Review of Hydrodynamic and Salinity Effects Associated with TSHD on the Gippsland Lakes

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Cover Photo: Aerial image of Lakes Entrance and Reeve Channel (http://www.lesmp.vic.gov.au/monitoring_aerial.php#)

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1. INTRODUCTION

Water Technology has been engaged by Gippsland Ports to provide an overview of hydrodynamic and salinity processes within the Gippsland Lakes and an assessment of the likely effects of the change in dredging practices on hydrologic and ecosystem processes in the lakes.

1.1 Objectives and Scope

The main objective of this report is to address concerns raised regarding the effects of on-going dredging at Lakes Entrance that may be having an impact on the ecological character of the Gippsland Lakes, and whether the change in dredging regime since 2008 (from side cast to trailing suction hopper) has contributed to any such effect on the lakes system.

The scope of work includes:

- A review of available data and reports relevant to the ecological character of the Gippsland Lakes, including changes in river flows, salinity and bathymetry of the lakes system;
- Provide an understanding of the hydrologic & salinity processes in the Gippsland Lakes; and
- Review available data and discuss the changes (if any) that have occurred in these processes since 2008 and any relationship between these processes and the dredging practises at the permanent entrance.

1.2 Available Reports and Data

This review has been limited to available information and existing studies with preliminary additional interpretation of water level and salinity data.

The following information has been reviewed:

- Ecos Environmental Consulting (2008). Gippsland Lakes Ecological Character Description. Report prepared for the West Gippsland Management Authority, June 2008: Volume 1. Ecos Consortium (Ecos Environmental Consulting, Dodo Environmental, Water Technology, Fluvial Systems, Lloyd Environmental, AES Applied Ecology Solutions, Chris Harty Planning and Environmental Management and Arthur Rylah Institute)
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- Water Technology (2005). Gippsland Lakes Changing Hydrodynamic Conditions, Report J144/R01 prepared for SKM as a component of the broader Gippsland Coastal Board project RT2 Changing Hydrodynamic Conditions for the Gippsland Lakes
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- Water Technology (2011). Hydrodynamic Study of Sale Common, Report prepared for the West Gippsland Catchment Management Authority
- Water Technology (in preparation). Environmental Water Requirements of the Latrobe River Estuary, Report for the West Gippsland Catchment Management Authority
- Webster, I.T. Parslow, J.S. Grayson, R.B. Molloy, R.P. Andrewartha, J. Sakov, P. Tan, K.S. Walker, S.J. and Wallace, B. (2001). Gippsland Lakes Environmental Study – Assessing Options for Improving Water Quality and Ecological Function, Final Report prepared for the Gippsland Coastal Board by CSIRO
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2. HYDROLOGIC AND SALINITY PROCESSES OF THE GIPPSLAND LAKES

The Gippsland Lakes are a series of large, shallow, coastal lagoons approximately 70 km in length and 10 km wide. They are connected to the ocean (Bass Strait) by a narrow, maintained artificial channel at Lakes Entrance. The surface area of the lakes is approximately 364 km^2 and the three main water bodies are Lakes Wellington, Victoria, and King. Lake Reeve, adjacent to the coastal dune of Ninety Mile Beach, has an area of approximately 50 km^2, but it is not tidal and is usually dry except following periods of high rainfall and/or flooding in the lakes, Figure 2-1

The bathymetry of the Gippsland Lakes is highly varied and includes shallow mudflats and sand banks that can be exposed as water levels in the lakes drop due to ocean mean sea level influences. Lake Wellington is quite shallow in areas (2 – 3 m deep), as are other areas in the lakes (Jones Bay in Lake King, the western end of Lake Victoria). The deepest areas, down to 10 – 12 m deep, occur in the central sections of Lake Victoria and Lake King (south of the Silt Jetties), and in Reeve Channel.

Water levels and salinity throughout the Gippsland Lakes system have a range of short (hourly), medium (daily) and longer term (fortnightly to monthly, seasonal) responses to the weather, river flows and tidal conditions (as noted by authors such as Fryer and Easton, 1980). In addition to these responses, there are also longer term forcings which will impact water levels and salinities such as the recent period of drought in South-Eastern Australia (post 1997) and surface water abstractions from the Thomson and Macalister Rivers which flow into the lakes system.

This section provides an overview of the different factors affecting water levels and salinity throughout the Gippsland Lakes and how they relate to both catchment and entrance conditions.

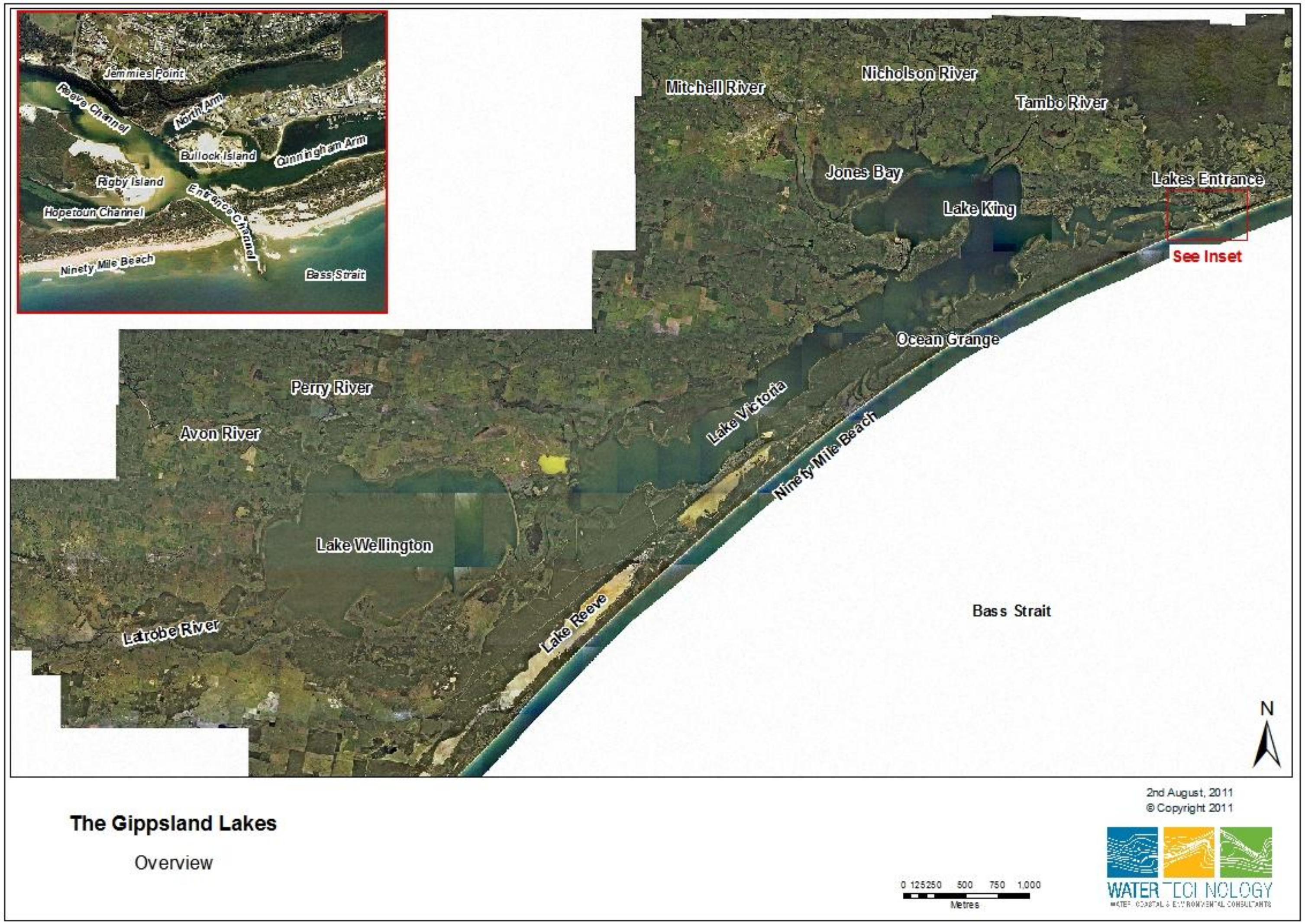


Figure 2-1 Locality Plan, Gippsland Lakes

2.1 Hydrologic Processes

Hydrologic processes cover those interactions between the catchment (rainfall and river flows), climate (temperature, atmospheric pressure and wind), and marine exchange (tidal inflows and outflows). These processes and their interactions can be pictorially described by way of a conceptual model, as shown in **Figure 2-2**.

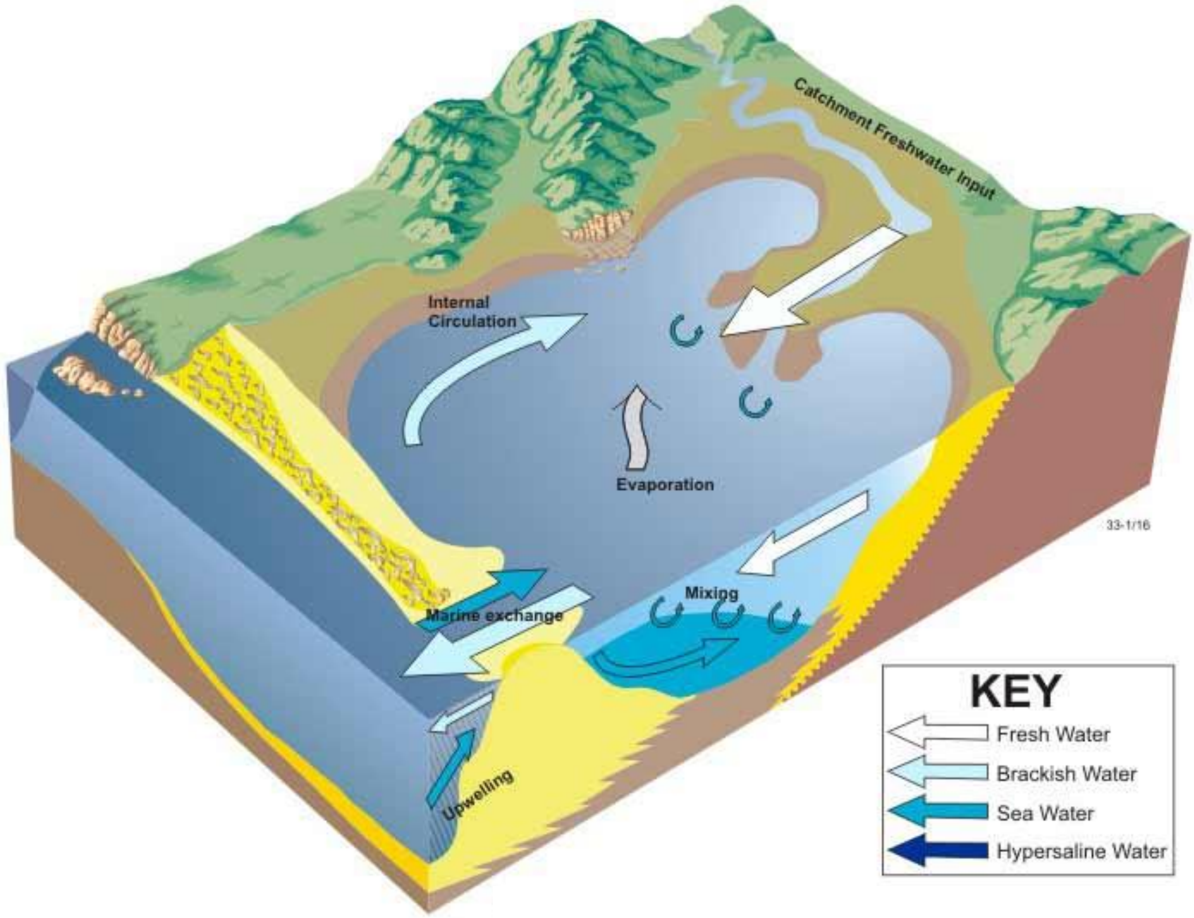


Figure 2-2 Conceptual model of estuary processes in the Gippsland Lakes (based on wave-dominated estuary model, http://www.ozcoasts.org.au/conceptual_mods/geomorphic/wde/wde_pos_hydro.jsp)

2.1.1 Catchment Freshwater Input

Rainfall and river flows make up the key catchment freshwater inputs to the Gippsland Lakes.

Rainfall

Rainfall in the Gippsland Lakes catchment varies significantly from the coastal strip, where the lakes are located, through to the upper catchment areas. This is due to the presence of the Great Dividing Ranges to the north, and the Strzelecki Ranges to the south of the Latrobe Valley.

Figure 2-3 shows the distribution of rainfall across the state of Victoria, illustrating the much higher rainfalls that occur along the ranges. **Figure 2-4** shows the rainfall trend across Australia since 1970. South-Eastern Australia in particular (which includes the Gippsland Lakes and their catchments) has experienced significantly lower rainfall over the recent dry period (post 1997). For instance the rainfall totals for South-Eastern Australia for the period 1997-2006 have been only 86% of the 1961-

1990 climate "base-line" adopted by the World Meteorological Organisation (WMO) (Kiem and Verdon-Kidd, 2009).

This reduced rainfall in the catchments of the Gippsland Lakes has resulted in reduced stream runoff and therefore reduced inflows into the lake system. Reduced rainfall and higher temperatures also has the related impact of greater evaporation from the lake surfaces, resulting in evapo-concentration of saline water in the system. Antecedent conditions in the contributing catchment areas also drive the conversion of rainfall to runoff.

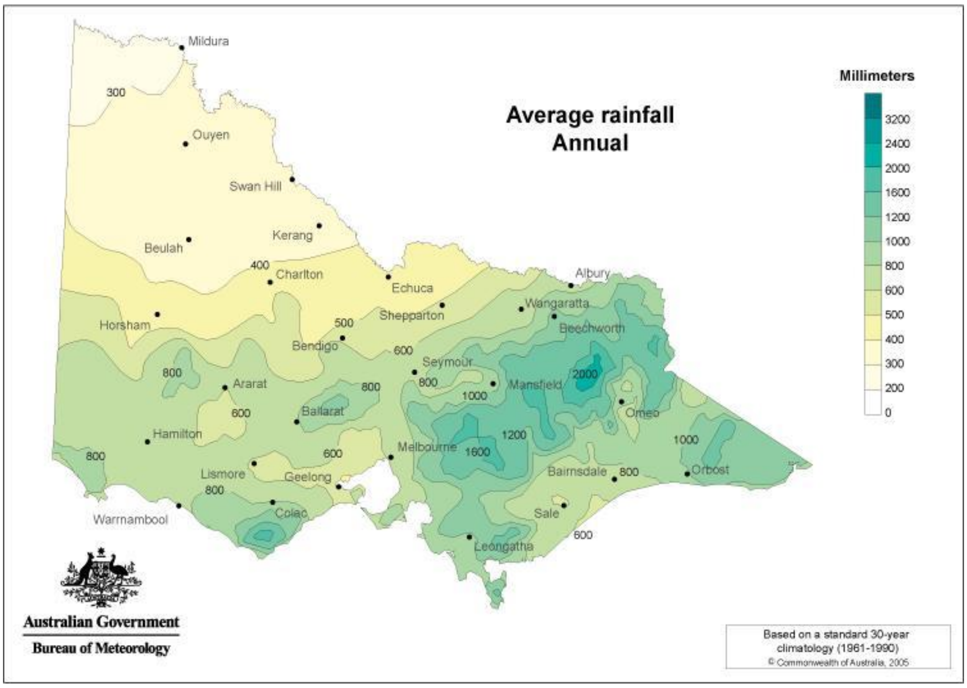


Figure 2-3 Annual Average Rainfall Distribution across Victoria

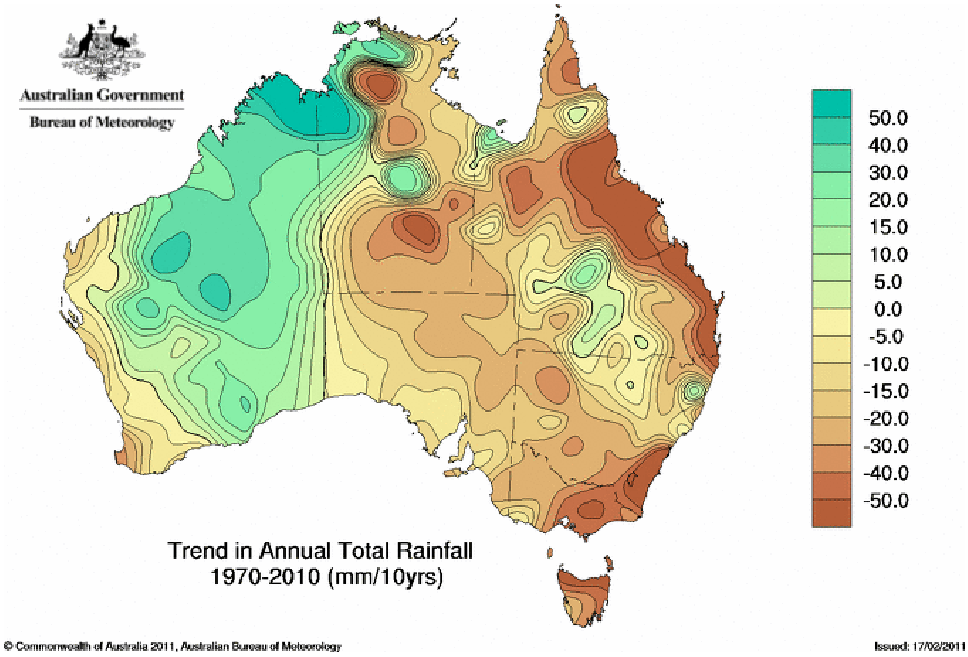


Figure 2-4 Rainfall trends across Australia

River Flows

River inflows provided the freshwater input to the Gippsland Lakes. Variations in river inflows cause the water level of the lakes to rise and fall and also have a significant impact on salinity levels throughout the system. As described by Tilleard, O'Connor and Boon (2009), there are over a dozen streams and rivers that supply freshwater to the Gippsland lakes system, with most freshwater delivered by the Latrobe River (44% of the mean annual inflow, includes the Thomson & Macalister Rivers), and the Mitchell River (35% of the mean annual inflow). The Avon (8%, including the Perry River), Tambo (11%) and Nicholson rivers (2%) make up the balance. The variability in rainfall is reflected in river flows, whereby flood flows can be 1,000 to 10,000 times greater than non flood flows. This can be seen in the monthly freshwater inflow volume record for Lake Wellington (Figure 2-5), which shows distinct peaks in freshwater inflow into the lake associated with flood events. Figure 2-5 also shows the general decline in freshwater inflows that occurred over the period 1997 to 2010, where the region experienced drought conditions.

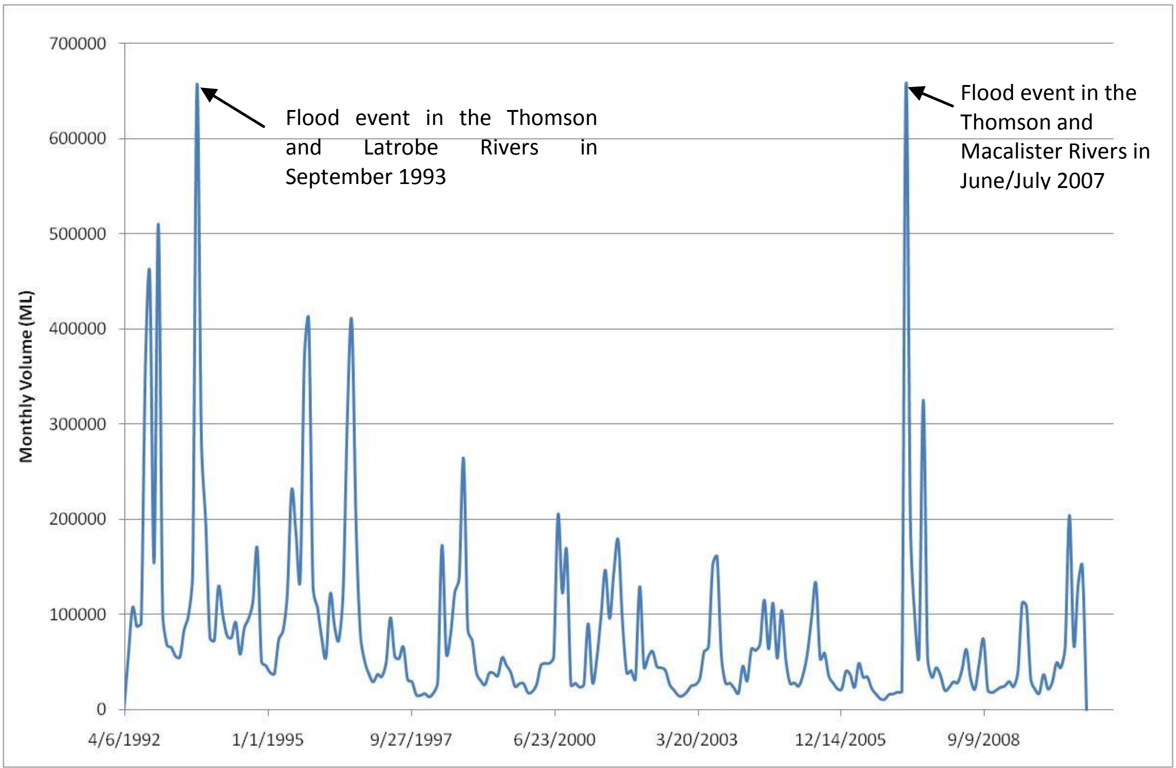


Figure 2-5 Monthly freshwater inflow volume into Lake Wellington (in ML) from 1992 to 2010

In addition to changes in rainfall; river inflows to the lakes are significantly impacted by water extractions, particularly in the west. Tilleard, O'Connor and Boon (2009) note that about 20% of the average annual riverine discharge to the Gippsland Lakes is extracted for agricultural, industrial and domestic purposes before it reaches the lakes. The western rivers are particularly affected (refer Figure 2-6). Tilleard, O'Connor and Boon (2009) note that:

> "*surface water extraction and storage from the Latrobe, Thomson and Macalister Rivers has reduced freshwater inflows to Lake Wellington to the extent that, on average, discharge is now reduced from natural condition by 33%*".

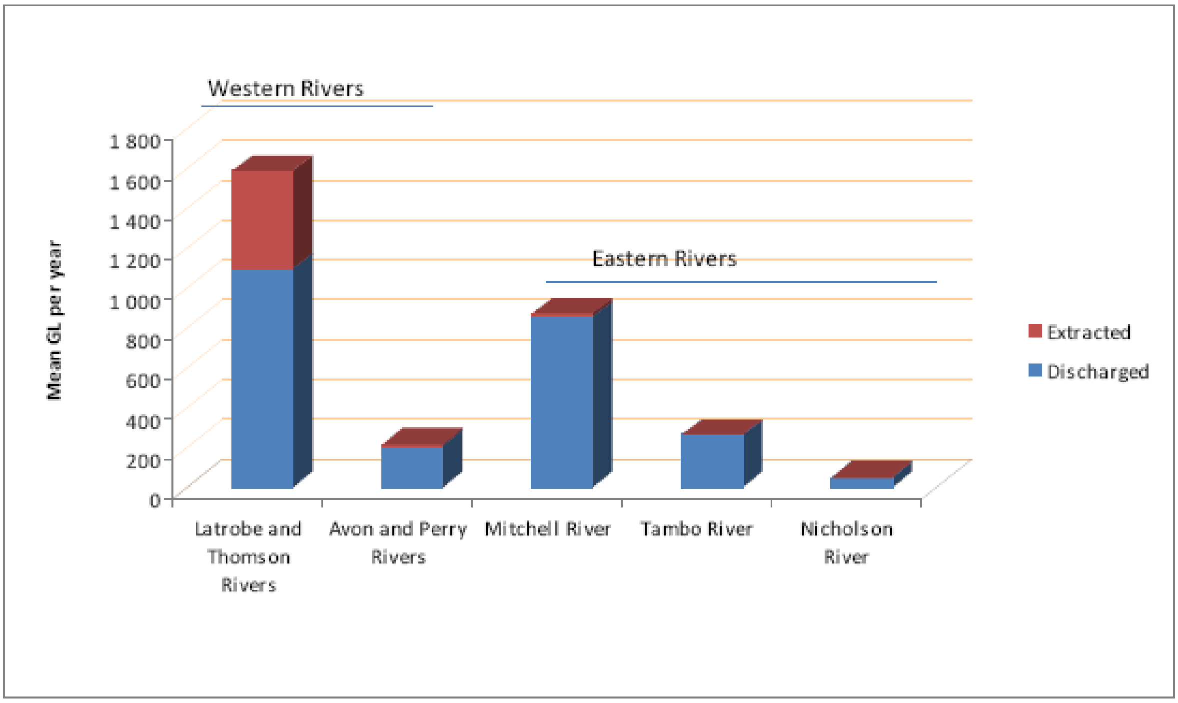


Figure 2-6 **Annual average discharge and surface water extraction from the major rivers entering the Gippsland Lakes system (1965 – 2003), from Tilleard, O'Connor and Boon (2009)**

Because of the constricted connection between the lakes and the sea at Lakes Entrance, large inflows of freshwater during floods can cause a significant rise in water level in the main lakes. The elevated water levels can last for several days. In contrast, during dry periods with low river inflows, the mean water level in the lakes follows the mean water level in the ocean (i.e. tidal and atmospheric effects). River inflows mix with the incoming saline ocean waters. Under flood conditions the entire lake system can become fresh water dominated, while under low fresh water flow conditions saline water has been noted within the estuarine regions of the inflowing rivers.

2.1.2 Climate

The weather can both directly and indirectly influence the water levels and salinity conditions in the lakes through changes in atmospheric pressure and wind. Evaporation can also have significant effects on conditions in the lakes, particularly in shallow areas such as Lakes Wellington and Jones Bay.

Atmospheric Pressure & Wind

Low pressure weather systems across southern Australia can result in elevated water levels in Bass Strait, which then translate to elevated water levels across the lakes on a moderate time scale (1 week or more). The changes in atmospheric pressure and storm set-up (or set-down) dominate the observed pattern of water level variation throughout the lakes and can result in mean water level variations within the lakes of ± 0.2 m about mean sea level. During large ocean surge events in Bass Strait the lakes respond with variations in mean water level of as much as 1.0 m change. These variations in mean sea level typically occur over periods of a week or more. Mean ocean levels in Bass Strait have a much greater influence on water levels in the lakes than ocean tidal variation, as discussed further in Section 3.3. Additionally, wind setup across the lakes can also have a significant influence on local water levels, and is the main driver of internal circulation processes. On timescales of a tidal cycle (approx 12.5 hours) water levels in the lakes are reasonably constant with only a small tidal variation (typically ± 0.1m).

An example of the relative impacts of weather and tides on water levels in Lake Wellington is shown in Figure 2-7. This figure is an illustrative data set of the typical variation in water level in the Gippsland Lakes that occurs throughout the year and from year to year. The observed water level in Lake Wellington has a range of around 0.5 m over the 6 month period shown (Aug 2010 – Jan 2011). The tidal component is at most only ±0.03 m whereas storm surge is the dominant water level control, raising water levels for extended periods. Over the period shown, the change in water level due to atmospheric changes associated with low pressure weather systems is in the order of 0.5m. The effect of wind set-up (and set-down) is less pronounced (around ±0.1m) and occurs over shorter, daily time scales but has an important role in internal circulation processes such as the mixing and transport of saline water, particularly for shallow areas such as Lake Wellington. Variations in water levels also occur on a seasonal basis, and levels are also affected by the strength of the southern oscillation index.

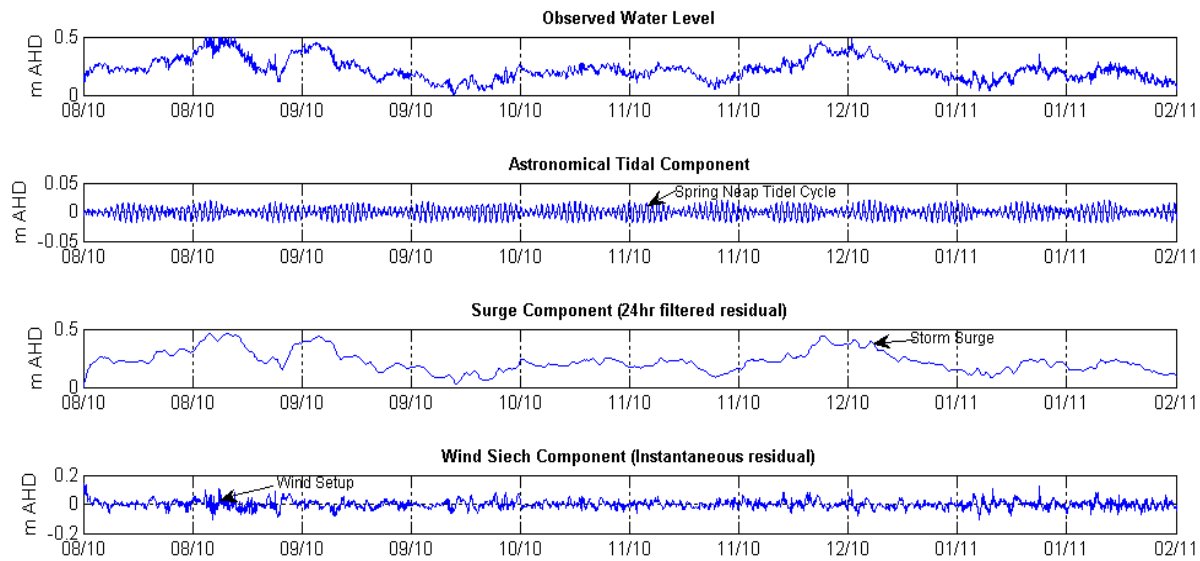


Figure 2-7 Example of relative impacts of weather and tide on water levels in Lake Wellington

Evaporation

Rainfall and evaporation also influence water and salinity levels within the lakes system. Analysing daily rainfall and evaporation data for the Gippsland Lakes, Webster et al. (2001) estimated that the average annual rainfall and evaporation rates between 1975 and 1999 were 1.6 mm/d and 3.7 mm/d respectively. Evaporation is strongly seasonal, ranging from a low of 1.4 mm/d in June to a maximum of 6.4 mm/d in January. In February, typically the monthly of lowest river inflows, the rate of water loss through evaporation can exceed average river inflows. Walker and Andrewartha (2000) for instance, note that Lake Wellington has the potential to lose around one third of its water volume to evaporation in a dry year. Under conditions where there is a net loss of water (evaporation exceeds rainfall and river inflows), evapo-concentration of saline water within the lakes system occurs.

2.1.3 Marine Exchange

Tidal effects

The tidal effect varies throughout the lakes. At Lakes Entrance, in Cunninghame Arm and North Arm the tidal range is about ±0.3m about mean sea level. This reduces with distance from the entrance, giving a tidal range of ±0.2 m about mean sea level at Metung, and only ±0.03m in Lake Wellington.

The entrance channel, Reeve and Hopetoun channels are reasonably constricted and result in significant attenuation of the tidal signal. Moreover, the volume of water that can pass through the entrance and these entrance channels is limited and once distributed over the area of the lakes results in a small change in water level (Water Technology, 2005). These volumes are discussed in more detail in the following section.

Investigations into the effect of entrance channel geometry on tidal range and flood levels (Walker & Andrewartha, 2000; Webster et al. 2001) found that a deeper entrance channel causes a slight increase in tidal range within the lakes and a lowering of water levels in the lakes associated with catchment generated flood inflows, while conversely a shallower entrance reduces the tidal range and increases water levels during catchment generated flood events.

Saline Intrusion and Mixing

The movement and mixing of saline ocean water with the fresher lake water is affected by the strength of freshwater outflows through the entrance channel and the ocean water level conditions (through both tides and longer period changes). As sea-levels in Bass Strait rise, saline water enters the Lakes through the permanent entrance. Some of the denser salt water sinks to the deeper parts of Reeve Channel and propagates as a density current into Lake King and the deeper parts of the lakes system. The amount of water delivered into the Lakes by this mechanism is dependent on the time-scales associated with the change in ocean water level. For instance, tidal variations have a limited effect but longer period changes (i.e. atmospheric pressure changes due to low pressure weather systems) may result in substantial ingress of saline water into the lakes system (Walker and Andrewartha, 2000; Webster et al, 2001).

> "*For a tidal range of 5 cm the volume of water exchanged from the ocean with Lake Victoria and Lake King is 9,000 ML. This is much less than the 45,000 ML volume of Reeve Channel (Bek and Bruton, 1979) which connects the Entrance to the main body of Lake King. Thus, water flowing through the Entrance penetrates only a fraction of the length of Reeve Channel on the flooding tide before the tide changes*" (Webster et al, 2001).

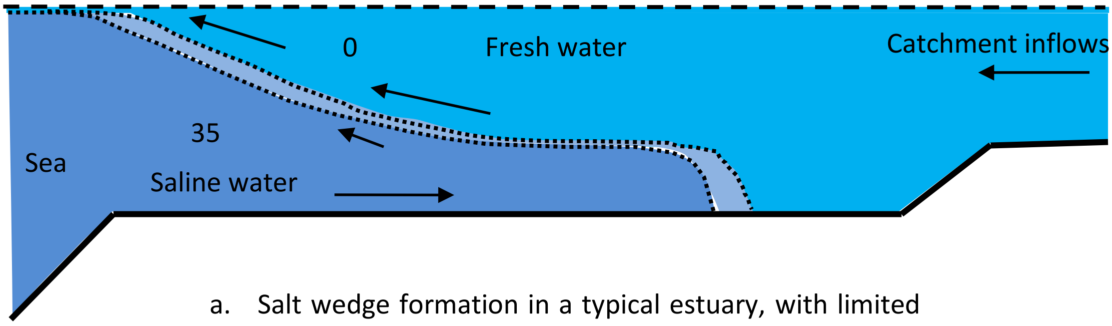
Marine exchange associated with longer period sea level fluctuations (storm surges, atmospheric pressure changes) appears to be much more effective than tidal exchange for flushing the Lakes. This is due to the following:

> "*Because the periods of these (sea-level) fluctuations are much longer than the tides (>7 days versus 12 hours), the water level fluctuations within Lake Victoria and Lake King are much better able to follow those in Bass Strait. The volume of water exchanged associated with a typical water level change within the Lakes of 30 cm is 52,000 ML, which is similar to the volume of Reeve Channel. Consequently, when sea level rises, salty oceanic water is able to penetrate the length of Reeve Channel. Being generally more dense than the water inside the Lakes, some of the Bass Strait water is able to sink to the deeper parts of Reeve Channel and propagate as a density flow (i.e. salt wedge) into the deeper parts of Lake Victoria and Lake King*" (Webster et al, 2001).

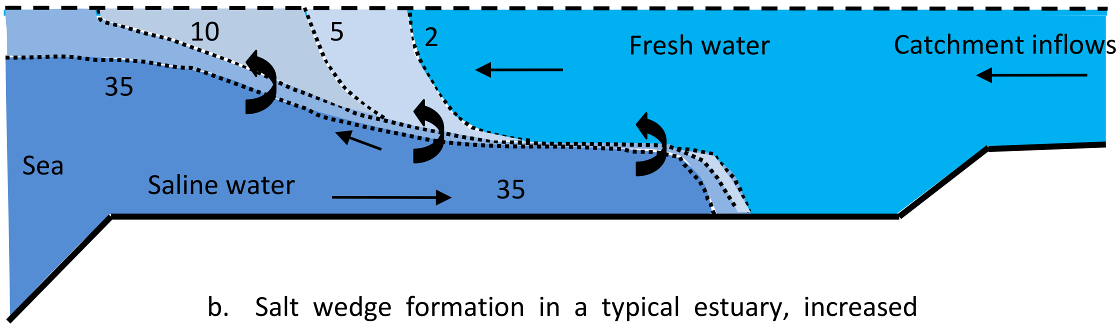
The result is that during a typical flood tide the volume of saline water entering the lakes is less than the volume of Reeve Channel and this saline water cannot progress into Lake King before the tide changes and flows back out the entrance. However, if the water level at the entrance is elevated over a longer period (>24hrs) due to atmospheric conditions or storm surge, an increased volume of saline water is enable to pass through the entrance channel over a tidal cycle so that the saline water can progress further along Reeve Channel and potentially further into the lakes system.

A conceptual model to describe the movement and mixing processes associated with saline intrusion into estuaries is shown in **Figure 2-8**. The mixing processes shown in (a) and (b) (**Figure 2-8**) describe how salt water typically moves into an estuary. In (a) there are significant freshwater flows resulting in strong stratification and reduced mixing between the fresh and salt water layers. While in (b) the freshwater inflow is reduced and this allows greater mixing to occur.

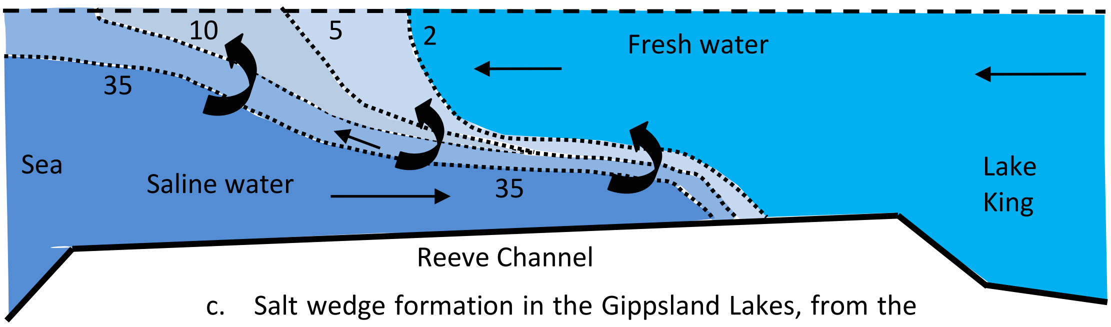
A schematisation of saline water movement into the Gippsland Lakes is shown in **Figure 2-8** (c) and (d) under average and elevated ocean water level conditions respectively. The slope of the channel describes the gradual reduction in channel area along Reeve Channel inside the entrance and then into the deeper Lake King. The salt wedge does in fact penetrate into Lake King and the rest of the Gippsland Lakes system over time, but the size and volume of Reeve Channel provides an initial constraint on its movement. Further discussion of the salinity processes throughout the lakes is provided in the following section.



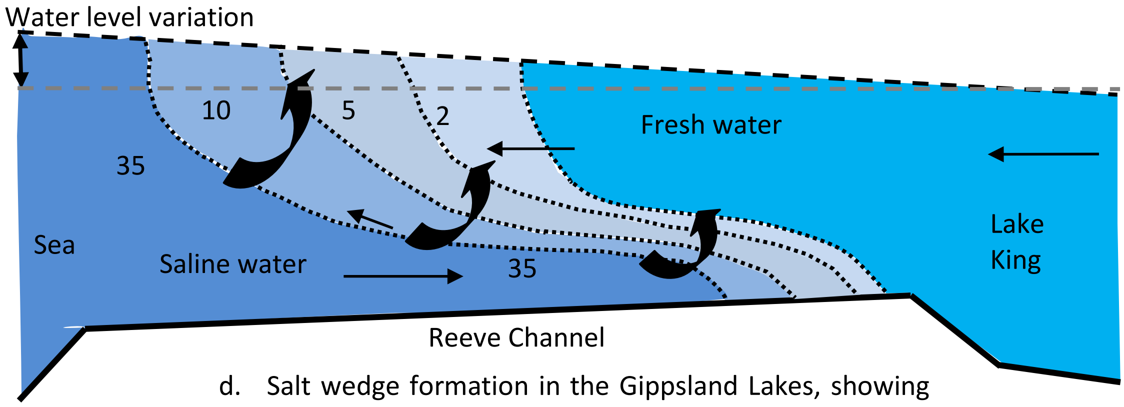
a. Salt wedge formation in a typical estuary, with limited mixing across the salt water – freshwater interface



b. Salt wedge formation in a typical estuary, increased mixing across the salt water – freshwater interface



c. Salt wedge formation in the Gippsland Lakes, from the Entrance Channel along Reeve Channel to Lake King – mean ocean level conditions



d. Salt wedge formation in the Gippsland Lakes, showing effect of change in ocean levels (either through tides or atmospheric pressure changes)

Figure 2-8 **Conceptual model of salt wedge formation in estuary entrances**

2.2 Salinity Processes

The following description of the salinity regime in the Gippsland Lakes was developed by Water Technology for Ecos Environmental Consulting (2008) as a component of the Gippsland Lakes Ecological Character Description, a report for the West Gippsland Catchment Management Authority.

The ocean entrance to the Gippsland Lakes was permanently opened in 1889 and has been maintained by dredging ever since. Before the opening, the Lakes were a series of coastal lagoons that only opened to the sea after heavy rainfall and runoff from the major catchments. Accordingly, the marine influences would have been small and the system of lakes and marshes were almost entirely populated by freshwater species. Saline intrusion into the system, as a consequence of the permanent entrance, has occurred, with the freshwater systems replaced by marine and estuarine habitats (and in some areas hyper-saline environments). Today, saline intrusion in the lakes can extend throughout the system. During periods of drought or low freshwater inflows, ocean salinity can penetrate well up into the river reaches. **Figure 2-9** provides an overview of salinity distribution throughout the lakes system.

As some parts of the lakes are quite deep (> 5 m), saline stratification can develop, and is considered one of the major influences on the occurrence of bottom hypoxia (low dissolved oxygen conditions) in these areas.

The ocean entrance essentially provides the lakes system with an infinite supply of sea water at a constant concentration. The significant spatial variation and temporal variability observed across the lakes is therefore driven by the variability in stream flows, with wind effects driving internal mixing particularly in shallow areas like Lake Wellington. Over dry periods the effect of concentration of salinity due to evaporation can also become important.

Superimposed over the background of the seasonal cycle of flows, the system experiences occasional large fresh and flooding flows. The high flow events can "flush" the estuarine sections of the rivers, making them completely fresh, and introducing large volumes of freshwater into the Gippsland Lakes.

A conceptual model of salinity throughout the Gippsland Lakes in provided in **Figure 2-9** (from Webster et al., 2001). This shows how the fresh and saline waters flow and mix.

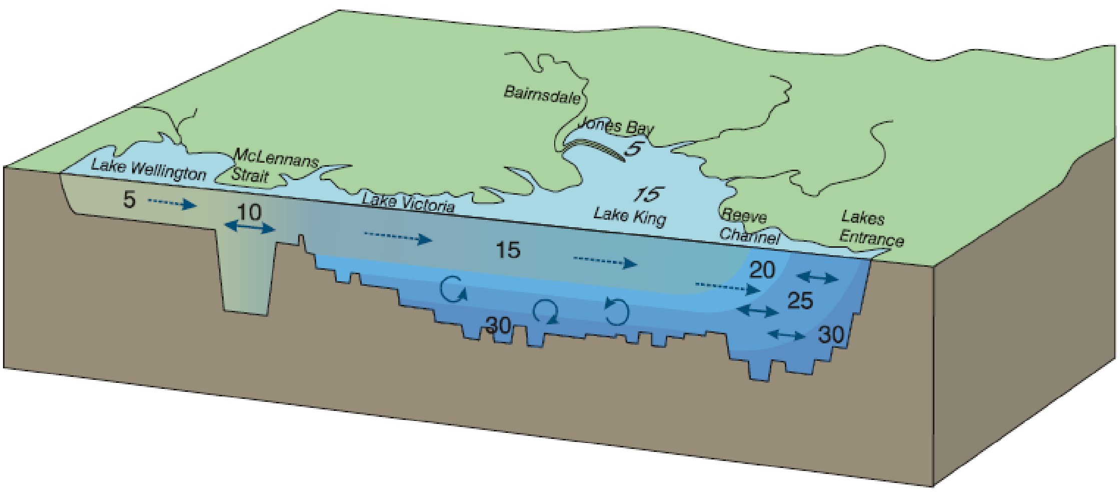


Figure 2-9 Conceptual model of salinity within the Gippsland Lakes (Webster et al, 2001). The numbers denote typical salinity concentration (ppt) and the colours show the salinity variation

Salinity information is available at a number of monitoring stations throughout the Gippsland Lakes. The most extensive record available is for Lake Wellington, the westernmost lake in the system, some 80km from the entrance.

Water Technology is currently undertaking an environmental flow requirements study for the Latrobe River estuary which flows into Lake Wellington. A component of this work is assessing the implications of freshwater river inflows on lake salinity levels. **Figure 2-10** shows the time series of monthly inflow volume versus salinity in Lake Wellington. This shows that prior to 1997, inflow volumes of over 200,000 ML/month occurred on an annual or more frequent basis. From 1997 to 2011 this has only occurred twice. The resulting gradual increase in the lake salinity levels can clearly be seen. As noted previously, the flushing effect of freshwater flows (where the saline water in the lake is flushed back into Lake Victoria) is clearly shown after the 2007 flood where the salinity in the lake goes from 25 parts per thousand (ppt) (ocean salinity is 35 ppt) before the flood to 5 ppt after the flood. However, it does not remain low for long as the monthly river inflow volumes after the flood have remained low. A flushing threshold of 130 GL/month is included in the figure. This is the freshwater inflow volume required to flush saline waters from Lake Wellington.

To allow the assessment of changes to river flow regime on salinity in Lake Wellington a water balance model has been developed. The original model (detailed in Grayson, 2003; SKM, 2010) was calibrated over the period 1976-2000 and this has been extended to include data up to the end of 2010 to include the dry period between 1997 and 2010 where lake salinity levels increased markedly. The model results compare well to observed salinity data and confirm that the salinity of Lake Wellington is predominantly driven by freshwater inflows, Figure 2-11.

The inflow of saline water through the permanent entrance therefore provides the baseline salinity coming into Lake Wellington through McLennan Strait; however the salinity concentration within the lake is predominantly controlled by freshwater inflows, which periodically flush the lake.

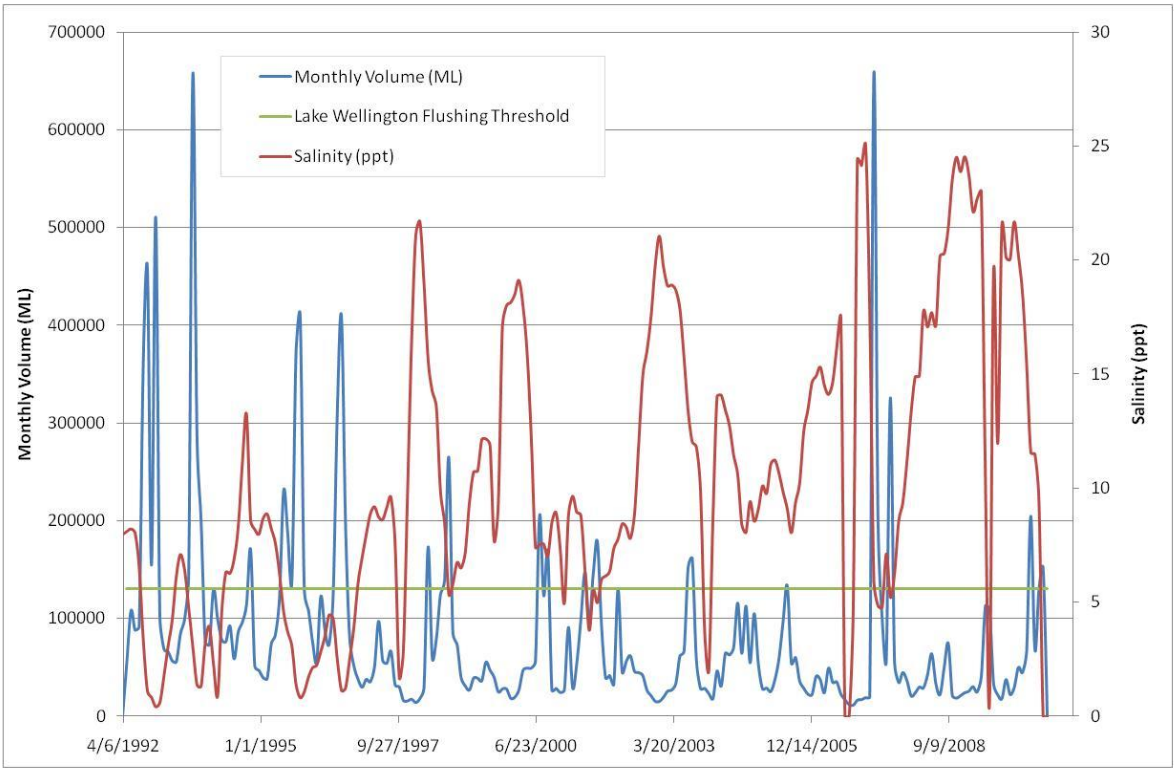


Figure 2-10 Monthly inflow volume versus salinity for Lake Wellington (1992 – 2010)

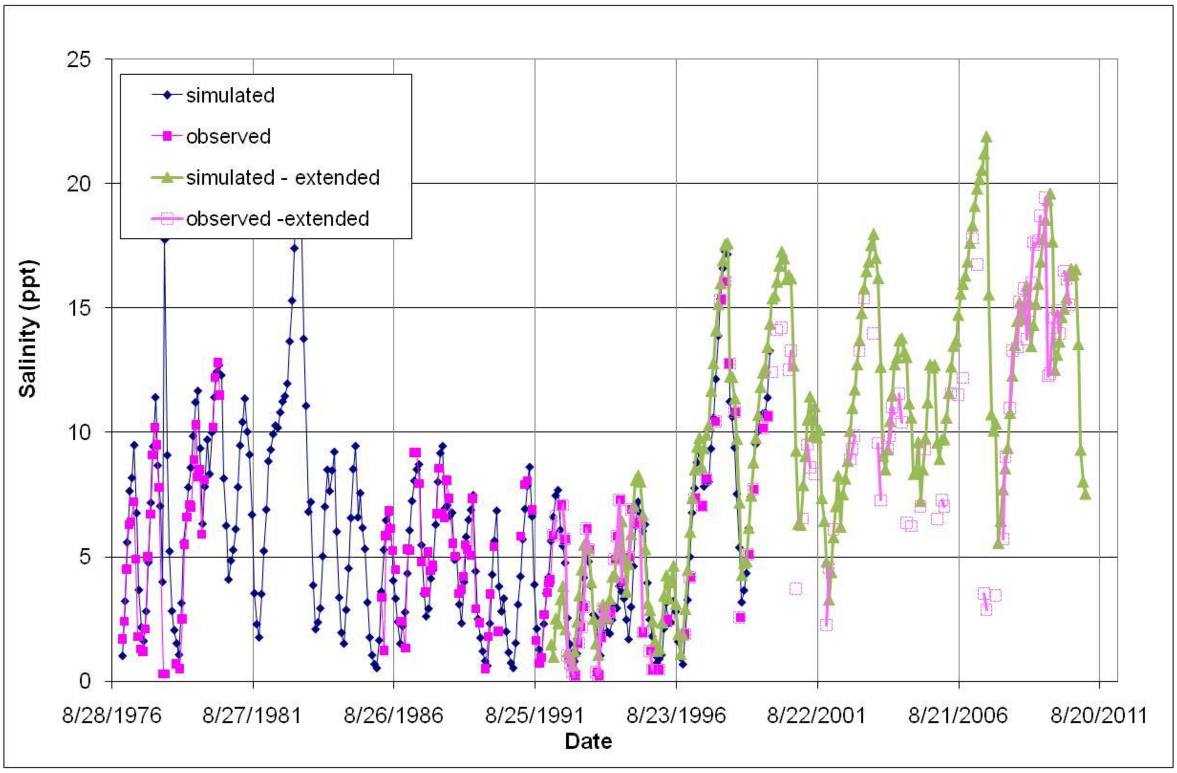


Figure 2-11 Measured and predicted salinity for Lake Wellington (1976 – 2011)

3. ENTRANCE CHANNEL EFFECTS

3.1 Bathymetric Changes to the Entrance Channel (pre and post 2008)

As detailed in Wheeler *et al* (2010a, 2010b and 2010c), maintenance dredging of the artificial entrance to the Gippsland Lakes has been required to maintain navigable channel depths for over a century. The analysis by Wheeler *et al* of bathymetric changes in the Entrance and Reeve Channel areas has shown that despite ongoing dredging efforts, since 1975 there has been accretion of sediment of the ebb- and flood- tide deltas and infill in the navigation channel. The flood tide delta region consists predominantly of Reeve Channel while the ebb tide delta is the sediment bar area offshore of the Entrance. Between 1975 and 2005 approximate sediment accretion of 708,600 m^3 occurred within Reeve Channel despite sediment removal operations via the sand transfer system of nearly 1,000,000 m^3 between 2001 and 2005 (Wheeler and Peterson, 2005).

Maintenance dredging trials were undertaken in 2008, and included the use of the trailing suction hopper dredge (TSHD) as part of the Gippsland Ports Lakes Entrance Sand Management Program (LESMP). During the dredging trial, the TSHD was operational in the Entrance Channel and entrance sand bar locations, and in parts of Reeve Channel. The volumes dredged by the TSHD were: 80,104 m^3 for the Entrance Channel, 166,624 m^3 from Reeve Channel, and 309,456 m^3 from the entrance sand bar (from Wheeler et al 2010a). In Reeve Channel the dredged material was removed from the Narrows immediately below Jemmy's Point downstream to the Swing Basin focussed on the eastern side of the channel. The western side of Reeve Channel adjacent to Rigby Island was then allowed to infill (Gippsland Ports pers. comm.).

GHD (2011) describes the variation in cross-sectional area of the Entrance Channel since the start of systematic hydrographic surveys in September 2007 as part of the LESMP. The memo indicates that there has been little change to the average navigable channel depth in the Entrance Channel both pre and post the trials of the TSHD in 2008, with depths generally varying between -3.9m and -5.4m CD. The navigable channel is located in the central zone between the training walls and has a nominal width of 50m.

Wheeler *et al* (2010a, b and c) also describe changes in the pattern of sedimentation that occurred after the trials of the TSHD in 2008. It was found that during the dredging trial there was a clear net loss of sediment from the ebb and flood tide deltas. Over the period of TSHD operation (Feb to June 2008) there was a loss of sediment from the flood tide delta of 120,970 m^3. After the trial, accretion of sediment in the flood-tide delta resumed, with a gain of 75,980 m^3 between July 2008 and March 2009. This period included a natural flood event in November 2008 that resulted in a loss of 52,070 m^3 from the channel. Comparison of cross-sections in Reeve Channel shows that the TSHD dredged channel profile visible in July 2008 had been in-filled by November 2008. This response was also found in the ebb tide delta region.

Analysis of Reeve Channel prior to 2008 shows that natural flood events can scour sediment volumes from the channel in the same order as the sediment loss during the TSHD trial. For example, flooding in the Gippsland Lakes catchments in 1998 resulted in a loss of around 89,444 m^3 from the channel, and a major flood event in June/July 2007 resulted in a net loss of 144,473 m^3 (Wheeler et al, 2010a).

3.2 Interaction of the Entrance and Reeve Channel

Section 2.1.3 discusses the interaction between ocean inflows through the Entrance and Reeve Channel and the exchange of water into Lake King and Lake Victoria. The conceptual model of ocean inflows through the Entrance Channel and Reeve Channel outlined previously is reproduced and expanded in **Figure 3-1**. As noted by Riedel (2005, 2010) and GHD (2011), the Entrance Channel itself provides the initial hydraulic control for water entering and exiting the Gippsland Lakes. The capacity of the entrance, determined by the channel cross-sectional area, controls the flow rates into and out of the lakes. However, the ability of the inflowing ocean water to penetrate into the lakes system is also affected by the capacity of Reeve Channel inside the entrance. Reeve Channel, being generally shallower than the Entrance Channel, acts as a further hydraulic control.

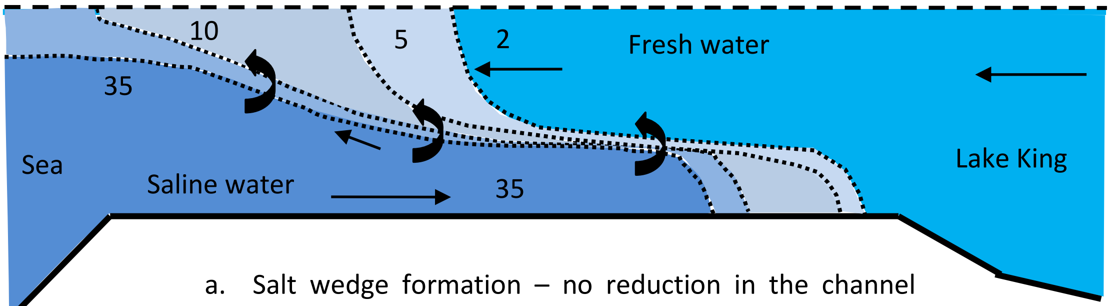
The volume of Reeve Channel is greater than the volume of ocean water that flows in through the entrance over a tidal cycle and so provides a limit for the penetration of this saline water into the Lakes (compare **Figure 3-1 (a)** with **(b)**). Longer period increases in ocean level, such as water level increases associated with storm surges can be greater in magnitude than tidal changes and can persist for several days or more **Figure 3-1 (c)**. These extended periods of elevated water levels allow inflow volumes through the Entrance that exceed the volume of Reeve Channel and therefore enhance the movement of denser salt water into the lakes system.

The effect of changes to the Entrance Channel capacity (i.e. deepening the entrance) can alter the initial volume of water flowing into the system, but the limiting factor for saline water movement remains the capacity of Reeve Channel **Figure 3-1 (d)**.

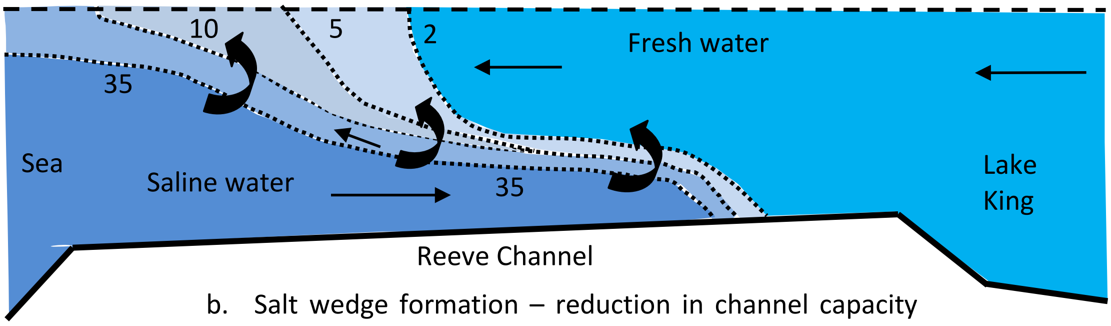
Work reported in Webster et al. (2001) found that a deeper entrance causes a slight increase in tidal range within the lakes while conversely a shallower entrance reduces the tidal range. These changes in tidal range resulted in “quite small” changes in salinity and flushing of Lake King and Lake Victoria. However, it was noted that increasing the tidal range increases the rate of horizontal mixing along Reeve Channel which in turn increases the salinity where the channel enters Lake King.

The hydrodynamic modelling report by Walker & Andrewartha (2000), on which Webster et al (2001) is based, found that a significant factor in calibrating the modelled salinity throughout the lakes system was relatively modest changes to the modelled bathymetry of Reeve Channel. This sensitivity arose due to the coarseness of the model grid used which was unable to accurately represent the variations in bathymetry of Reeve Channel. The effects of bathymetric change in

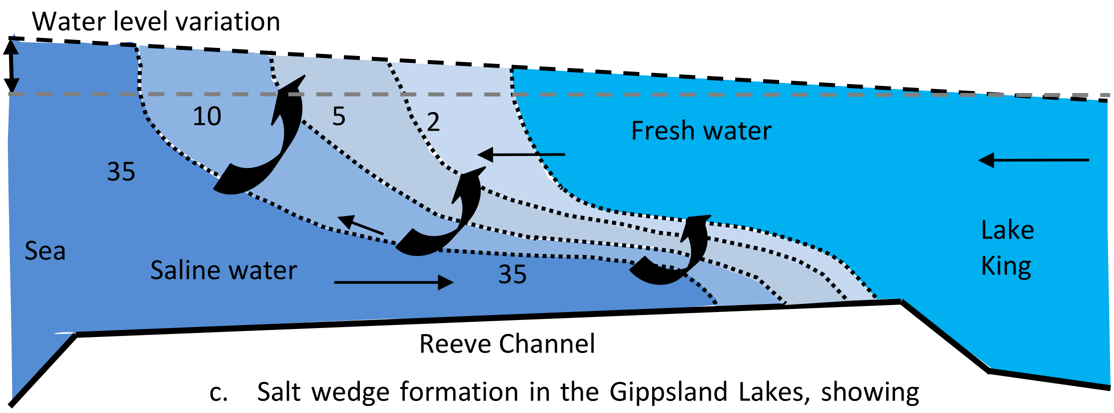
Reeve Channel on salinity concentrations throughout the lakes noted in the model calibration therefore likely overstates actual changes that would occur.



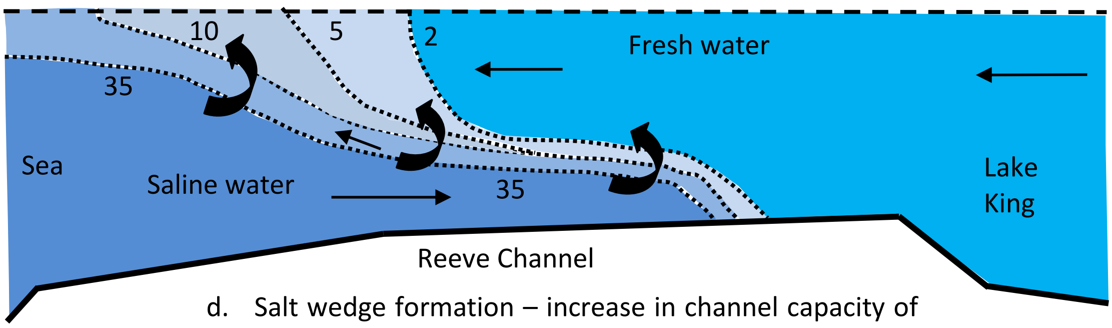
a. Salt wedge formation – no reduction in the channel capacity along Reeve Channel compared to the Entrance Channel (mean ocean water level conditions)



b. Salt wedge formation – reduction in channel capacity along Reeve Channel compared to the Entrance Channel (mean ocean level conditions)



c. Salt wedge formation in the Gippsland Lakes, showing effect of change in ocean levels (either through tides or atmospheric pressure changes)



d. Salt wedge formation – increase in channel capacity of the Entrance Channel (mean ocean level conditions)

Figure 3-1 Conceptual Model of Ocean Inflows through the Entrance Channel and Reeve Channel

3.3 Effects on Marine Exchanges (pre and post 2008)

The total volume of marine water that can enter the lakes on a flood tide is known as the tidal prism. The tidal prism is a function of a number of hydrodynamic processes that operate at the tidal entrance and is *not* solely a function of the Entrance Channel cross section. Energy or head loss across the entrance can also be significantly influenced by friction losses created by flow boundary roughness (i.e. the presence or absence of bed features such as sand waves and/or ripples can dramatically increase/decrease energy/head losses through the entrance and therefore the tidal prism). In addition, eddy losses associated with flow turbulence and flow separation generated by two and three dimensional constrictions and expansions in the flow fields through the entrance can also significantly influence the tidal prism. As noted by Webster et al. (2001) in the case of the Gippsland Lakes the capacity of Reeve Channel also significantly influences the tidal prism.

The astronomical tides generate predictable rise and falls in water level inside the entrance that are a function of the tidal prism. In the absence of detailed current velocity measurements through the entrance to calculate the tidal prism, it is possible to infer relative changes in the tidal prism by undertaking spectral analysis of the tidal water level variations inside the entrance. The spectral analysis deconstructs the time series of water levels into a frequency spectrum that enables the relative magnitudes and phases of the main solar and lunar constituents of the astronomical tide inside the entrance to be estimated. Relative changes to the amplitudes and phases of the main astronomical tidal constituents inside the entrance over time can therefore be used as a proxy indicator of change in the hydrodynamics of the tidal entrance. This information can then be used to assess changes to the tidal prism (and hence salt water exchange) pre and post 2008 that could be related to the change in dredging techniques at the entrance.

Data sets are available to enable changes in the hydrodynamics of the tidal entrance to be inferred by spectral analysis of long term water level data within the Gippsland Lakes. A review of available long term water level data sets in Gippsland Lakes provided the following data sources:

- Bullock Island (Lakes Entrance) water level data collected by Gippsland Ports. The water level data set at Bullock Island is fragmented but contains relatively continuous water level observations for the years 1998, 1999, 2000, 2009 and 2010. Of particular note is the complete absence of data between 2003 and 2008 as a result of the physical loss of the monitoring gauge at Bullock Island;
- Bull Bay (Lake Wellington) water level data collected by DSE. The water level data set extends from 1975 to present. The quality and time step of the data before 1990 is however not considered appropriate for spectral analysis. It should be noted that Lake Wellington is located approximately 80 kilometres from the entrance and is physically separated from the rest of the Gippsland Lakes by the narrow McLennan Strait. Any changes to the entrance hydrodynamics are therefore significantly attenuated within Lake Wellington; and
- Entrance Channel training walls (seaward) water level data collected by Gippsland Ports. The water level data set at the Entrance Channel training walls location is available from April 2008 to present. The Entrance Channel training wall water level data set provides data for analysing the degree to which variations in Bass Strait water levels influence water levels in the Gippsland Lakes.

The available water level data for the above locations and available periods was analysed over 30 day increments of time; considered the minimum to enable reliable estimation of the main diurnal and semi diurnal tidal constituents.

The results of this analysis for the Bullock Island data set are presented for the amplitudes of the main semi diurnal, M_2 and S_2 constituents and the main diurnal O_1 and K_1 constituents in **Figure 3-2**.

The results from the analysis of the Bull Bay data are presented in **Figure 3-3** for the amplitude of the main semi diurnal, lunar constituent M2, as well as a 360 day (~ 1 Year) running mean.

Figure 3-2 and **Figure 3-3** show that there is variation in the estimates of the magnitudes of the tidal constituents from month to month in the Gippsland Lakes. These variations may be associated with phenomena such as meteorological surges, flood flows, coastal processes controlled accretion and scouring in the Entrance, and dredging, which can all potentially influence the tidal hydrodynamics of the entrance channel and hence tidal prism in the lakes.

Figure 3-3 displays a comparison of the variations in the amplitude of the M2 constituent between the Entrance Channel training wall and Bullock Island locations. As can be seen from Figure 3-3, the short term variations in M2 between the two locations are correlated and indicates that short term variations in the amplitude of M2 in the Gippsland Lakes are associated with variability in the dynamics of the tide in Bass Strait caused by shelf waves and other meteorological phenomena that can influence the astronomical tide signature at the entrance to the lakes.

Figure 3-2 displays the mean magnitudes of all four major tidal constituents at Bullock Island, adjacent to the entrance. The data shows evidence of a modest (0.05m) increase in tidal constituent amplitudes between the 1998-2000 data and the 2009-2010 data. This compares to an astronomical tidal range of ±0.3m at this location.

Figure 3-3 displays the amplitude of the M_2 constituent at Bull Bay (Lake Wellington) from 1991 to 2011. The amplitudes of M_2 in Lake Wellington appear to have gradually increased since 1990 in the order of 0.002m with an additional short term increase of 0.002m between 2009 and mid 2010, followed by a decrease since mid 2010 of 0.002m. This compares to an astronomical tidal range of ±0.03m in Lake Wellington.

At both locations the observed change in the amplitude of the M_2 constituent pre and post 2008 is small in absolute terms (0.05m at the Entrance and <0.002m in Lake Wellington), although this equates to around a 16% increase in the tidal range at the Entrance.

However, Walker and Andrewartha (2000) found that

> "*modest changes in entrance depth at Lakes Entrance appear to have very little effect on the modelled salinity or flushing in the Lakes, despite causing significant relative changes in tidal range (though small absolute changes). It can perhaps be concluded from this finding that the tides are not the dominant flushing mechanism in the Lakes. This is because the tidal ranges are still very small .... To make tidal flushing a significant mechanism in this system might require a much larger increment in tidal range (up to a substantial fraction of the range on the adjacent coast).*"

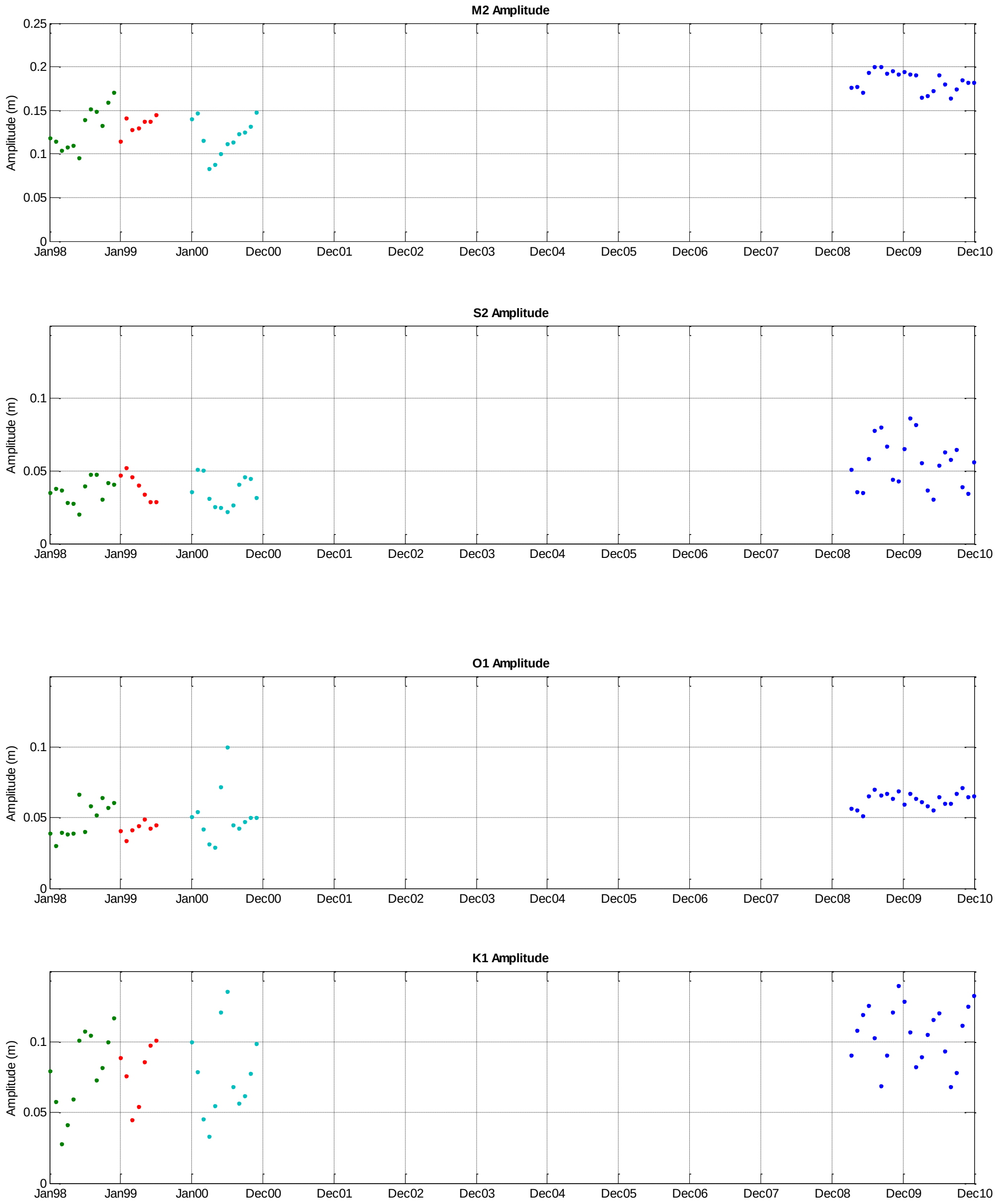


Figure 3-2 30 Day Amplitudes of M_2, S_2, O_1, K_1 tidal constituents at Bullock Island

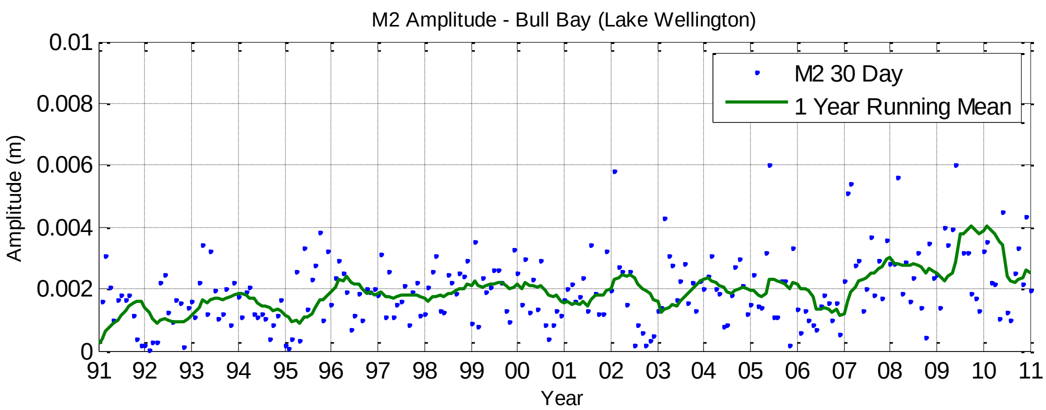


Figure 3-3 30 Day M_2 Amplitudes at Bull Bay

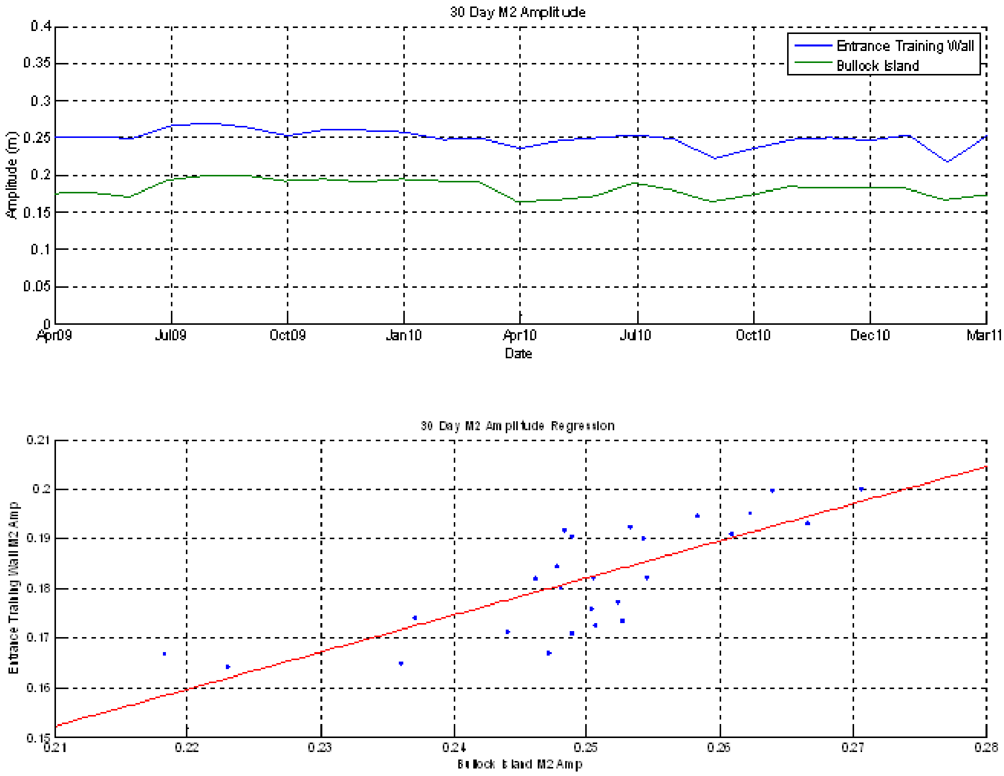


Figure 3-4 Comparison of 30 day M2 between Entrance Channel training walls and Bullock Island

4. PRINCIPAL FINDINGS

A review and analysis has been undertaken of available data and reports relevant to the ecological character of the Gippsland Lakes, focusing on freshwater inflows, salinity and bathymetry of the lakes system.

This information has provided an understanding of the hydrologic and salinity processes in the Gippsland Lakes, which has been outlined through the use of conceptual models.

In regard to effects on the Gippsland Lakes system as a consequence to changes in dredging practises in 2008, the following conclusions can be drawn:

- Since the construction of the permanent entrance maintenance dredging of the artificial entrance to the Gippsland Lakes has been required to maintain navigable channel depths for over a century. The analysis by Wheeler *et al* (2010a, b & c) of bathymetric changes in the Entrance and Reeve Channel areas has shown that despite ongoing dredging efforts, since 1975 there has been accretion of sediment of the ebb- and flood- tide deltas and infill in the navigation channel;
- This period of accretion coincides with changes to catchment inflows to the Gippsland Lakes;
  - Through increases in water extraction such as those associated with construction and operation of the Thomson Dam in 1983, and the Blue Rock Dam on the Latrobe River system in 1984, as well as land use changes that have occurred throughout the catchments; and
  - An extended period of dry conditions in the catchments since 1997.

- The Entrance Channel provides the initial hydraulic control for water entering and leaving the Gippsland Lakes. Reeve Channel, being generally shallower than the Entrance Channel, acts as a further hydraulic control;
- Previous modelling of the Gippsland Lakes (detailed in Walker and Andrewartha, 2000; Webster et al, 2010) has indicated that small changes in tidal prism (such as those associated with a deeper entrance) have very little effect on the salinity or flushing in the Lakes. These previous authors have concluded that tides are not the dominant flushing mechanism in the Lakes. This is because the tidal ranges are still very small. To make tidal flushing a significant mechanism in this system would require a much larger increase in tidal range;
- Of greater effect on salinity concentrations in the lakes are longer period changes in ocean water levels (such as through atmospheric pressure changes, storm setup) which elevate the water level at the entrance over longer periods (>7 days) compared to tides. This allows greater inflow volumes of saline water into the system over a longer duration as the effective cross-sectional area of the Entrance Channel is increased over the duration of the event;
- The trial of the trailing suction hopper dredge (TSHD) in 2008 resulted in:
  - Minimal change to the capacity of the entrance channel (GHD, 2011);
  - A reduction in the volume of Reeve Channel (flood-tide delta region). It is also noted that post-2008, accretion of the channel has occurred; and
  - The volume reduction observed in Reeve Channel is of the same order as that experienced due to scouring of Reeve Channel and the Entrance Channel that has occurred after significant flood events in the Gippsland Lakes catchments.
- As a result of these changes there has been a small (in absolute terms, 0.05m at the Entrance) increase in tidal prism (and hence tidal exchange) into the lakes;
- Changes observed in the salinity concentration of the Gippsland Lakes over recent years can be predominantly attributed to the reduction in freshwater inflows through the inflowing river systems which is associated with lower rainfall conditions and water abstraction; and
- These findings are supported by analysis of available data sets, reports and previous studies of the Gippsland Lakes and the Entrance Channel in particular.