Lake Wellington Salinity

PRELIMINARY INVESTIGATION OF MANAGEMENT OPTIONS

- Final
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Executive Summary

The salinity regime in Lake Wellington depends on the relative contributions of freshwater from rivers, removal of freshwater water via evaporation and addition of saline water from Lake Victoria via McLennan Strait.

At times of low inflows from rivers, more salt is transported to Lake Wellington via McLennan Strait and salinity in Lake Wellington increases. During droughts such as in 1967/68, 1982/82 and most of 1996 to 2009, salinity can increase to 20 ppt or higher (seawater is 35 ppt). Lake Wellington salinity is also increased when inflows are reduced because of water harvesting for irrigation and other purposes.

We collected and analysed available historical salinity data for Lake Wellington and used a computer model to simulate Lake Wellington salinity for six cases:

1) 'Natural' inflows i.e. no extraction
2) Inflows under current level of development
3) Inflows under full level of development i.e. uptake of all extraction licenses
4) Inflows under climate change for natural conditions (historical inflows were scaled to the 1997 to 2008 climate - Scenario D in the Gippsland Sustainable Water Strategy)
5) Inflows under climate change and current level of development
6) Inflows under climate change and full level of development

As inflows are decreased (because of diversions and a drying climate) the average salinity in Lake Wellington increases and so does the range of salinity, i.e. salinity becomes more variable. Modelling results suggest that climate change (modelled as a continuation of 1997 to 2008 climate) has a large influence on salinity levels in Lake Wellington. Under climate change, even if all diversions cease, Lake Wellington becomes more saline than with full development under historical climate.

The ecological implications of a more saline Lake Wellington include; opportunistic marine fish species are likely to become more common than freshwater dependent species, such as Black Bream and sea grasses may colonise some areas of the bed of Lake Wellington that are currently bare.

The salinity regime of Lake Wellington has a strong influence on the fringing wetlands, which are the largest single component of the Gippsland Lakes Ramsar site and are listed as nationally important in *A Directory of Important Wetlands in Australia*. Actions to protect the values of these wetlands, even under scenarios where Lake Wellington salinity increases, are considered in a companion report (Tilleard and Ladson, 2009).

Five management options for managing salinity in Lake Wellington and the fringing wetlands have been considered:

1) Do nothing - salinity is likely to continue to increase under climate change and increased level of development.
2) Increase inflows by reducing extractions
3) Decrease import of salt through McLennan Strait by a constructing partial barrier
4) Prevent saline inputs to Lake Wellington by completely blocking McLennan Straight with a large barrier that prevents all flows from Lake Victoria entering Lake Wellington i.e. attempt to make Lake Wellington fresh
5) Construct works and provide a specific watering regime to allow management of fringing wetlands separately from the main lake and provide freshwater to lower reaches of inflowing rivers at critical times.

The complex nature and combination of factors that influence salinity in Lake Wellington and the fringing wetlands is likely to require a range of management options to achieve the desired conditions. Management solutions such as providing specific inflows to wetlands and constructing several smaller barriers to increase control of saline waters is likely to be the answer to reducing the rate of change as well as protecting those areas of greatest ecological value, namely the fringing wetlands.

Table E.1 Summary of management options

No	Management option	Effect on Lake Wellington Salinity	Comment
1	Do nothing	Further increases in median salinity and variability	Lake Wellington will become increasingly Marine. Fringing wetlands will be threatened
2	Increase freshwater inflows	Likely to move salinity regime closer to natural conditions i.e. reduce median salinity and decrease variability. Provides some protection of current wetland values	Not robust to climate change: under climate change Lake Wellington becomes increasingly saline even if water extractions are reduced
3	Construct barrier(s) in McLennan Strait	Salinity is reduced in magnitude and range compared to the cases without this option	Requires hydrodynamic modelling to confirm effectiveness
4	Complete barrier across McLennan St	Lake Wellington is fresh most of the time	High risk, high cost option with uncertain benefits
5	Works and flows to protect fringing wetlands	No effect on Lake Wellington salinity	Aims to protect the most valuable ecological features of the Gippsland Lakes from degradation With a much lower water requirement than option 2. Robust to climate change.

Contents

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1. Introduction

There is a long history of concern about the salinity regime of Lake Wellington. The simplistic view is that Lake Wellington was once fresh and since the establishment of the artificial entrance to the Gippsland Lakes is becoming increasingly saline. In fact, the salinity regime in Lake Wellington depends on the relative contributions of freshwater from rivers, removal of freshwater water via evaporation and addition of saline water from Lake Victoria via McLennan Strait. In recent years there has been a trend of increasing salinity that is driven by a reduction in freshwater inflows caused by river regulation, water extraction and a drying climate (Tilleard et al. 2009).

Although increasing salinity in Lake Wellington is seen as a problem, it also presents an opportunity, for example, lake water may become clearer and the few species that can tolerate brackish conditions may be replaced by a richer marine flora and fauna. However, increased salinity does pose a threat to the high value wetlands (Ecos, 2008).

1.1. Project objectives

The objectives of this project are to:

1) Describe and evaluate salinity inputs into Lake Wellington using current data and information;
2) Develop management adaptations and options to modify the salinity in Lake Wellington, including description of a barrier of various heights and types in McLennan Strait; and
3) Identify knowledge and data gaps that should be addressed prior to implementing adaptations or solutions.

1.2. Report structure

This report briefly describes the physical environment and ecological values in Lake Wellington and fringing wetlands (Section 2). Section 3 describes the factors that influence salinity in Lake Wellington and discusses the development of a computer model that relates salinity to these factors. Section 4 describes five options for managing salinity in Lake Wellington, including:

1) Do nothing
2) Increase freshwater inflows
3) Construct barrier in McLennan Strait
4) Construct individual barriers for fringing wetlands; and
5) Manage Lake Wellington and the fringing wetlands for a changing environment.

Section 5 summarises the key findings and describes the feasibility of implementing each of the management options.

The salinity units used throughout this report are parts per thousand (ppt) which is similar to the Practical Salinity Unit (PSU) used in oceanography. As an alternative to ppt, salinity is sometimes expressed in terms of electrical conductivity (EC). By way of reference, 1000 EC = 0.64 ppt and the salinity of seawater is 35 ppt or 55,000 EC.

2. The Lake Wellington system

2.1. Lake Wellington

Lake Wellington is the shallowest of the Gippsland Lakes and is generally well mixed. Lake Wellington is fed by the Latrobe, Thomson, Macalister and Avon Rivers and linked to Lake Victoria via McLennan Strait (Figure 1). Physical properties of Lake Wellington and McLennan Strait are listed in Table 1.

Lake Wellington and lower parts of the inflowing rivers provide critical habitat for a range of important estuarine dependent bird and fish species, including Black Bream (Ecos 2008). Almost all of the Gippsland Lakes is recognised under the Ramsar Convention as being of international importance for its wetlands and large bird populations (Ecos 2008; SKM 2008). Lake Wellington and its fringing wetlands are the largest single component in the Ramsar site and are listed as nationally important in *A Directory of Important Wetlands in Australia.*

- **Table 1 Physical properties of Lake Wellington and McLennan Strait**

Lake Wellington		**Source**
Surface Area	148 km^2	(Robinson 1995)
Mean length	17.8 km	(Robinson 1995)
Mean width	9.7 km	(Robinson 1995)
Mean depth	2.8 m	(Robinson 1995)
Max. depth	6 m	(Robinson 1995)
Volume	414×10^6 m^3	(Robinson 1995)
McLennan St		
Surface area	2 km^2	(Webster & Ford undated)
Length	9.7 km	(Hatton et al. 1989)
Mean width	150 m	(Hatton et al. 1989)
Mean depth	5 m	(Webster & Ford undated)
Max. depth	8 m	(Webster & Ford undated)
Volume	10×10^6 m^3	(Webster & Ford undated)

2.2. Fringing wetlands

Lake Wellington has the most number of fringing wetlands of the three main Gippsland Lakes (Ecos, 2008). The wetlands include Lake Coleman, Heart and Dowd Morass, Clydebank Morass and Sale Common (Figure 1). The wetlands receive inflows from the catchment and backflows from Lake Wellington and salinities in the wetlands can range from hypersaline to fresh. The wetlands support important environmental values, diverse habitats and have high socio-economic values associated with tourism and recreational activities (SKM, 2003a; 2003b, Ecos, 2008). They provide important habitats for waterbirds and other fauna, most notably:

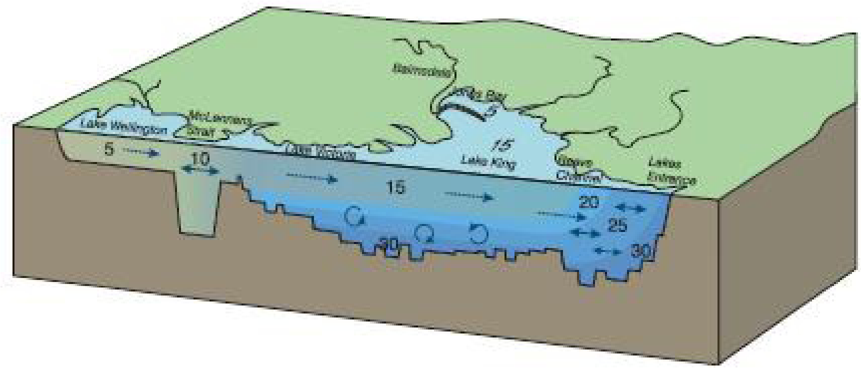
- The Roseneath Peninsula wetlands between Lake Wellington and Lake Victoria (e.g. Victoria Lagoon and Morley Swamp); and
- Sale Common, Dowd Morass and Heart Morass along the lower Latrobe River floodplain (Tilleard et al. 2009).

Sale Common and the wetlands in the vicinity of the Long Waterhole are the largest area of freshwater wetlands remaining in the Gippsland Lakes system. Sale Common, Dowd Morass and part of Heart Morass are part of the Gippsland Lakes Ramsar site. Management of these wetlands has been recently considered in Tilleard and Ladson (2009).

■ **Figure 1 Lake Wellington, McLennan Strait and fringing wetlands**

2.3. Salinity regime

Salinity levels in the Gippsland Lakes system vary depending on relative influence of freshwater inflows from the catchment and marine water inflows through Lakes Entrance via Lake Victoria. Typically, salinity is close to seawater near the Lakes Entrance and in the eastern area of Lake King (Figure 2). However, during periods of low freshwater flow the salinity can be high throughout the Lakes. A wedge of highly saline water can also move many kilometres upstream into the inflowing rivers.



- **Figure 2 Conceptual diagram of salinity levels (g/L ≈ ppt) (Webster et al., 2001).**

Focusing on Lake Wellington in particular, there are a number of factors that determine its salinity, including:

- Magnitude of river inflows
- Salinity of river inflows
- Salinity of Lake Victoria
- Important and export of salt to/from Lake Wellington via McLennan Strait.
- Rainfall and evaporation
- Groundwater interactions
- Tides
- Wind
- Ocean levels which are influenced by atmospheric pressure, wind and tides.

2.3.1. Historical salinity observations

Prior to the opening of the permanent entrance in 1889 the Lakes were, on occasion, sealed off from the ocean in dry conditions and low salinity conditions would have prevailed in Lake Wellington and throughout the Lakes (Bek and Bruton, 1979). During these times it is likely that Lake Wellington would have been considered ‘fresh’. There would also have been occasions when the Lakes were connected to the sea, perhaps following a flood event, so Lake Wellington would have had increased salinity levels.

Some historical accounts of salinity in Lake Wellington are available with the frequency and reliability increasing over time:

- 1841: W. A. Brodribb named Lake Wellington and reported that the water was "fresh-at least drinkable by man and beast" (Robinson, 1995)
- 1842: W. A. Raymond found Lake Wellington to be brackish (Robinson, 1995)
- 1844: Watson and Hunter reported Lake Wellington to be fresh (Robinson, 1995)
- 1861: Lake Wellington reported fresh by Acheson (Robinson, 1995)
- 1874: Lake Wellington reported fresh by Skene and Smyth (Robinson, 1995)
- 1898: Lake Wellington described as being "usually brackish, with few fish and bare of bottom vegetation over many areas" (Robinson, 1995)
- Bird (1966) reported salinities for the centre of Lake Wellington varying between 0.7 ppt and 9.6 ppt.
- 1968: substantial die-back of *Phragmites* and *Vallisneria* caused by high salinities in May 1968 (resulting from the 1967-1968 drought when surface salinity reached 16.7 ppt and bottom salinity reached 22 ppt (Arnott, 1968; Bek and Bruton, 1979; Robinson, 1995)
- 1976 Lake Wellington found to be barren of any bottom vegetation. Sampling in 1958 found abundant Ribbon weed (*Vallisneria spiralis*) but this had disappeared by 1976 (Drucker et al, 1977)
- A 1973-1974 EPA study reported salinities in Lake Wellington of 1.5 to 11.1 ppt.
- There has been systematic measurements of Lake Wellington Salinity since the mid 1970s (a summary of observations are listed in Table 2)
- High salinities were observed in Lake Victoria and the eastern end of McLennan St during the 2006/07 drought with surface salinities reaching 31 PSU (EPA, 2008). Salinities rapidly decreased following the floods of 2007.

All available salinity measurements are shown in Figure 3. Reliable, frequent salinity measurements began at Bull Bay (Site No. 226041) in 1992 and continue to the present. These data are summarised as a duration curve and boxplot in Figure 4. Similar summaries are used for modelling results discussed in Section 3.

Average Lake Wellington salinity has a seasonal cycle with peak salinities occurring in June with lowest salinities occurring in December (Figure 5). In winter, freshwater inflows are high enough to flush salt out of Lake Wellington via McLennan Strait so salinity decreases until January when more salt water enters than leaves and salinity increases again. The actual salinity of the lake depends on the flows in a particular year and there is quite a lot of scatter around this average seasonal relationship (Figure 5).

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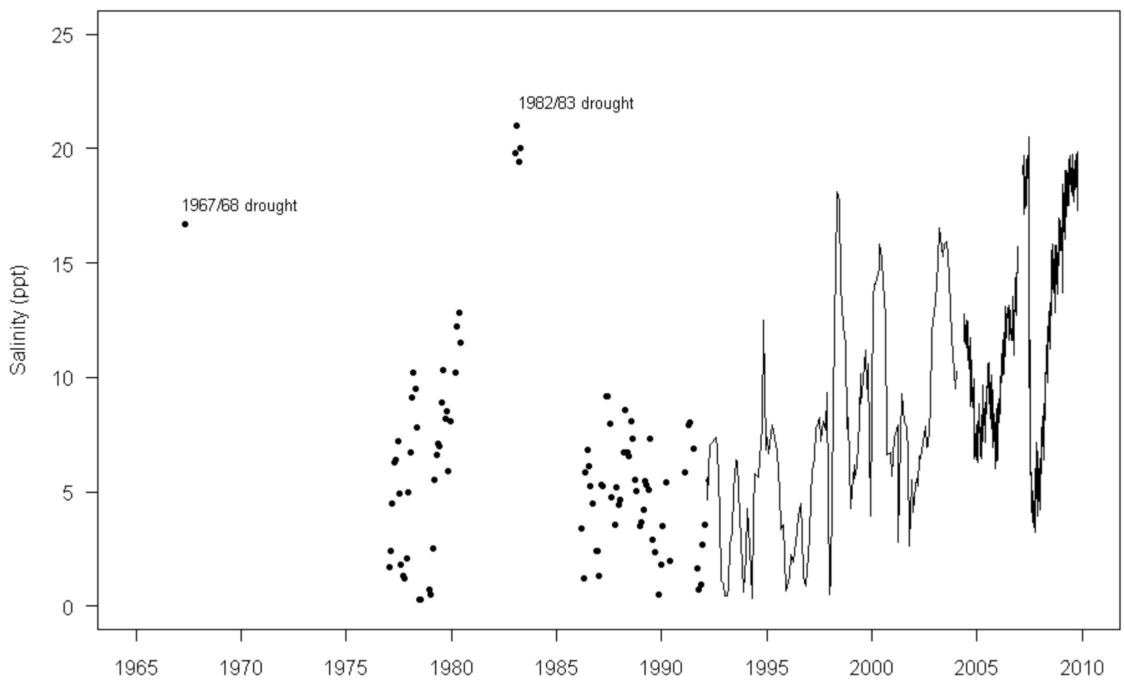
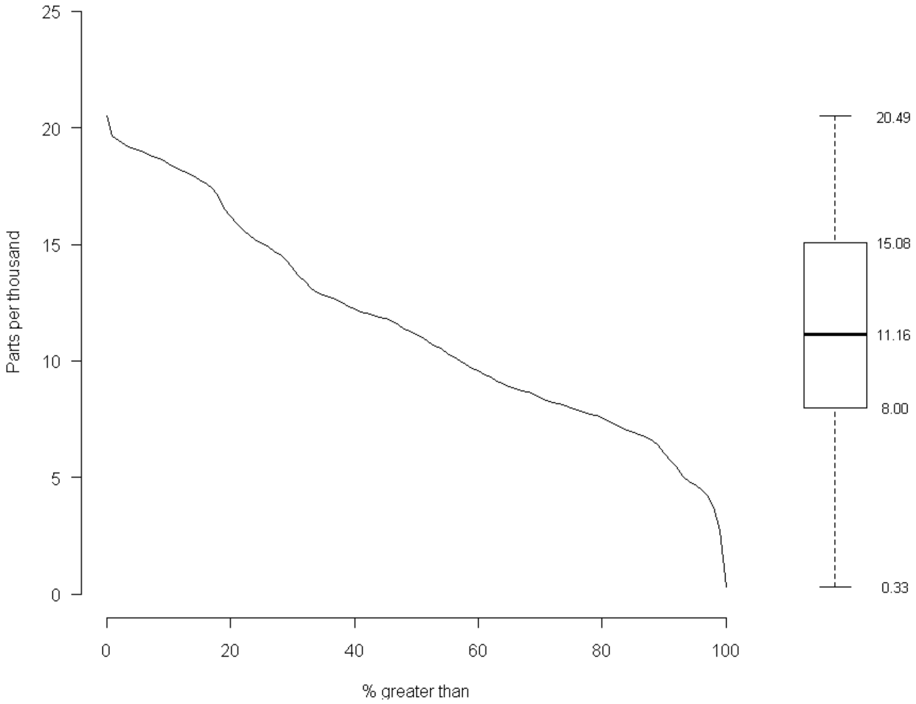
- **Table 2 Observed salinity in Lake Wellington and Lake Victoria (1984-1996) (Brown et al.- 1998; Longmore et al. 1988)**

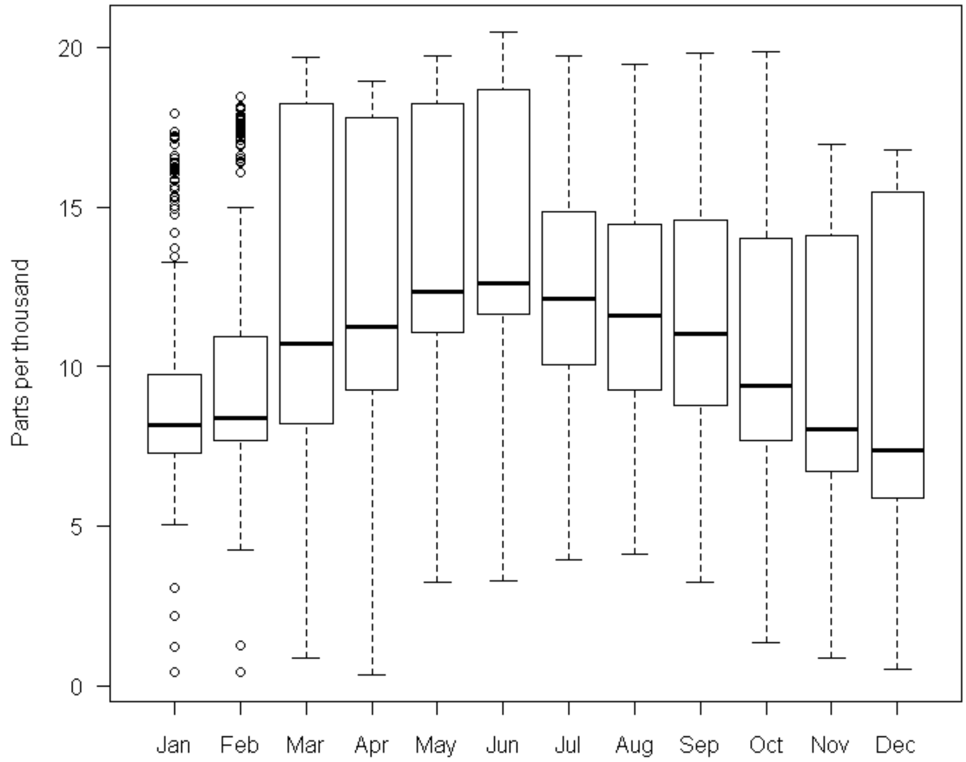
Site	Sample location	Period	Median	Mean	Range	25th %-ile	75th %-ile
Lake Wellington	Surface	1984-1996	4.9		0.2-21.1	2.4	6.4
	Surface	1976-1978		4.4	0.3-10.2		
	Bottom	1984-1996	5.3		0.2-15.7	2.5	7.0
	Bottom	1976-1978		4.7	0.4-11.5		
Lake Victoria	Surface	1984-1996	16.2		3.0-26.0	11.1	19.2
	Surface	1976-1978		13.6	1.2-24.8		
	Bottom	1984-1996	21.9		3.3-34.7	16.3	26.1
	Bottom	1976-1978		19.3	16.0-32.0		



- **Figure 3 All available salinity in Lake Wellington. After 1992, regular observations were made at Bull Bay (Site No. 226041). Before 1992, scattered measurements are available.**



- **Figure 4 Duration curve and boxplot summarising salinity data from Bull Bay (Site No. 226041)**



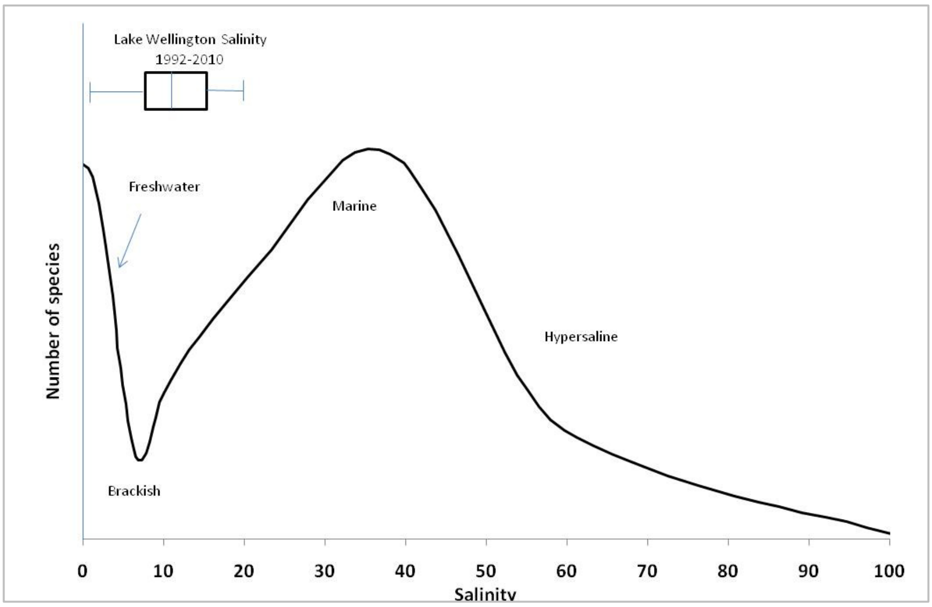
- **Figure 5 Seasonal salinity regime of Lake Wellington (based on salinity data from Bull Bay Site No. 226041, 1992-2010)**

2.4. Ecological implications of salinity regime

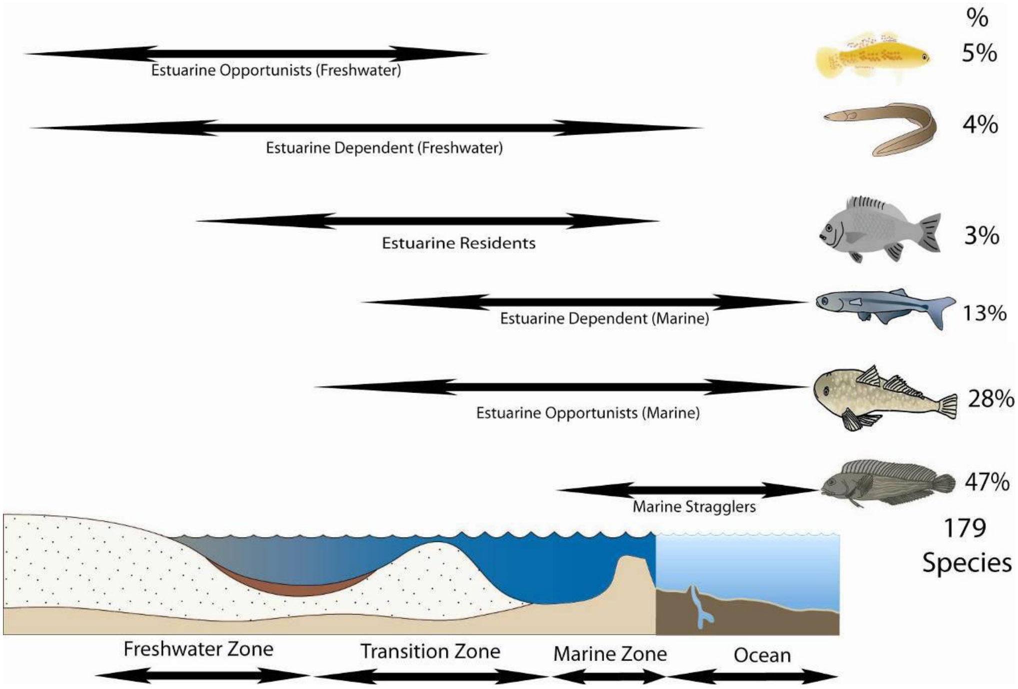
Most organisms have a preferred range of salinity with a major divide between 'freshwater' and 'marine' species. Freshwater is commonly defined as having less than 2 to 3 ppt (although the definition varies) (Hart et al., 1991). For less tolerant freshwater species, adverse effects begin when salinity approaches 1 ppt (Hart et al., 1991) and there seems to be a critical level of salinity at about 5 to 8 ppt. This corresponds to the upper limit of survival of most salinity-tolerant 'freshwater' species (Dallas and Day, 1993). This is obvious when relating number of species to salinity (Remane and Schlieper, 1971) (Figure 6). Plotting historical Lake Wellington salinities (1992-2010) on this figure (Figure 6) reveals the challenges for Lake Wellington. For about 25% of the time the lake can be considered as fresh, for about 25% of the time it could be considered as marine, while for about 50% of the time it is between the two where few species can thrive.

For species that are mobile, such as fish, the available habitat depends on salinity and they can respond to changes in salinity regime by shifting to different areas in the Lakes (Figure 7). For example, during the highly saline period in 2006/2007 (see Figure 3) sea horses which have a salinity tolerance of 18-35 ppt, depending on the species, were found in large areas of the Lakes. These disappeared in late 2007 following the large freshwater inflows that occurred as a result of floods (EPA, 2008).

For less mobile species such as plants, rapid changes in salinity can be a problem. For example, there are reports of substantial die-back of *Phragmites* and *Vallisneria* caused by high salinities in May 1968 that resulted from the 1967-1968 droughts (Arnott, 1968; Bek and Bruton, 1979; Robinson, 1995).



- **Figure 6 Number of species as a function of salinity (after Remane and Schlieper, 1971). Lake Wellington salinity (1992 to 2010) is also shown.**



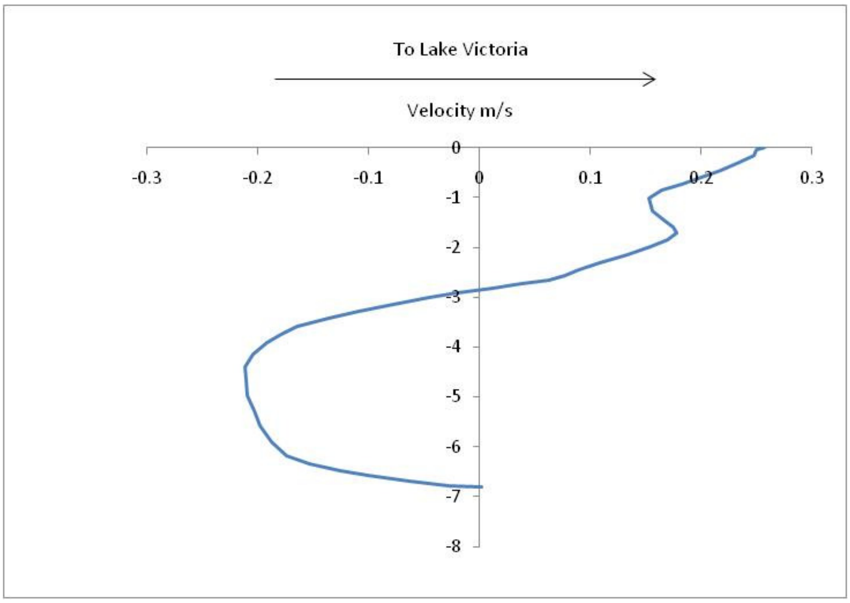
- **Figure 7 Fish groups found in the Gippsland Lakes, their distribution as a function of salinity and percentage of species in each group as a percentage of the 179 species found in the Lakes (Tilleard et. al 2009).**

3. Understanding the factors that influence salinity in Lake Wellington

Although there are a larger number of factors that have the potential to influence salinity in Lake Wellington, much of the variation can be explained by considering the following variables (Grayson 2003):

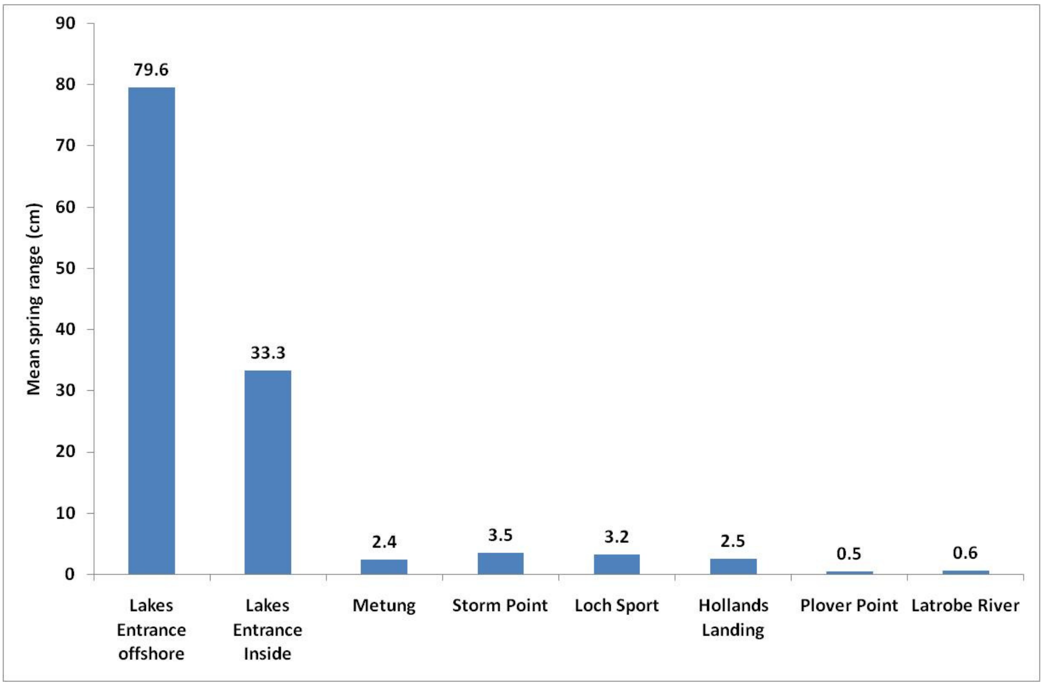
- River inflows;
- Net evaporation from the lake (rainfall minus evaporation); and
- Salt inputs via McLennan Strait.

Salt transport through McLennan Strait has been assessed in a number of previous investigations (Roy, 1972; Bek and Bruton, 1979; Black & Hatton 1989, Hatton 1989, Hatton et al. 1989, Marwood 1989, Longmore 1990, Robinson 1995). These investigations demonstrated that salt water can be transferred from Lake Victoria to Lake Wellington even when there is a net outflow of water through McLennan Strait from Lake Wellington (Figure 8). This is because dense saline water can be driven through the Strait and into Lake Wellington by tidal or wind induced currents even when fresher Lake Wellington water is flowing out near the surface of McLennan Strait.



- **Figure 8 McLennan St, velocity profile at Secomb (after Roy 1972). Salt water is moving into Lake Wellington even when surface flows are moving toward Lake Victoria.**

The tidal influence on the transfer of saline water affects a significant portion of the Gippsland Lakes region. While the tidal influence decreases further inland the influence is still measurable as far upstream as the lower Latrobe River (Figure 9).



- **Figure 9 Tidal influence (mean spring range) at points throughout the Gippsland Lakes (Tan and Grayson, 2002)**

3.1. A model of Lake Wellington salinity

Grayson (2003; 2006) building on earlier work by Marwood (1989) developed a computer model of Lake Wellington salinity. This has been further tested and modified for the present study to take account of very low inflows (which was not considered in this earlier work) and increased data which has become available as part of work done for the Gippsland Sustainable Water Strategy. The key features of this model are:

- Salt and water transfers are based on a mass balance where the change in the storage of water and salt is calculated from the difference between the inflows and outflows to Lake Wellington;
- Water is provided by flow from rivers and is lost by evaporation. Water flows both into and out of Lake Wellington via McLennan Strait depending on the relative riverine and evaporative fluxes;
- Salt is contributed by river inflows and transfer of saline water through McLennan Strait;
- River inflow and net evaporation can be based on measured data while the salt inputs from McLennan Strait depend on a range of factors, particularly the balance between river inflows and currents within the Strait;
- During high riverine inflows (when flow out through McLennan Strait is greater than 130 GL/month), salt is flushed from Lake Wellington;

- Once outflow drops below 130 GL/month down to 0 ML/month there are additional saline inflows to Lake Wellington through McLennan Strait. Below this threshold of 130 GL/month, saline inflow was assumed to be linearly related to:
  i. Lake Wellington river outflows; and
  ii. The difference in salinity between Lake Wellington and Lake Victoria.

  Mathematically, these additional saline inputs via McLennan Strait, at a monthly time step, can be represented as:

$$S = k\left(\frac{130 - Q_w}{130}\right)\left(\frac{35 - S_w}{35}\right) \quad (1)$$

  S = 0 if Q_w > 130 GL/month

  Where:

  S is tonnes of salt inflowing from Lake Victoria to Lake Wellington via McLennan Strait because of currents in McLennan Strait

  Q_w is outflow from Lake Wellington in GL per month

  130 GL/month is a threshold outflow from Lake Wellington

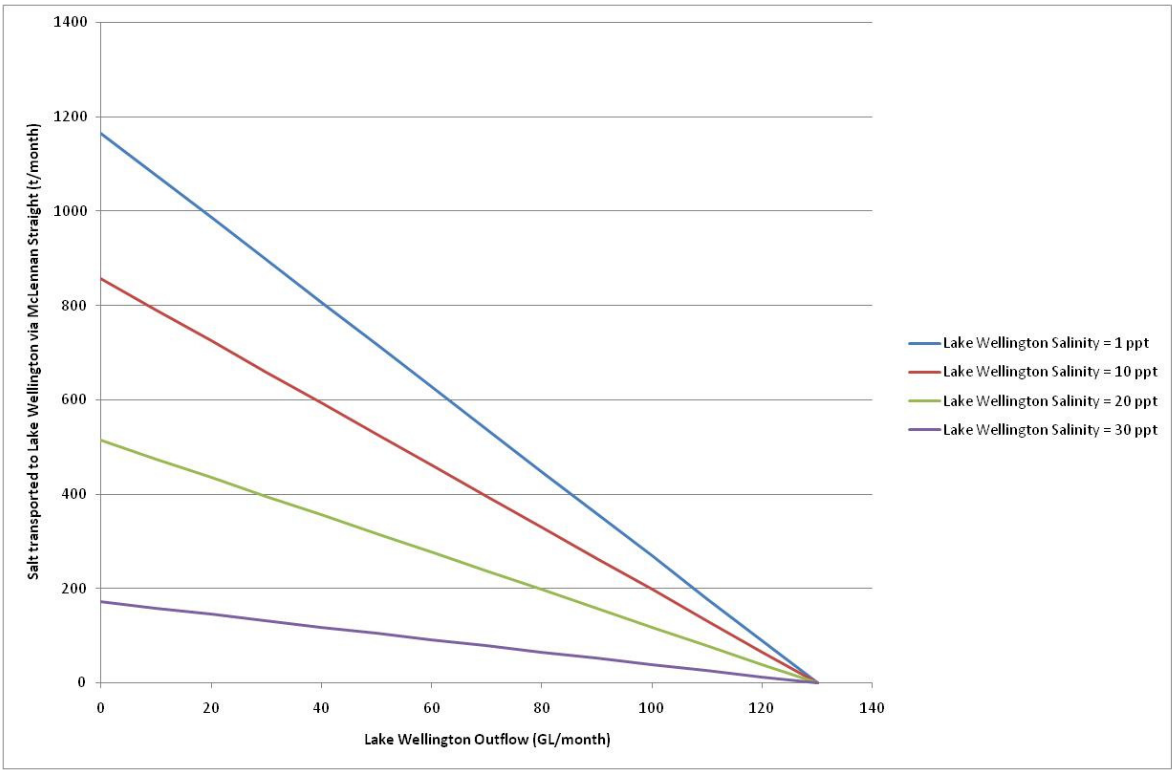
  S_w is the salinity of Lake Wellington (ppt)

  k is a dimensionless constant that was found to be 1300

  Some examples of this relationship are shown in Figure 10.

- Once outflow drops below zero, i.e. there is net inflow from Lake Victoria to Lake Wellington, the salt transfer to Lake Wellington is the inflow rate multiplied by the Lake Victoria salinity. In these cases, Lake Victoria salinity is assumed to be 35 ppt. This case only occurs under very dry conditions when measured Lake Victoria salinities are high (e.g. see peak Lake Victoria salinities for the 2006-2007 drought in EPA, 2008).

This modelling approach was calibrated to represent salinity in Lake Wellington during the period 1976 to 2000.



- **Figure 10 Typical quantities of salt transferred as a function of Lake Wellington Salinity and Lake Wellington**

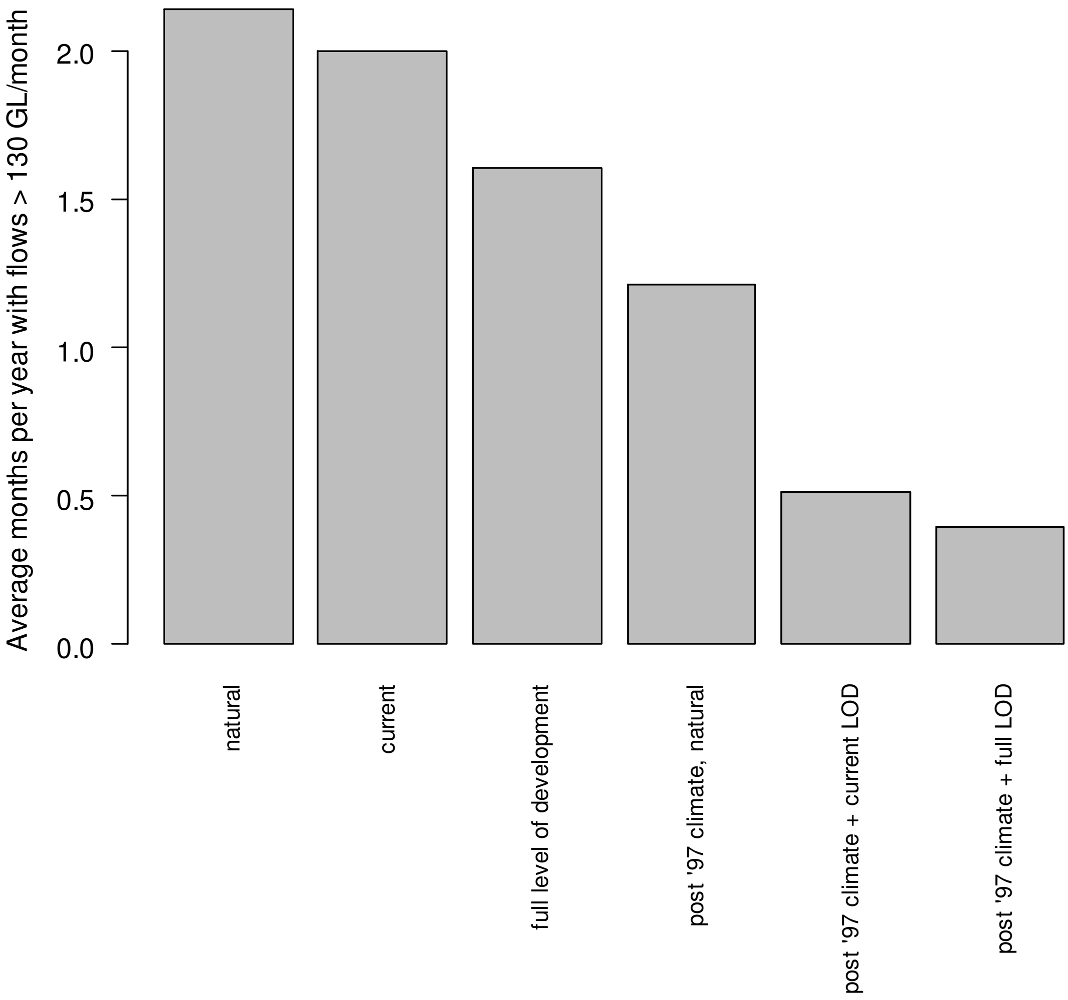
3.2. Salinity regime under future scenarios

The computer simulation model was used to examine the Lake Wellington salinity regime under a range of scenarios. Lake Wellington salinity for 1965 to 2005 was calculated for 6 cases:

1) 'Natural' inflows i.e. no extraction
2) Inflows under current level of development
3) Inflows under full level of development i.e. uptake of all extraction licenses
4) 'Natural' Inflows under climate change, where historical inflows were scaled to the 1997 to 2008 climate (this is referred to as Scenario D in the Gippsland Sustainable Water Strategy)
5) Inflows under climate change (scenario D) with current level of development
6) Inflows under climate change (scenario D) and full level of development.

For all cases except 4, inflows were taken from REALM modelling undertaken for Gippsland Sustainable Water Strategy. For case 4, inflows have been generated by adding back 30% of flow from case 5 to take account of the 30% of extraction that occurs under 'current' development. Results from this case should be considered less certain than the others.

The average occurrence of months with flows greater than 130 GL/month are shown for each scenario in Figure 11. These are the months were salt is flushed from Lake Wellington. Under natural conditions there was more than 2 months per year, on average, with these high flows, while with climate change and extractions, the frequency decreases. For the most extreme scenio (post 1997 climate change and full level of development), there is only 1 month every 2 years where flows are high enough to prevent salt entry.



▪ **Figure 11 Average months per year with flows > 130 GL/month for 6 scenarios**

Reduced inflows mean that Lake Wellington salinity will increase. Results are summarised in Figure 12 and Figure 13. In summary, a drying climate and increased extractions will lead to:

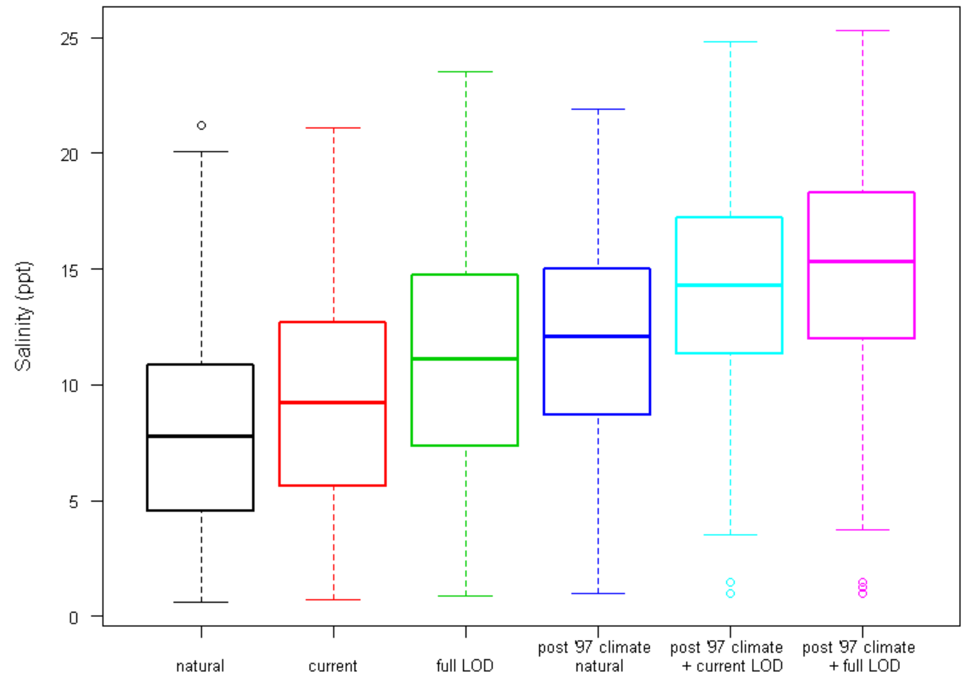
- Higher average salinity (as shown by increasing median salinity levels);
- A greater range in salinity (the difference between the highest and lowest Lake salinity increases as diversions increase and inflows decrease);

- Less time that Lake Wellington can be considered fresh for example for scenario 5 and 6 (post ’97 climate) there are only 2 months out of 486 where salinity is less than 3.5 ppt (2200 EC); and
- The conversion of Lake Wellington to a more marine system (Figure 14).

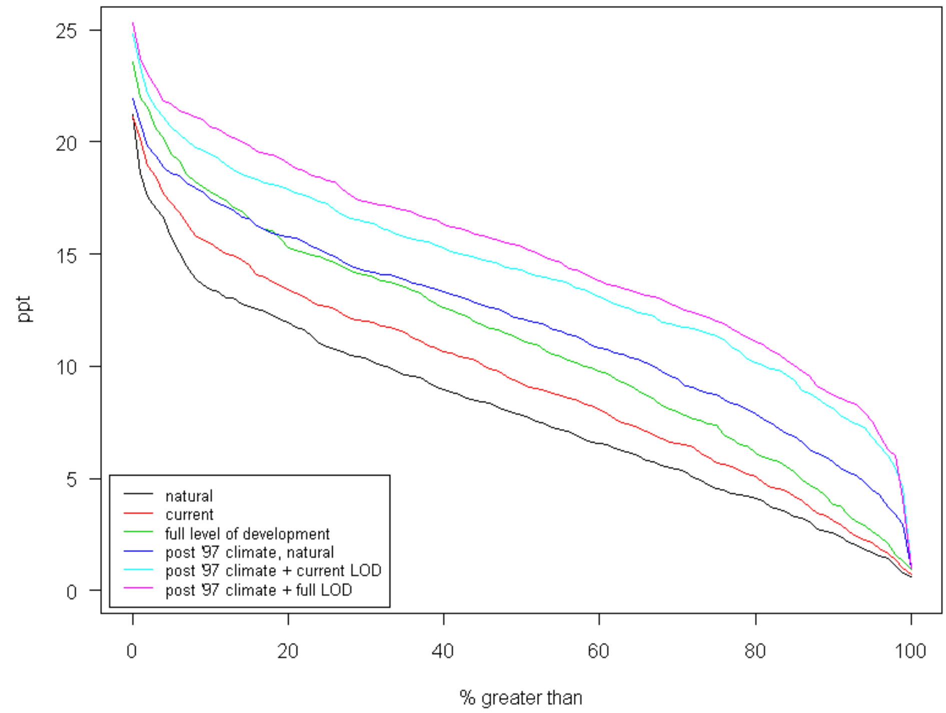
Results show that climate change (as modelled by a continuation of the 1997-2008 climate) has a major effect on Lake Wellington salinity levels. The results from scenario 4 suggests that even if there was no diversions, salinity of Lake Wellington under climate change is higher than under full development and historical climate.

In addition to the increasing salinity predicted by this modelling, there is likely to be additional increased saline imports to Lake Wellington because of sea level rise. The Victorian Coastal Strategy states that Victoria will plan for a minimum sea level rise of 0.8 metres by 2100 (VCS, 2008). To understand the full impacts of sea level rise on salt balances in the Gippsland Lakes will require separate assessment which is yet to be undertaken. The salinity contribution of sea level rise is not considered in the modelling results within this report therefore Lake Wellington salinity under climate change scenarios are likely to be higher then shown here.

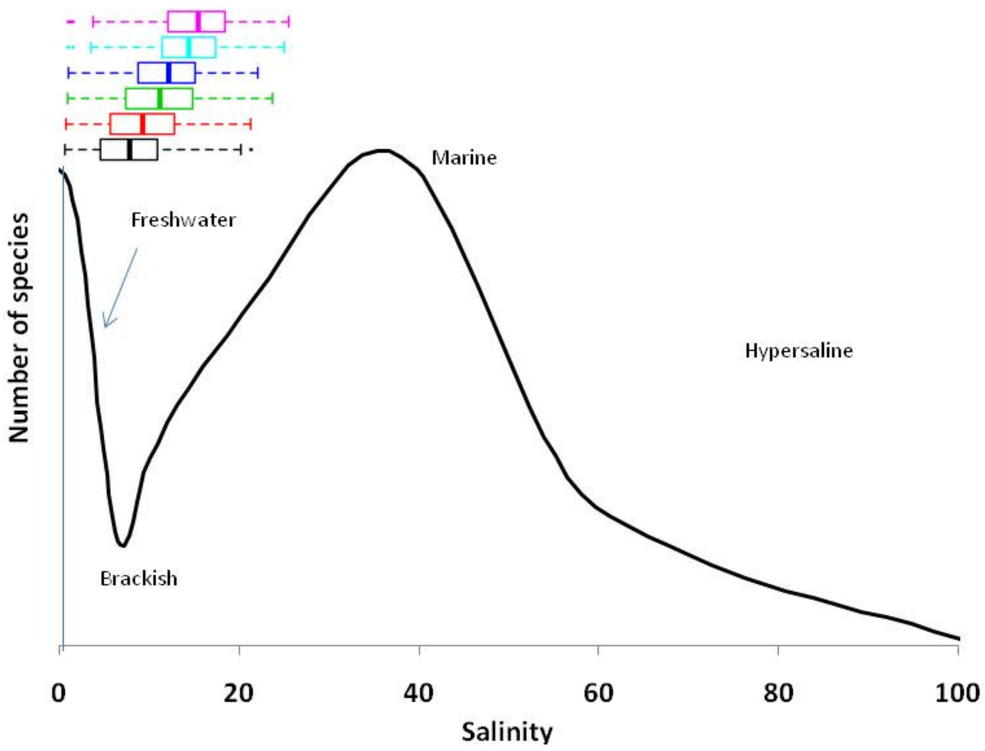
The potential ecological implications of increasing salinity are summarised in Figure 14. Modelling results suggest that Lake Wellington will become more marine which would mean an increase in marine species and loss of freshwater species. For example, there is likely to be more sea grass and less ribbon weed (most of this has already disappeared) and there are likely to be more marine fish and fresh water fish (Figure 7).



- **Figure 12 Salinity regime in Lake Wellington for 6 scenarios (results are summarised as boxplots). LOD = Level of Development**



- **Figure 13 Salinity regime in Lake Wellington for 6 scenarios (results are summarised as duration curves)**



- **Figure 14 Lake Wellington salinity under 6 scenarios superimposed on the relationship between number of species and salinity**

4. Options for managing salinity

Without intervention, Lake Wellington is likely to become increasingly saline because of three main drivers:

- Decreased inflows to Lake Wellington caused by a drying climate;
- Increased sea levels which will tend to increase salt import via McLennan Strait; and
- Decreased inflows to Lake Wellington caused by increased diversions (depending on the outcomes of the Gippsland Sustainable Water Strategy).

If lower salinity levels are desired, consideration of the water and salinity balance for Lake Wellington suggests there are 2 main options:

1. Increase Lake Wellington outflows, to transport salt out of the Lake via McLennan Strait.

   Lake Wellington outflows depend on river inflows and net evaporation from the lake. It is probably not possible to change net evaporation so changing river inflows may be one mechanism to manage salinity.
2. Decrease import of salt via currents in McLennan Strait once Lake Wellington outflows drop below a threshold value.

   It may be possible to manage salinity by decreasing these saline inputs, by constructing a partial or complete barrier across the Strait.

Although it's stating the obvious, the best approach to mitigating the impacts of climate change (i.e. reduce the likelihood of a drying climate) is by decreasing worldwide green house gas emissions. In the absence of a national and international approach to do this it would be prudent not to rely on this as an approach to managing Lake Wellington salinity.

The magnitude of required intervention depends on the desired salinity level. For example, to make Lake Wellington fresh (less than say 2 ppt) all salt import via McLennan Strait would need to be stopped. This would require a large barrier, an example of which is discussed below.

Note that both historical data and modelling confirm that Lake Wellington has never been continuously fresh since the construction of the permanent entrance and even before then, would have had periods of increased salinity has confirmed by historical reports (see Section 2.3.1).

The effectiveness of any option in managing salinity needs to be compared against the 'do nothing' scenario.

4.1. Do Nothing

The consequences of 'doing nothing' will be increasing salinity in Lake Wellington and fringing wetlands. Flora and fauna in Lake Wellington will become more marine (Table 3). The distribution of aquatic plant species, seagrass, freshwater macrophytes and emergent reeds, such as

Ribbonweed (*Vallisneria*) and Common Reed (*Phragmites*) are likely to change (SKM 2003a; 2003b; Ecos, 2008).

Further increases in salinity are also likely to effect bird and fish species in the area. For example, Eurasian Coot, are intolerant to salinities above 5 ppt. If salinities in Lake Wellington increase to levels above this there could be significant effects on habitat suitability and distribution of the local Eurasian Coot and other bird populations. Estuarine fish species such as Black Bream, River Garfish and Estuary Perch require variably saline water. If salinities in Lake Wellington become closer to marine levels there is likely to be declines in numbers of such species (Ecos 2008). However, there may also be positive changes. Water is likely to become clearer because clay particles will flocculate (Dallas and Day, 1993) and marine fish species will move further into Lake Wellington (Figure 7). Sea grasses may colonise some areas of the bed of Lake Wellington that are currently bare.

Perhaps the biggest threat would be to the fringing wetlands. The current objectives for these wetlands are that they should be managed predominantly as freshwater wetland ecosystems (Parks Victoria, 2008). Management of fringing wetlands are discussed further below.

- **Table 3 Ecological consequences of increased salinity in Lake Wellington and fringing wetlands (adapted from Tilleard et al. 2009)**

Issue	Environmental consequences
Increase salinity in Lake Wellington	Seagrass colonise upper reaches of estuary and lower reaches of rivers. Decline of less-tolerant seagrass species. Increase risk of invasion by marine pest species (plants and animals). Increase number and diversity of marine taxa.
Increase in salinity in fringing wetlands	Hypersaline waters to develop in wetlands Loss of fringing macrophytes and possible replacement by exotic taxa

4.2. Increasing river inflows

The modelling discussed in Section 3 can be used to assess the effect of increasing river inflows on Lake Wellington salinity. As inflows are increased (moving from right to left on Figure 12) there is a decrease in median salinity, the variability and the time spent above any critical threshold. Broad flow thresholds were identified by Tilleard *et al.* (2009) (Table 4). However, the figure also shows the large effect of a drying climate, even when there is no extraction.

The financial costs and feasibility in increasing freshwater inflows is difficult to estimate but it is likely to be significant for individual users and the WGCMA. It will become increasing difficult in the future to provide additional water due to climate change and increasing demand for water, which would make this option difficult to implement.

Even though increasing river inflows to freshen Lake Wellington is not likely to be feasible, there is likely to be a role for a water reserve and specific release enhance and protect the fringing wetlands (as discussed below).

- **Table 4 Inflows from Latrobe, Thomson, Avon and Perry Rivers to Lake Wellington (Tilleard et al. 2009)**

Indicative flow threshold	Ecological Consequences
≥ 200 GL/month	Short-term salinity reduction to support flora and fauna species in Lake Wellington that are less tolerant to high salinity levels.
≥ 130 GL/month	Sustained flow required to prevent saline intrusion into Lake Wellington.

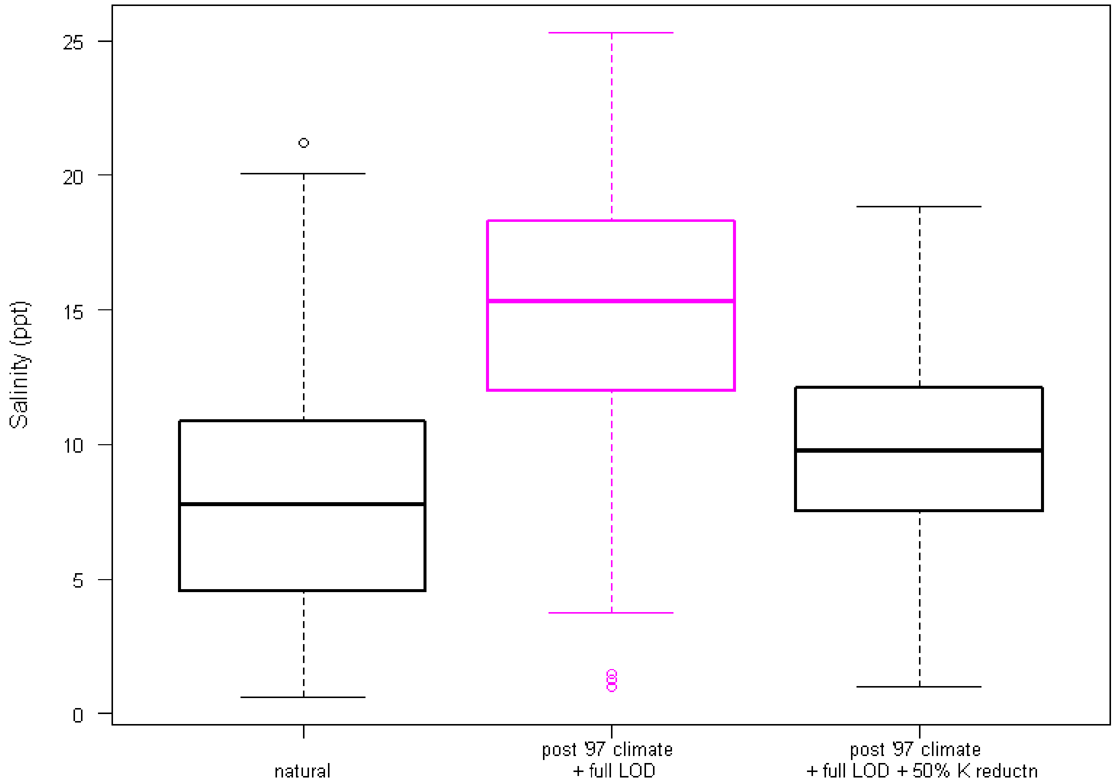
4.3. Construct barrier in McLennan Strait

If less salt was imported to Lake Wellington via McLennan Strait then the overall salinity of Lake Wellington would decrease. It may be possible to reduce saline inflows by constricting flow through the construction of a barrier.

The effect of reducing saline inflows has been considered and was estimated using the salt and water balance model discussed in Section 3. The "k" parameter in equation 1 was modified to simulate a reduction in the effectiveness of salt transport through the Strait.

Figure 14 shows that a 50% reduction in salt transport when applied to case 6 - Inflows under climate change (scenario D) and full level of development - means the salinity regime becomes close to what it would be under natural inflows. Similar results were obtained when considering the other cases.

Note that previous reports have investigated a partial blockage of McLennan Strait to achieve salinity reductions in Lake Wellington and have come up with similar results to those described here. For example, Black (1990) developed a numerical model of salt movement in McLennan Strait and studied various barrage options to decrease high salinity flows from entering Lake Wellington.



- **Figure 15 Effect of decreased salt transport through McLennan Strait on salinity of Lake Wellington (right boxplot shows a 50% reduction in salt transfer through McLennan Strait).**

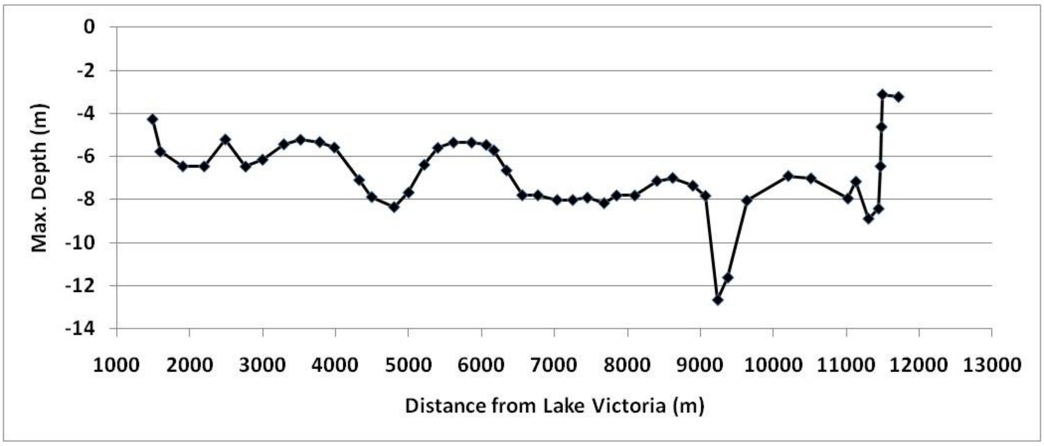
A number of structural intervention options are available to reduce the rate of saline inflows from Lake Victoria into Lake Wellington. Two main options that have been considered for the purposes of this project 1) partial blockage and 2) full (controllable) blockage in McLennan Strait.

There are many examples of locks, tidal barrages, caissons, weirs etc. which have been successfully installed on major rivers around the world including over 45 locks and weirs on the Thames River in the UK. The option of installing a tidal intrusion barrier in McLennan Strait is therefore considered a potential option provided the costs and benefits can be justified.

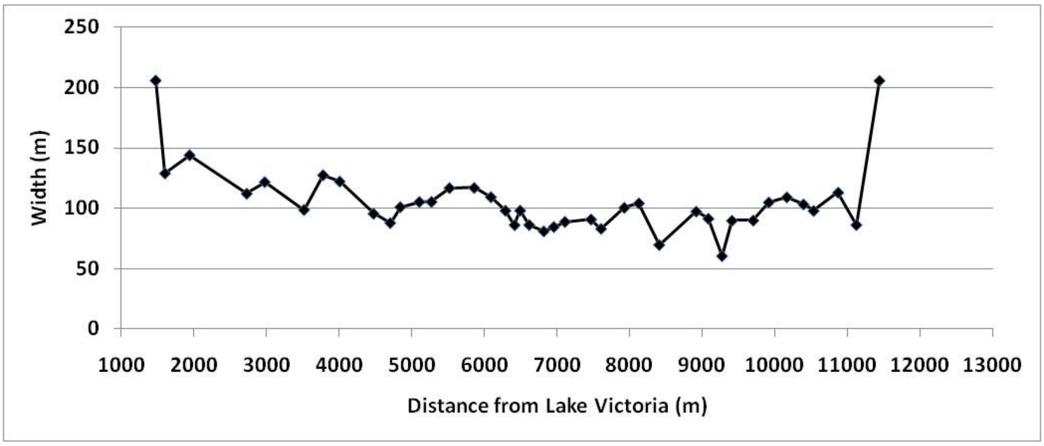
4.3.1. McLennan Strait

As stated previously, McLennan Strait links Lake Victoria to Lake Wellington and is a major conduit of highly saline inflows to Lake Wellington, particularly under low/no flow conditions from the riverine environment.

The width and depth of McLennan Strait are approximately 100 m and 7 m respectively. Profiles are shown in Figure 16 and Figure 17. To restrict salt intrusion, construction of a barrier across the Strait would be required. A preferred location for a structure would be either at a natural constriction point where both the channel and floodplain widths are reduced, or alternatively at the inlet or outlet of the Strait. The floodplain width is estimated to be up to 2500 m.

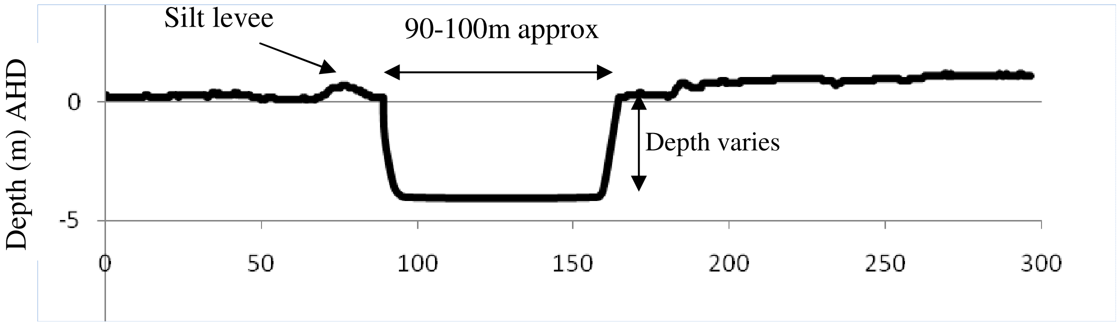


- **Figure 16 Maximum depth profile for McLennan Strait (Hatton et al. 1989)**



- **Figure 17 Width profile for McLennan Strait (Hatton et al. 1989)**

From available LiDAR data, the presence of natural silt levees along the Strait is evident. These have the effect of containing flows within the confines of the Strait until such time that flood waters overtop, breach or go around them (Figure 18).



- **Figure 18 Approximated cross section of McLennan Strait with vertical exaggeration 10 x horizontal (depth subject to confirmation through survey).**

Note: area beneath water level is approximate only and has been manually added for context. Current depths can be confirmed through bathymetric survey. Area above water level has been extracted from available LiDAR data.

Bathymetry data for McLennan Strait including cross-sections is available from Hatton *et al.* (1989) although this is now 20 years old so more current survey data would be required before detailed analysis is undertaken.

The geology of McLennan Strait is understood to be on a Mesozoic basin of sedimentary origin with a Cretaceous estuary (Jenkins 1968). Site specific characteristics of in-situ material would require a geotechnical assessment to determine actual conditions to inform feasibility study for potential installation of a structure.

4.3.2. Partial blockage

A partial blockage could be constructed across the Strait to reduce (but not totally exclude) salt intrusions to Lake Wellington. This would involve the construction of a structure beneath the water level that is keyed into the bed of the Strait as well as both banks. A structure may take the form of a submerged rock chute or a concrete structure that would limit the salt wedge intruding at depth. The crest level would depend on factors such as boat passage requirements and stratification of salt content in the water column. Construction would most likely require the construction of a series of coffer dams to enable materials to be progressively placed across the Strait; however construction from barges may also be possible. A partial blockage would help reduce salt transfer which occur in the Strait, but would have limited benefit in controlling salt balances for overbank flows which occur on the floodplain.

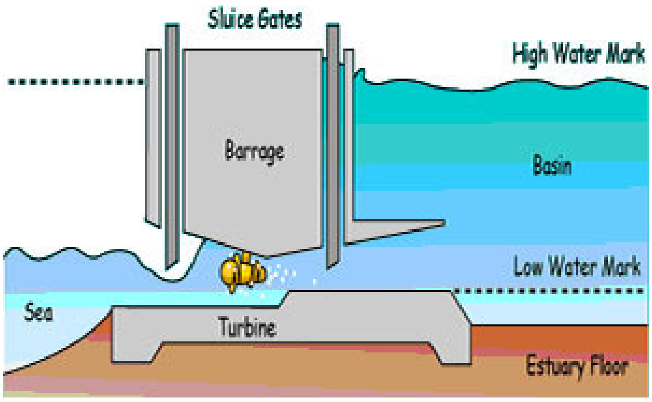
A partial blockage will have the effect of reducing the transfer of salt into Lake Wellington from Lake Victoria, but not as effectively as a full controllable blockage. Benefits of a partial blockage structure are that it is a cheaper option, will reduce the rate and volume of salt transfer while further assessment is undertaken to determine the need and benefits of a full structure. Minimal increase in water levels in Lake Wellington would be expected since water would freely overflow to Lake Victoria when inflows to Lake Wellington exceed evaporation from the Lakes surface.

The cost to build a partial blockage structure is estimated to be in the order of $4M (Appendix B). This estimate is conceptual only and based on the assumption that a rock structure will be built to 1/2 bank full height to convey less saline flows and provide clearance to allow shallow hulled or retractable keeled boats to pass over.

4.3.3. Full blockage

If it is considered desirable to make Lake Wellington ‘fresh’ then a full block would be required to ensure there is no transfer of salt water from Lake Victoria. A structure could be constructed to control flows solely within McLennan Straight i.e. to top of existing bank level or alternatively, above bank height, which would enable floodplain flows to be contained but would require levees to be constructed across the floodplain to contain overbank flows. Construction of levees would have a significant impact on upstream water levels and introduce a range of additional management considerations and likely trigger the need for an Environmental Effects Statement, which would include a number of sub studies including (but not limited to) flood, geotechnical and ecological assessments. Initial estimates suggest that a levee would need to be a minimum of 3.8m in height across the floodplain to ensure that saline water was not passed from Lake Victoria to Lake Wellington during large floods (Appendix A, Appendix D).

Full blockage structure would need to be keyed into the bed of the Strait as well as both banks and extend up to and above the design flood height. As mentioned above, to minimise salt transfer in large flow events would require construction of a levees that tie in with the structure so as to prevent overbank flows bypassing the barrier in the Strait. A full blockage barrier would likely take the form of a steel and concrete structure such as a variable caisson, tidal barrage or buoyancy barrage along with a levee that crosses low lying floodplain area adjacent to McLennan Strait. The floodplain width is approximately 2.5 km wide, likely to be close to saturation at most points so this would require careful construction planning. An example of the form that a barrier may take is shown below in Figure 19, Figure 21 through Figure 23. To provide flexibility in management of water and salt levels, a structure could have multiple compartments each one of which could have adjustable segments or gates (either undershot or overshot) and adjustable crest levels. These types of structures are often associated with gates in canal locks to allow boat passage or for management of hydroelectricity generators. Construction could most likely occur off-site with the main components being individually floated into place before being fixed by compression or pneumatic means. A coffer dam arrangement would be needed to construct bed control and anchor points.



- **Figure 19 Example of a mechanical tidal barrage**

(Source: www.mutr.co.uk/images/barrage1.jpg&imgrefurl)

An estimated cost to build a structure of these types would be at least $20M. This cost estimate is conceptual only and based on the assumption that, maximum clearance is required to allow various keeled boats to pass over, the Strait has width of 100m, and that no/minimal flow of saline water is desirable into Lake Wellington from Lake Victoria. The cost of a structure could vary significantly depending on the type of preferred structure.

In addition to this, the cost of constructing levees over the floodplain is estimated to be in the order of $19.5M (Appendix C and D). The cost will depend heavily on the depth and bedding material that is present at the site.

Collectively, the cost of a full blockage together with levees is therefore likely to be in the order of $40M.

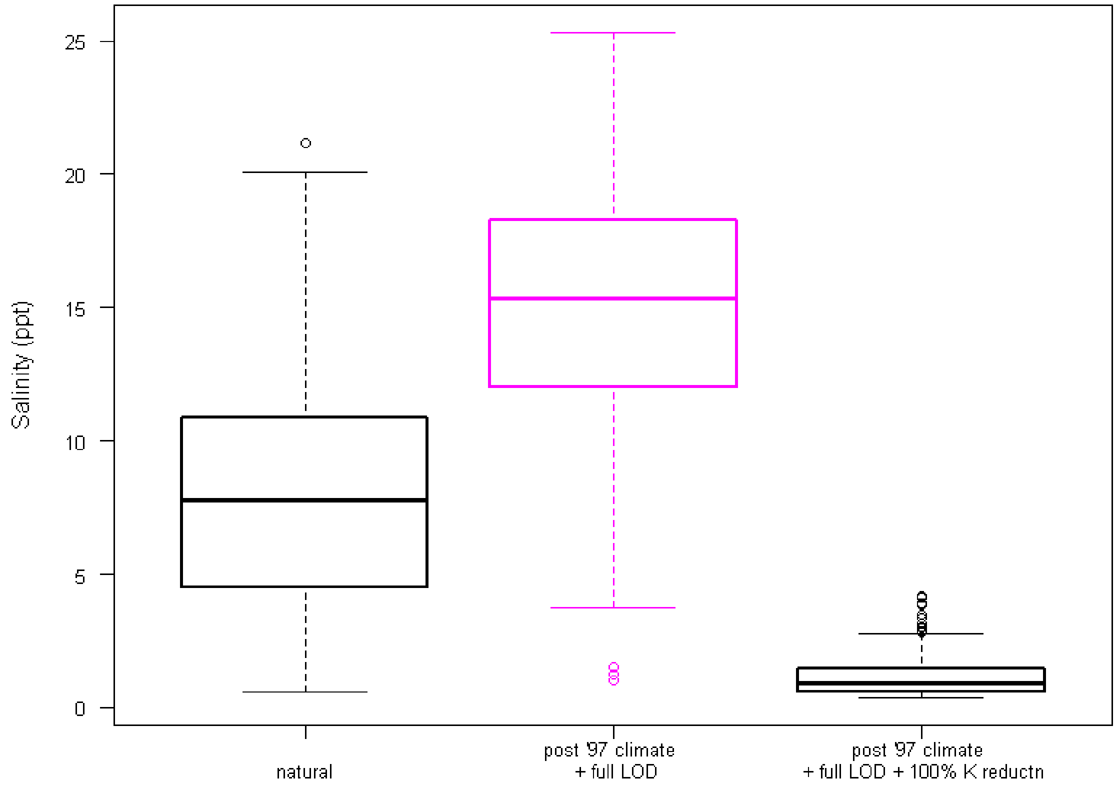
A major benefit of a full blockage or controllable structure are that crest levels can be adjusted, the rate of salt transfer into Lake Wellington from Lake Victoria can be minimised and boat passage can be accommodated. Control features to gauge flow, salinity and water depth could be incorporated together with solar or hydro power to regulate chambers and adjustable crest levels. A potential disadvantage of a full barrier is that water levels in Lake Wellington and further upstream could be substantially increased if the crest level is fixed i.e. not controllable and this coincided with high flows from the Latrobe, Thomson and Avon Rivers. A preliminary estimate of flooding depth during a probable maximum flood is noted in Appendix A.

A full barrier will change the salinity regime in Lake Wellington. If a barrier eliminates salt input to Lake Wellington via McLennan Strait the salinity will be greatly reduced. An example for a complete barrier combined with a scenario of post 1997 climate and full level of development is shown in Figure 20. Under this scenario Lake Wellington salinity would still be variable but likely to be less than 5 ppt with a median of 0.9 ppt. Salinity varies because there is some evaporative concentration when freshwater inflows cannot supply all the evaporative demand. The Lake level will also drop during these times. Currently, water flows in from Lake Victoria to maintain the level of Lake Wellington.

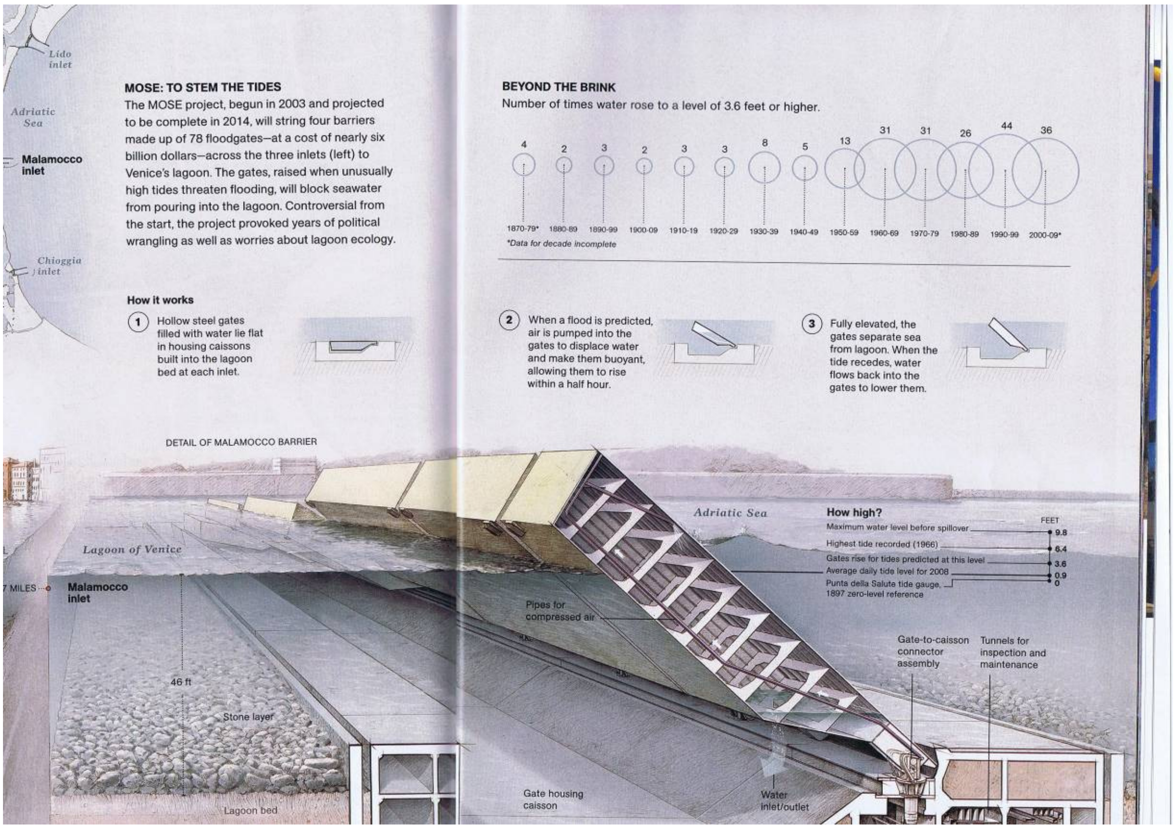
Full blockage of McLennan Strait i.e. construction of a barrier across the strait and integrated levee across the adjacent low lying areas is a high risk option.

- There are high risks associated with project approval because assessment of environmental impact is likely to require a public process and substantial reporting by experts
- Political risks are high because the project would be likely to face substantial opposition
- Environmental risks are high because the ecological impacts of permanently freshening Lake Wellington are uncertain
- Construction risks are high because of the need to build in wet conditions both within the McLennan Strait and across the adjacent wetlands
- Flood risks would need to be considered because the blockage would increase upstream flood levels during times of significant inflow.

In short, the implementation of this option is difficult and even if it can be successfully built, the outcome is uncertain and there are likely to be major unintended impacts on a range of third parties.

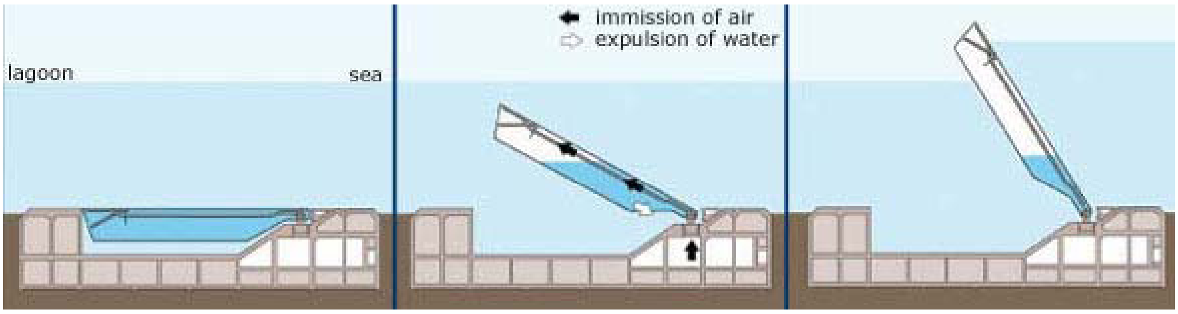


- **Figure 20 Effect of decreased salt transport through McLennan Strait on salinity of Lake Wellington (right boxplot shows a 100% reduction in salt transfer through McLennan St i.e. complete barrier)**



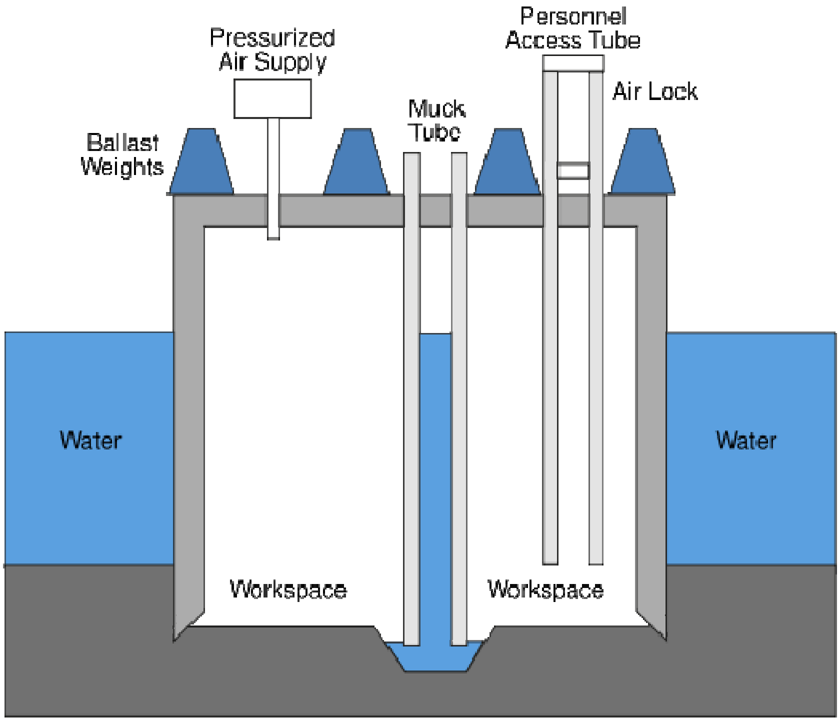
- **Figure 21 Malamocco controllable tidal barrage in Venice**

(Source: National Geographic 2009)



- **Figure 22 Storm surge caisson barrier in the for the Malamocco and Lido-San Nicolo Inlets**

Source: http://www.smit.com/sitefactor/public/downloads/pdf/Marine%20Projects/Venice%20flood%20barrier.pdf



■ **Figure 23 Section view of a mechanical tidal barrage**

(Source: http://commons.wikimedia.org/wiki/File:Caisson_Schematic.svg)

4.4. Construct individual barriers for fringing wetlands

Constructing barriers is an option for preventing further increases in salinity levels and environmental degradation in the fringing wetlands (Section 2.2). It does not provide a solution for managing salinity in Lake Wellington but may be a viable compromise if options to manage salinity in Lake Wellington are not feasible.

Engineering structures that restrict inundation from Lake Wellington are already in place in some of the fringing wetlands, including:

- Two barriers between Lake Coleman and Lake Wellington (Figure 24);
- The breach between Lake Wellington and the eastern section of Clydebank Morass has been filled by a rock wall. However, there is still likely to be inundation from the Lake to both sections of the Morass via Diamond Creek; and
- Engineering structures between the Latrobe River and Down Morass (Figure 25).

(a) Eastern structure

(b) Western Structure

- **Figure 24 Barriers between Lake Coleman and Lake Wellington**

- **Figure 25 Barriers between Latrobe River and Dowd Morass**

Additional engineering structures could be installed to control flow from Lake Wellington and the adjoining rivers between:

- Avon River and western Clydebank Morass;
- Sale Common and the Latrobe River;
- Dowd Morass and Lake Wellington; and
- Upgrade of structures between Lake Coleman and Lake Wellington.

The complex interplay between the catchment processes and lake processes and relative influences over inundation in the wetlands will need to be considered when designing and installing additional structures. For example, an engineering structure between Dowd Morass and the Latrobe River will need to control the salinity levels in the wetland with one way structure between the wetlands and Lake Wellington to allow flushing during flood events without letting saline lake water back in (SKM 2003b).

The watering regime of these wetlands and the potential to use structures to protect and enhance wetland environmental values, and make best use of any available water is discussed in Tilleard and Ladson (2009). The WGCMA is currently investigating a range of options for improved watering structures. Water supply to wetlands is being considered as part of the Gippsland Sustainable Water Strategy.

4.5. Manage for a changing environment

There has been a gradual shift in the types of ecological communities associated with Lake Wellington and the fringing wetlands from freshwater to estuary and salinity tolerant communities. This is due to a combination of factors including the permanent opening of the Lakes Entrance, as well as reduced freshwater flows because of, irrigation, urban supply and farm dams. Further stressors on freshwater flows and marine water intrusion will come from a changing climate. It is predicted that the combined effect of climate change and future water use may reduce inflows to Lake Wellington by 68% (Tilleard et al. 2009). Indicative results from modelling are that this will increase median salinity in Lake Wellington (Section 3). Climate change is also resulting in sea level rise which has the potential to increase the salt inflows through McLennan Strait.

Given the complex combination of factors that influence salinity in Lake Wellington and the fringing wetlands a combination of management options is required to respond to changing climatic and environmental conditions. Management solutions such as minimising the reduction of freshwater inflows and constructing several smaller barriers to increase control of saline waters would help reduce the rate of change and possible degradation of those areas of greatest ecological value, the fringing wetlands.

5. Recommendations

Five management options for managing salinity in Lake Wellington and the fringing wetlands have been considered:

1) Do nothing - salinity is likely to continue to increase under climate change and increased level of development.
2) Increase inflows by reducing extractions
3) Decrease import of salt through McLennan Strait by a constructing partial barrier
4) Prevent saline inputs to Lake Wellington by completely blocking McLennan Straight with a large barrier that prevents all flows from Lake Victoria entering Lake Wellington i.e. attempt to make Lake Wellington fresh
5) Construct works and provide a specific watering regime to allow management of fringing wetlands separately from the main lake and provide freshwater to lower reaches of inflowing rivers at critical times.

The complex nature and combination of factors that influence salinity in Lake Wellington and the fringing wetlands is likely to require a range of management options to achieve the desired conditions. Management solutions such as providing specific inflows to wetlands and constructing several smaller barriers to increase control of saline waters is likely to be the answer to reducing the rate of change as well as protecting those areas of greatest ecological value, namely the fringing wetlands.

Table 5 Summary of management options

No	Management option	Effect on Lake Wellington Salinity	Comment
1	Do nothing	Further increases in median salinity and variability	Lake Wellington will become increasingly Marine. Fringing wetlands will be threatened
2	Increase freshwater inflows	Likely to move salinity regime closer to natural conditions i.e. reduce median salinity and decrease variability. Provides some protection of current wetland values	Not robust to climate change: under climate change Lake Wellington becomes increasingly saline even if water extractions are reduced
3	Construct barrier(s) in McLennan Strait	Salinity is reduced in magnitude and range compared to the cases without this option	Requires hydrodynamic modelling to confirm effectiveness
4	Complete barrier across McLennan St	Lake Wellington is fresh most of the time	High risk, high cost option with uncertain benefits
5	Works and flows to protect fringing wetlands	No effect on Lake Wellington salinity	Aims to protect the most valuable ecological features of the Gippsland Lakes from degradation With a much lower water requirement than option 2. Robust to climate change.

6. Knowledge and data gaps

The main knowledge gaps that exist relate to how the flora and fauna of Lake Wellington will respond to increased salinity, and data required to undertake feasibility assessment for construction of either a partial or full barrier across McLennan Strait.

It is conceivable that increased salinity could increase the environmental values of Lake Wellington (although it would threaten the values of the fringing wetlands). Monitoring of Lake Wellington Environmental values as salinity changes should be considered.

Additional knowledge gaps include:

- Bathymetry data for McLennan Strait including cross-sections is available from Hatton *et al.* (1989) so is now over 20 years old. Detailed Bathymetry would assist in conceptual design of a barrier. Availability of current and accurate survey would enable a hydraulic model to be developed to simulate flow conditions and verify geomorphic processes such as deposition, incision etc. through the Strait. This would be useful to quantify the risk of a structure being undermined or outflanked. It would also provide valuable information to cost the value of potential works.
- The geology of the subsurface as well as the abutments/banks will have a major impact on the on the cost of construction. The characteristics of in-situ material may be available from existing reports however a geotechnical assessment of actual conditions would be required as part of any detailed design being undertaken.
- Detailed hydrodynamic modelling would be required to confirm the performance of a partial barrier in McLennan St. Black (1990) provides guidance on what is required.

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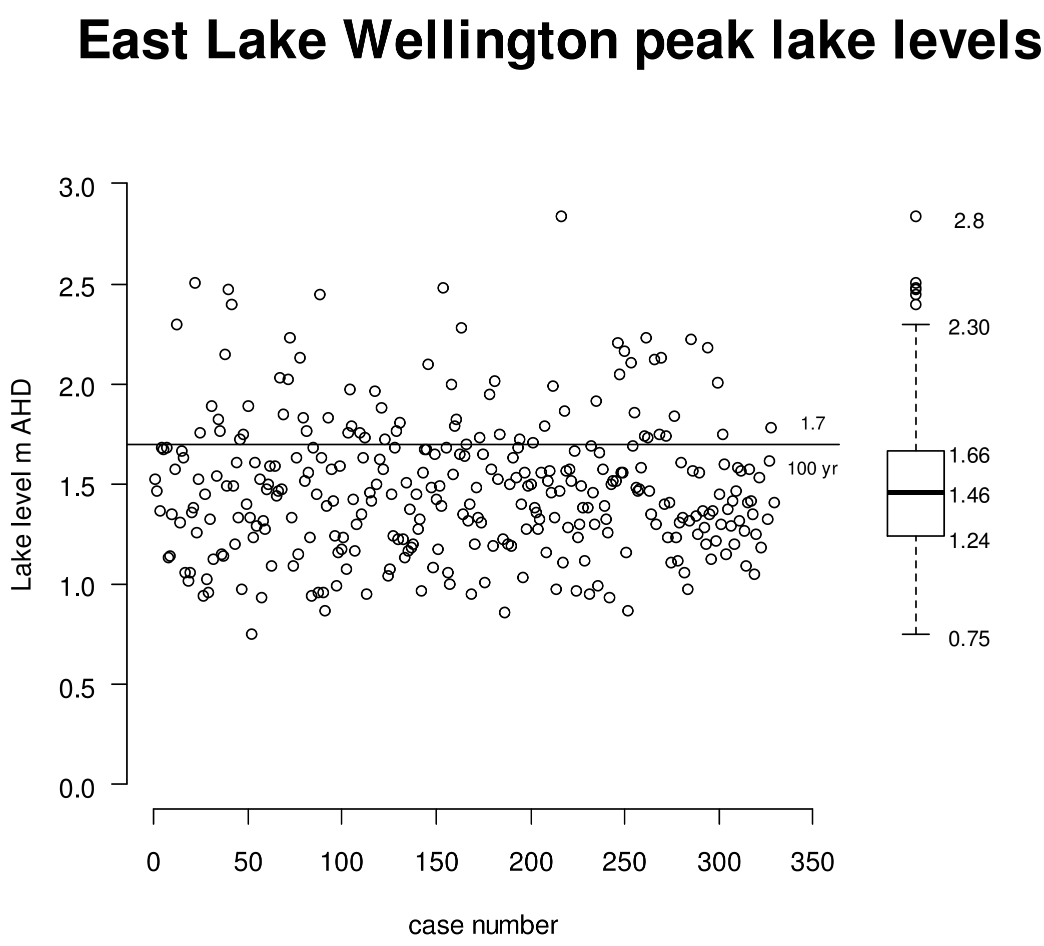
Appendix A Estimation of flood levels at McLennan St

Peak lake levels on the east and west side of McLennan Strait during floods can be estimated from the flood modelling undertaken by Tan (2004). Tan modelled over 3000 floods with the largest 320 shown in figures 1 and 2.

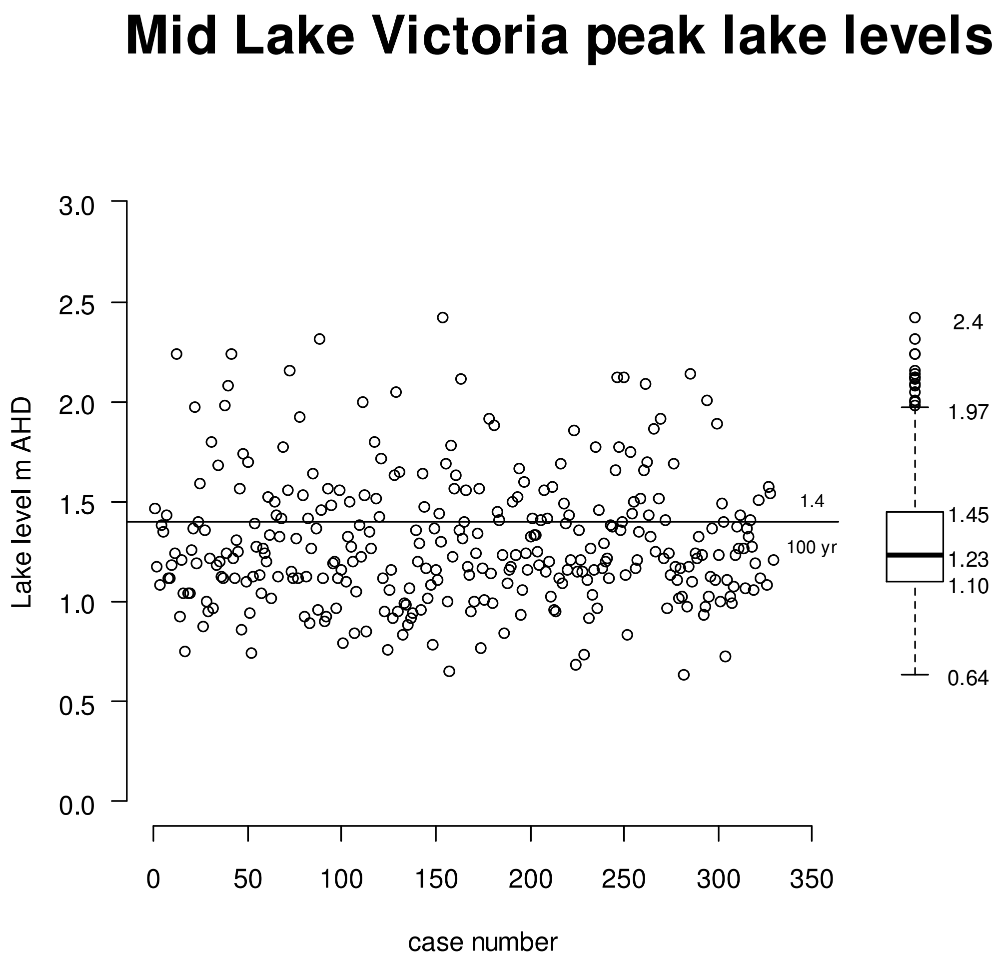
The highest peaks are 2.8 m AHD in east Lake Wellington and 2.4 m in mid Lake Victoria.

To avoid salt transport to Lake Wellington, a barrier at McLennan St would have to be at least 2.4 m high, plus an allowance for freeboard (0.6 m) and an allowance for sea level rise (0.8 m) giving a total height of 3.8 m.

An approximate calculation was undertaken to check the performance of such a structure during a Probable Maximum Flood (PMF) using the method in Grayson et al. (1996). A spillway 2500 m wide (i.e. the whole width of the proposed barrier across McLennan St), along with flow through the Strait would limit to depth of flow above the crest height to approximately 3 m. Therefore the total flood height would be about 6.8 m AHD. A thorough hydraulic analysis would be required to confirm these levels.



- **Figure 26 Flood levels at East Lake Wellington. The 100-year flood level is 1.7 m AHD**



▪ **Figure 27 Flood levels in mid Lake Victoria. The 100-year flood level is 1.4 m**

Appendix B Cost Estimate: Construction of Partial Structure

ITEM	DESCRIPTION - PARTIAL ROCK BARRIER	NO.		PRICE	
		Qty	Unit	Rate ($)	Amount ($)
1	Preliminaries - contract establishment	1	Ea.	$150,000	$150,000
2	**Partial Rock barrier**				
2.1	Supply and transport of D_{50} 350mm rock	7000 4375	Tonne m^3	$70	$490,000
2.2	Construct coffer dams	6	Ea.	$250,000	$1,500,000
2.4	Supply & placement of geofabric (GCL)	6000	m	$10	$60,000
2.5	Trim banks and place rock	1536	Hrs.	$150	$230,400
2.6	Access road materials	1	Ea.	$50,000	$50,000
2.7	Construct access roads	160	Hrs.	$150	$24,000
		$2,354,400			
3	**Site supervision**	640	Hrs.	$180	$115,200
	Subtotal				$2,619,600
	Contingency (50%)				$1,309,800
ESTIMATED COST OF PARTIAL ROCK STRUCTURE (Ex GST)					**$3,929,400**

Appendix C Cost Estimate: Construction of Levee Across Floodplain

Item	Description - Construction of 3.8m levees across floodplain (excludes cost of barrier in McLennan Strait)	Quantity	Unit	Rate $	Amount $ (ex GST)	
1.	**Preliminaries**					
1.1	Contractor Admin, Establishment/Disestablishment, QA, Permits and Approvals	1	Item	$150,000	$150,000	
	Sub-Total					$150,000
2.	**Foundation Preparation**					
2.1	Site strip incl. trim and compaction desposited on site	80,000	m2	$5.80	$464,000	
	Sub-Total					$464,000
3.	**Embankment Construction**					
3.1	Bulk earthworks - cut to dispose off site (Assume clay)	3,200	m3	$20	$64,000	
3.2	Supply and placement of clay core (Imported)	30,000	m3	$25	$750,000	
3.3	Supply and Placement of Fine Filter (Imported)	6,000	m3	$75	$450,000	
3.4	Supply and Placement of Shoulder Fill	187,500	m3	$32	$6,000,000	
3.5	Supply and Placement of Rip Rap (Imported)	80,000	m3	$70	$5,600,000	
3.6	Placement of Topsoil	5,400	m3	$5	$27,000	
	Sub-Total					$12,891,000
4.	**Inlet/Outlet Works**		Note		N/A	
	Sub-Total					$0
5.	**Reservoir Preparation**		Note		N/A	
	Sub-Total					$0
6.	**Spillway Construction**		Note		N/A	
	Sub-Total					$0
7.	**Miscellaneous Works**					
7.1	Access Roads	1	Item	$75,000	$75,000	
7.2	EES assessment	1	Item	$300,000	$300,000	
7.3	Flood study	1	Item	$100,000	$100,000	
7.4	Dam risk assessment	1	Item	$100,000	$100,000	
7.5	Dam risk assessment	1	Item	$100,000	$100,000	
7.6	Feasability study	1	Item	$100,000	$100,000	
7.7	Dam risk assessment	1	Item	$100,003	$100,003	
7.8	Geotechnical assessment	1	Item	$200,000	$200,000	
7.9	Site Survey	1	Item	$50,000	$50,000	
7.10	Hydrogeological assessment	1	Item	$150,000	$150,000	
7.11	Traffic management	1	Item	$150,000	$150,000	
	Sub-Total					$1,425,003
	DIRECT COST (DC)				$14,930,003	$14,930,003
	Contingencies					
	CONTINGENT COST (CC)				30%	$4,479,001
	TOTAL CONSTRUCTION COST					$19,409,004
	Land Acquisition		Note		Excluded	
	COST OF LEVEES					$19,409,004
	ESTIMATED COST TO CONSTRUCT LEVEES (SAY)					**$19,500,000**

Appendix D McLennan Strait: Schematic of levee across floodplain