset HOBO\(^{14}\) pressure/temperature loggers (Model U20-001-04-Ti) were deployed along the Gellibrand estuary. Four loggers were mounted below the water surface at bridges across the estuary (Table 11-2). The fifth logger was deployed on land near the lower bridge (at Murray Park) to measure atmospheric pressure.

The loggers were deployed on the 3\(^{rd}\) of September and retrieved on the 10\(^{th}\) of September. The short duration of the deployment was necessitated by project deadlines. The data obtained was

adequate for calibration of the hydraulic model (a deployment of 30 – 60 days is recommended for future Estuary Flow studies).

Table 11-2. Deployment details for tide gauges

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude*</th>
<th>Longitude*</th>
<th>Distance to entrance</th>
<th>Site description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Bridge (Murray Park)</td>
<td>143°09’18” E</td>
<td>39°18’11” S</td>
<td>1.3 km</td>
<td>Old submerged pile, downstream, W side</td>
</tr>
<tr>
<td>Rivernook Bridge</td>
<td>143°10’52” E</td>
<td>39°17’10” S</td>
<td>5.4 km</td>
<td>Downstream bridge pile, E side</td>
</tr>
<tr>
<td>Theo’s Bridge</td>
<td>143°12’23” E</td>
<td>39°16’11” S</td>
<td>8.6 km</td>
<td>Downstream bridge pile, E side</td>
</tr>
<tr>
<td>Great Ocean Road Bridge</td>
<td>143°15’03” E</td>
<td>39°16’22” S</td>
<td>13.7 km</td>
<td>Submerged tree 10-15m upstream of bridge</td>
</tr>
</tbody>
</table>

* Positions determined from VicMap 1:25,000 topographic data (GDA.94)

Mouth dimensions were approximated as ~15m² at both the date of deployment (14 m² at 14:45 on 3 September, 2007) and the date the tide gauges were removed (17 m² at 13:20 on 10 September 2007). Salinity was <0.1 at all sites except the Lower Bridge between 11:20 (Great Ocean Road Bridge) and 12:40 (Lower Bridge) on 10 September. At the Lower Bridge a halocline was observed at depths between 1m (sal: 4.9) and 1.5m (sal: 19.2). Water levels on the gauge at the lower bridge were 3.57m at 14:00 on 3/9 and 3.37m at 13:50 on 10/9.

The design sampling interval was 1 minute, with the high frequency possible due to the short deployment duration. However, the loggers at the Lower Bridge and the Great Ocean Road (GOR) Bridge were incorrectly initialised to take measurements at 5 minute and 15 second intervals respectively. Consequently, the memory of the GOR logger filled up at 06:47 on September 6th. The lower resolution of the Lower Bridge record was not a concern, in fact the sampling interval that will be recommended for tide gauging (in the Estuary Flow Method Report) is 6 minutes (allowing 60 day deployments with existing logger technology).

Water depths at each sensor were calculated from the measured pressure data using HOBO Pro software. The software accounted for variations in atmospheric pressure through the deployment using the record of the fifth logger. It also accounted for different water densities with a fresh water density of 1000 kg/m³ used to calculate depth at the three upstream sites, and a brackish density of 1010 kg/m³ used at the Lower Bridge. Temperature, pressure and calculated sensor depth were recorded in a spreadsheet (included on Data CD accompanying this report).
Logger elevations were not surveyed and consequently the water level results could not be accurately reduced to Australian Height Datum. Instead, water levels were reduced to approximately the same 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 11-2). Measured water surface elevation increases in an upstream direction (i.e. from the Lower Bridge to GOR) due to the water surface slope along the 13.7 km reach.

The gauges were installed just prior to the peak of a minor fresh (Figure 11-3) that had a maximum discharge on the 4th of September at 367 ML/day. Water levels slowly declined over the period of record with the water levels at the two downstream sites declining more rapidly than the upstream sites. Variation with the tide is also greater at the two downstream gauges, with water level variation at the upstream gauges driven more by the inflow hydrograph. However, it should be noted that tidal variation at Theo’s Bridge became far more pronounced on around the 7th of September when the inflow discharge dropped below 300 ML/day. This observation suggested that a flow of around 300 ML/day limits upstream progression of the tidal wave to around Theo’s Bridge (based on prevailing conditions at the time, especially mouth opening status which was measured pre- and post-tide gauge deployment at approximately 15 m²).
Figure 11-2. Measured tide gauge data at four sites corrected approximately to Australian Height Datum with predicted tides for Port Campbell shown for reference. Note Great Ocean Rd record is short due to incorrect logging interval being set.

Figure 11-3. Hydrograph measured by the Burrapa gauging station (freshwater inflow discharge to the estuary) over the period of tide gauge deployment.
11.3 Tide Model Development and Calibration

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 Gellibrand Estuary is long (13.7km) and flows within a relatively narrow channel with banks topped in many places by natural levees. 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.

11.3.1 Model Construction

Five key elements were required to define the 2DV Gellibrand Tide Model: (1) channel and floodplain geometry; (2) a downstream boundary condition; (3) atmospheric conditions; and (4) the specification of hydraulic roughness for the channel and floodplains. The final element is to define an inflow hydrograph (5).

a) Geometry

The model bathymetry was developed using the survey data. The 2DV averaging scheme represents the channel cross-section as trapezoidal sections. An optimisation program was written to automatically find the best-fit trapezoid. Optimisation aimed to minimise the difference between the stage-area curve of the surveyed cross-section and that of the fitted trapezoid while ensuring the bankfull area of the trapezoid matched the surveyed channel area. The bankfull width and the depth to the channel thalweg (i.e. bankfull elevation – thalweg elevation) were held to within ±2% of their measured values.

The geometry of the estuary entrance was initially estimated from the survey data. However, given the dynamism of the entrance and the difficulty of surveying the controlling cross-section, the invert level and bankfull cross-sectional area of the entrance were varied during model calibration to achieve a best fit to the measured tide gauge data.

b) Downstream Boundary Condition

The downstream boundary condition was defined by reconstructing the tidal sequence predicted for Port Campbell, the most proximal port in the Australian National Tide Tables (Australian Hydrographic Service, 2004).

c) Atmospheric Conditions

Water levels, both inside and outside the estuary, will respond to wind and barometric pressure. However, it was outside the scope of this investigation to consider variations in these parameters. Consequently, wind speed was set to zero and a constant barometric pressure assumed (101 325 Pa).
d) **Hydraulic Resistance**

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 two different sections on the basis of field observations. The lower 4 km (relatively wide channel) of the estuary was assigned a Manning’s n of 0.026, while the narrower upper reach was assigned a starting value of 0.030 (given the channel was narrower and lined with macrophytes for much of its length). The magnitude of the hydraulic resistance was later refined via calibration of the Tide model to water level fluctuations measured by the tide gauges.

e) **Upstream Boundary Condition**

Freshwater inflow discharge is the upstream boundary condition and one of the primary variables of interest. The discharge hydrograph recorded at the gauging station on the Gellibrand River at Burrapa (ID: 235 224) over the period of the tide gauge deployment was used to specify the inflow during model calibration. The model was subsequently for a range of steady flow discharges during scenario testing.

f) **Test Simulation**

The configuration phase was completed when a test simulation, executed with a constant upstream inflow and a neap-spring tide cycle at the downstream boundary, executed successfully and produced sensible water level results.

11.3.2 Tide 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 simulated and measured tidal signals were compared by plotting the measured versus modelled water surface variations together. The features of the water level traces that were examined included:

- magnitude of the peaks and troughs should be similar to the measured and show no bias (i.e. model should not consistently over or under predict floods/ebbs);
- the phase shift (in time) of the tidal wave correctly (e.g. arrival time of the flood);
- the correct increase/decrease in magnitude of water level variation both:
  - over the tidal cycle at a gauging site; and
  - along the estuary from one gauge point to the next;
- reproduce any estuary-specific variations in the shape of the tidal wave (e.g. truncation of the wave trough due to presence of a sill in the channel).
The results of these comparisons allowed the parameters of the numerical model to be adjusted in an iterative fashion until a satisfactory match was achieved. The key calibration parameters were:

- Flow coefficients: hydraulic resistance along the channel (may vary spatially), and hydraulic resistance across the entrance bar.
- Bathymetry: flow area and sill (invert) of the estuary entrance; and the representation of hydraulic control points (e.g. channel contractions/expansions, riffles/bars).

The correspondence of measured to modelled data was not expected to be perfect, partly because it is not possible to reproduce the exact conditions over the measurement period and partly due to data limitations. For example, a key assumption was that the downstream boundary condition could be adequately represented by the predicted (rather than actual) tide. The objective was to minimise differences between the measured and simulated results while keeping model parameters within realistic bounds.

**a) Calibration Results**

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 level of calibration achieved is shown by Figure 11-4.

The Tide Model was able to reproduce to an acceptable level the water level dynamics observed along the Gellibrand River estuary. Water level variation over the first part of the record could not be reproduced with sensible parameter values, suggesting that uncontrolled boundary conditions (e.g. barometric pressure) may have significantly influenced the measured data. Calibration effort therefore focussed on results at the end of the gauging period (Sept. 7 – 10). Ultimately, good agreement in tidal range and timing was achieved at the two downstream bridges (Rivernook and Lower). The results at the upstream bridges (Theo’s and Great Ocean Rd) were not as good. However most ecological interest focussed on the downstream section of the estuary and hence further work to improve model performance at these sites was not done.
11.3.3 Scenarios run with the Tide Model

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 three different freshwater inflow discharges: 100, 300 and 900 ML/day. These were chosen by inspection of the hydrological data as approximately representing summer baseflow (100 ML/day), winter baseflow (300 ML/day) and bankfull flow (900 ML/day). A moderate estuary entrance area was assumed (15 m² – as per tide gauging) and the downstream boundary was defined by a repeating spring-neap tidal cycle (based on constituents for Port Campbell from: Australian Hydrographic Service, 2004). In this case, the neap-spring cycle chosen was 15 days in length.

Each of the three model configurations (i.e. inflow variants) were run over a 60 day simulation period. The salinity of the water in the estuary was started completely fresh. The first 30 days of simulation (2 tidal cycles) provided time for salt to enter from the downstream boundary and allowed the salinity structure to reach dynamic equilibrium. The next 15 days of simulation were used to characterise the dynamics of water levels and the salinity structure for this entrance area.

Figure 11-4 Results of model calibration at the four tide gauging stations showing measured water levels (solid line) and predicted (modelled) water levels (dashed line).
and inflow combination. Over the final 15 days of simulation the inflow discharge was increased to 1500 ML/day for 3 days then reduced to 750 ML/day for 4 days to examine whether this was sufficient to flush salt from the estuary and hold it out (as per the estimates of Sherwood, 2006, Section 4.2).

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:

- Animation of the longitudinal salinity profile.
- Snapshot of the salinity structure (1 each on the ebb and flood).
- Time series variation of vertical salinity profiles (top, middle and 2nd from bottom layers) at 4 – 5 discrete locations along the estuary.
- Variation of velocity (top, middle and 2nd from bottom layers) at 4 – 5 discrete locations along the estuary. This data may also be used to estimate shear stresses for preliminary sediment transport estimates (derived using Area-Discharge relationship).
- Residence time. The e-folding time provides a practical measure of the time interval taken for a certain volume/parcel of water in the estuary to be exchanged with new water (Abdelrhmans, 2005; Monsen et al., 2002). 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 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 rate of development in the initial 4 weeks of simulation (that started with the estuary completely fresh) were compared to the mature salinity profiles of weeks 5 and 6.

A series of more specific evaluations were undertaken to develop the final flow recommendations at the Scientific Panel Workshop and thereafter. These evaluations involved extracting salinity/velocity/water depth data at particular locations of interest, often interpolating between inflow discharges.

11.3.4 Sample Water Level and Salinity Results
This section presents a sample of the results produced from the hydraulic simulations. These are intended to provide the reader with an indication of the type of information that the Scientific Panel had to work with; in particular the variables (water depth, salinity, etc) that the model makes available.

The predicted water surface elevations were plotted on a cross-section to ‘reality check’ the numerical model as well as to assist in ecological and geomorphic interpretation. Such a plot for
the three inflow cases at cross-section 10 is shown in Figure 11-5. Each inflow is colour coded (with the inflow discharge listed at the right of the figure), with levels indicating the mean (solid line), minimum (dash-dot line) and maximum (dashed line) water surface elevation over the 15 day tidal cycle. The chart shows that the range of water surface elevations contracts as inflow discharge increases. The results indicate that 900 ML/day just slightly exceeds the bankfull capacity of the channel.

Figure 11-5 Summary of predicted water surface levels at cross-section 10 (500m upstream of the Lower Bridge) for different inflow discharges (100, 300 and 900 ML/day). The mean water level (solid line) and the maximum (dashed line) and minimum (dash-dot line) water levels over a full cycle of tides are highlighted.
Two sets of plots were prepared for each of the three test inflow cases:

- time series of the variation of the simulated water level at cross-section 10 (500 m upstream of the Lower Bridge) - Figure 2, Figure 4 and Figure 6 for 100, 300 and 900 ML/day respectively;
- snapshots of the salinity profile at the ebb and flood tides at neap and spring in the tidal cycle - Figure 3, Figure 5 and Figure 6 for 100, 300 and 900 ML/day respectively.

**Water Level Results**

The water surface elevation ('tide height') predicted by the Tide model over a typical 15 day cycle of tides varies both with both tide and the upstream inflow discharge to the estuary (Figure 2, Figure 4 and Figure 6). Over the first week the cycle of tides is diurnal (one tide per day) moving into a semi-diurnal (two tides per day) variation for the later half of the cycle (e.g. Figure 2). Comparing the tide height variation shown by the three charts indicates that the magnitude of the tidal signal is damped as the upstream inflow discharge increases. The difference between the minimum and maximum predicted water surface elevation exceeds 0.4 m for inflows of 100 and 300 ML/day, but declines to only 0.16 m at 900 ML/day.

**Salinity Distribution Results**

The salinity distributions predicted for the 100 ML/day case (Figure 3) suggest that the larger magnitude spring tides are required to push salt up into the estuary and form a strong and extensive (>5 km long) halocline. When the inflow rises to 300 ML/day (Figure 5) the maximum penetration of salt is restricted to around the first 3 km of the estuary at spring tides, and for the majority of the time only up to the Lower Bridge (~ 1 km). The results suggest that a bankfull flow of 900 ML/day (Figure 6) will push salt entirely from the estuary. On the basis of these snapshots, the distance along the channel that estuarine conditions can be found somewhere in the water column were estimated (Table 11-4).
a) Inflow of 100ML/day

Figure 2 Points at which snapshots of the salinity distribution were taken.

Figure 3 Salinity distributions at four times through the tidal cycle; 100ML/day inflow.
b) Inflow of 300ML/day

Figure 4  Points at which snapshots of the salinity distribution were taken.

Figure 5  Salinity distributions at four times through the tidal cycle; 300ML/day inflow.
c) Inflow of 900ML/day

Figure 11-10 Points at which snapshots of the salinity distribution were taken.

Figure 6 Salinity distributions at four times through the tidal cycle; 900ML/day inflow.
**d) Salinity variation at-a-station**

Specific analyses were requested of the variability of salinity at various points through the water column at cross-sections 10 and 12 (XS10, XS12). Salinity variability over a 15 day tidal cycle at these locations for freshwater inflows of 100 ML/day (Figure 8) and 300 ML/day (Figure 9) were extracted from the model and median values computed (Table 11).

![Figure 7](image7.png)  
**Figure 7** Salinity variation over a full cycle of tides at XS10 (left) and XS12 (right) with 100 ML/day inflow

![Figure 11-13](image11-13.png)  
**Figure 11-13** Salinity variation over a full cycle of tides at XS10 (left) and XS12 (right) with 300 ML/day inflow

Table 11-3  
Median salinity of surface waters and 2\textsuperscript{nd} bottom layer over a full tidal cycle at cross-sections 10 and 12 for the four simulated freshwater inflow discharges.

<table>
<thead>
<tr>
<th>Inflow (ML/day)</th>
<th>XS</th>
<th>layer</th>
<th>100</th>
<th>300</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>surface</td>
<td>5.7</td>
<td>0.6</td>
<td>fresh</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2\textsuperscript{nd} bottom</td>
<td>14.7</td>
<td>6.2</td>
<td>fresh</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>surface</td>
<td>7.6</td>
<td>1.5</td>
<td>fresh</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2\textsuperscript{nd} bottom</td>
<td>19.5</td>
<td>10.3</td>
<td>fresh</td>
<td></td>
</tr>
</tbody>
</table>
e) Penetration of Saline Waters

With respect to the salinity profiles it must be remembered that detailed calibration of the salinity predictions was not able to be undertaken. A limited reality check was performed by comparing model predictions of estuary extent to those prepared by Sherwood (2006) to support his original specification of the environmental water requirements of the Gellibrand Estuary (reproduced as Figure 8). Sherwood reported measurements of the length of the salt wedge which can be equated to ‘estuarine length’ in the Gellibrand River Estuary.

Table 11-4 Predicted length along the river that estuarine conditions can be found (estuarine conditions = 5 > salinity > 30; somewhere in the vertical profile)

<table>
<thead>
<tr>
<th>Inflow (ML/day)</th>
<th>Predicted Estuarine Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neap</td>
</tr>
<tr>
<td></td>
<td>Ebb</td>
</tr>
<tr>
<td>100</td>
<td>5740</td>
</tr>
<tr>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>900</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 8 Variation of the salt wedge length with discharge (after Sherwood, 2006, p.6)

The Tide model predictions are consistent with Sherwood’s (2006) data. For example, Sherwood reported that the toe of the salt wedge can be found at around 6km (Rivernook Bridge) at flows up to 300 ML/day, this was predicted by the Tide model (Figure 3 and Table 11-4). However, Sherwood’s data also show that saline conditions can be found beyond 3 km upstream at freshwater inflow discharges of 500 ML/day; whereas the Tide model scenario (Figure 5) suggests that salt ingress will be insignificant at 300 ML/day. The wide variability in salt penetration shown by Sherwood’s (2006) data indicates that unsimulated factors such as storm surge, barometric pressure effects and estuary entrance area variation are likely to play a significant role in the distribution of salt. To understand sensitivity to these factors it is suggested...
that future assessments should include scenarios that look at the effect of varying entrance area as well as inflow discharge (as a minimum).

Overall, on the basis of the foregoing comparison, it was judged that the Tide model predictions of the salinity profile were reasonable given that the predictions fell within the range of the measured data. However, the predictions could be made with greater confidence if suitable data were measured as part of the field work program to allow the mixing coefficients that influence the salinity profile to be calibrated. It is important that the sensitivity of the salinity distribution be well understood as many of the flow-ecology relationships were determined on the basis of this information.

11.3.5 Tracer Study Results

Hydrodynamic simulations were undertaken incorporating a numerical tracer to estimate the residence times at various locations in the estuary under varying steady inflow rates. This technique involves an initial concentration of a conservative dissolved or suspended substance (tracer) being distributed uniformly through the estuary waters. Fresh water inflows and the tidal boundary are assumed to have zero concentration of the substance and an advection-dispersion transport formulation is then 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 can help characterise the time take for various sections of the estuary to be ‘flushed’ with ‘new’ saline water from the ocean boundary or ‘new’ fresh water from the inflow boundary.

The numerical tracer simulations undertaken employed relatively low dispersion coefficients to provide a conservative estimate of the flushing/residence times in the estuary. The dispersion coefficients drive the amount of mixing or exchange that occurs and acts together with, but is independent of, hydrodynamic mixing (i.e. due to water movement alone). Wind induced overturning and other turbulent mixing processes may result in lower residence times than those calculated.

The e-folding time (Table 11-5) 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.

Table 11-5  E-folding time (estimated residence time) in days at specific locations along the estuary for different steady freshwater inflow discharge rates.

<table>
<thead>
<tr>
<th>Inflow (ML/day)</th>
<th>Xsec12</th>
<th>Xsec10</th>
<th>Xsec9</th>
<th>xsec6</th>
<th>Xsec4</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.0</td>
<td>2.5</td>
<td>7.3</td>
<td>6.9</td>
<td>6.8</td>
</tr>
<tr>
<td>300</td>
<td>1.25</td>
<td>1.5</td>
<td>2.1</td>
<td>4.8</td>
<td>3.8</td>
</tr>
<tr>
<td>900</td>
<td>0.7</td>
<td>0.9</td>
<td>1.3</td>
<td>1.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>
11.4 Flood Model Development

A MIKE 11 hydraulic model was developed to simulate overbank flow behaviour in the Gellibrand River estuary. The objective of the simulations was to estimate the inflow discharge required to cause various overbank water levels at different points along the estuary. The model allowed two flooding mechanisms to be examined:

Two scenarios were run:

- Scenario 1 - Ramped Gellibrand flow up to maximum of 20,000 ML/d.
- Scenario 2 - Constant Gellibrand flow of 50 ML/d with sandbar at river mouth.

11.4.1 Model Development

Five key elements were required to define the Gellibrand Flood Model in MIKE 11:

(1) Channel and floodplain geometry – derived primarily from survey data measured for this project. To adequately represent the floodplain storage in large floods a number of additional cross-sections were constructed based on the survey and also 10 m contours and ortho-photographs of the floodplain. A combination of the surveyed and constructed cross-sections was utilised for the model schematization (Figure 9).

(2) Downstream boundary condition – reconstructed tidal water levels based on constituents published for Port Campbell 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 resistance of the channel and floodplain – initial roughness estimates were made with reference to published studies. 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.
11.4.2 Description of Scenarios

The first scenario examined the progressive degree of inundation caused by a ramped inflow discharge on the upstream end of the Gellibrand River. The inflow hydrograph was defined starting from 100 ML/day and increasing to 20,000 ML/day with a constant inflow of 0.1 ML/d on the Latrobe River was used to simulate a high Gellibrand River flow. A stage-discharge relationship (Q-H boundary) was defined at the estuary entrance (river mouth) calculated by MIKE 11 using the surveyed cross-section. The Q-H relationship assumed a constant high tide value of 0.5 mAHd, above which outflow was possible. A simulation was also run with a fixed downstream boundary of 0 mAHD to check the sensitivity of the downstream boundary.

The second scenario ran constant inflow boundaries of 50 ML/d on the Gellibrand River and 0.1 ML/d on the Latrobe River. A Q-H boundary was used on the river mouth simulating the typical discharge that could be expected should the mouth be completely blocked by a sandbar. Assuming a mean sea-level, discharge was calculated for a range of water level elevations upstream of the sandbar using Darcy’s Law [1] (Sturm, 2001). The model was run twice with different downstream boundary conditions, assuming different hydraulic conductivity (k) estimates for the sandbar of 10 and 100 based on low and high conductivity estimates for fine and coarse sand respectively (Gordon et al., 2004).

\[ Q = k \cdot A \cdot \frac{dh}{dx} [1] \]
11.4.3 Sample Model Results – Freshwater Flood

The ramped flow progressively inundates the floodplains of the estuary from the upstream end down toward the mouth. Water backs up behind each of the bridges at higher flows, especially Theo’s Bridge (Figure 11-16). This model behaviour is consistent with observations by local residents.

The model was run twice with the Q-H downstream boundary first representing the open river mouth with a high tide of 0.5 mAHD and second, at mean sea level simulated as a constant downstream boundary of 0.0 mAHD. The simulation results suggest that the tail water condition has noticeable, but local influence on water surface levels for flows above around 1000 ML/day. At 1000 ML/day, predicted water levels upstream of the Lower Bridge are essentially the same in both cases. Simulation results from the Tide Model support this conclusion - it was shown (in Figure ) that the tidal range decreased from 0.9 m outside the estuary to only 0.16 m (at XS10) with an inflow discharge of 900 ML/day. Consequently, the results presented herein are those for the run with the high tide downstream boundary.

a) Longitudinal profile of a large flood

A longitudinal profile of the water surface elevation along the estuary was plotted (Figure 11-16) for a moderate to large flood (10,000 ML/day) to identify the key hydraulic controls along the reach. Breaks in the slope of the water surface profile occur at each of the bridges (as highlighted by the vertical arrows), with Theo’s Bridge creating the largest jump. The importance of the bridges as controls on flooding was noted by local residents and land owners during the initial inspection. It can therefore be said that the Flood Model reproduces some of the fundamental aspects of flooding along the Gellibrand River Estuary.
Figure 11-16 Water surface profile (blue zone – top is water surface, bottom is bed) for Gellibrand River with 10,000 ML/day freshwater inflow. Vertical arrows indicate the location of the key structures along the reach.

b) Water level versus discharge at-a-station

The ramp simulation predicted 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 water surface elevation at particular locations along the estuary. For example, Figure 11-17 shows stage height versus discharge curves at two key locations along the Gellibrand estuary: just upstream of the entrance, and 2 km further upstream (at XS10). The chart highlights the discharge required to attain water levels of 1.0, 1.25, 1.50 and 2.0 mAHD at XS10, which are relevant to some of the flow-ecology relationships.

Note that there are a number of sources of uncertainty associated with the flood model, these include:

- the model employs a fixed downstream boundary morphology, when in practice the size of the opening in the bar will likely increase with flood discharge;

- no calibration data was available, and the selected roughness values for the floodplains and the channel have not been able to be verified.

Given these uncertainties, the estimated discharges must be considered approximate.
Figure 11-17 Inflow discharge versus water surface level predicted just upstream of the estuary entrance and at cross-section 10. The line annotations cross-reference the discharge predicted to achieve different water surface levels at cross-section 10.

c) Sediment Transport Assessment

In addition to water surface elevation, the MIKE11 simulation predicts mean channel velocity (i.e. velocity within the banks of the river channel, excluding floodplain regions). Velocity versus discharge curves can be extracted for particular locations along the estuary. One key assessment that can be undertaken with this data is to examine sediment entrainment.

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 Hjulstrom curve predicts the limits for erosion of fine sands down to clay size sediment, and values for various sediment classes can be read from the curve (Gordon et al., 2004, p.192).

This approach was applied to two locations near the estuary entrance (Figure 11-18): 200 m upstream of the entrance at approximately the upstream end of the entrance bar; and, 400 m upstream of the entrance in the central part of the lagoon. Note that the ‘200 m’ cross-section is far more confined than the broader lagoon section. The relationship of mean channel velocity to discharge at these locations is shown in Figure 11-19 along with Hjulstrom entrainment thresholds for five different sediment classes. This data indicates that erosion occurs at a much lower discharge at the ‘200 m’ location, with a flood having a discharge around 2000 ML/day
sufficient to entrain coarse, medium and fine sand. The degree to which the entrance bar is altered by a flood with such a peak will depend on the duration over this threshold and the distribution of sediment calibres within the entrance bar (amongst other things).

![Figure 11-18 Cross-sections near the estuary entrance: 200 m upstream (red) and 400 m upstream (blue – XS12).](image)

![Figure 11-19 Inflow discharge versus mean channel velocity just upstream of the entrance (lower curve) and in the lagoon (upper curve). Horizontal lines indicate velocity thresholds required to move sediment of a particular grade based on Hjulstrom curves (Gordon et al., 2004, p.192).](image)
11.4.4 Sample Model Results - Entrance Closure

The second set of scenarios was designed to mimic closure of the estuary entrance by a sandbar. The sandbar was modelled with a leakage flow that varied with water level behind the bar. Due to the low outflow and high tail water condition imposed on the estuary by the sandbar and the low inflow rate, the water surface profile back up the river is very flat, with almost zero grade up to the extent of ponding.

The model was run twice with different downstream boundary conditions, assuming different hydraulic conductivity (k) estimates for the sandbar of 10 and 100 based on low and high conductivity estimates for fine and coarse sand respectively (Gordon et al., 2004). The difference between the two leakage coefficients was negligible.

It was found that the Q-H relationship assumed for the downstream boundary for the sandbar scenario had a very minor effect on model results, as the inflows were orders of magnitude larger than the outflows. The sensitivity of the model results to loss through the sandbar is thus very low. This result is demonstrated by the water level hydrographs for the two different downstream boundaries presented in Figure 10 wherein the difference between the cases cannot be discerned as the lines are essentially overlaid.

The relationship between water surface elevation and volume stored in the estuary is listed in Table 2. The rate at which a given volume will accumulate (i.e. number of days after mouth closure) depends on the inflow discharge rate (integrated over time).

![Figure 10](image.png)

**Figure 10** Time series of water surface level just upstream of the sandbar with varying sandbar hydraulic conductivities (50 ML/day inflow to Gellibrand River, 0.1 ML/day inflow to Latrobe Creek).
Table 2  Water surface elevation just upstream of sandbar compared with estimate of the volume of water stored in the estuary.

<table>
<thead>
<tr>
<th>Elevation (m AHD)</th>
<th>Volume Stored in Estuary (GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.52</td>
</tr>
<tr>
<td>0.25</td>
<td>0.62</td>
</tr>
<tr>
<td>0.50</td>
<td>0.75</td>
</tr>
<tr>
<td>0.75</td>
<td>0.95</td>
</tr>
<tr>
<td>1.00</td>
<td>1.32</td>
</tr>
<tr>
<td>1.25</td>
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<td>1.50</td>
<td>2.93</td>
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</tr>
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<td>2.50</td>
<td>7.82</td>
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