GIPPSLAND LAKES
FLOOD LEVEL MODELLING PROJECT

FINAL REPORT

CEAH Report 01/04
June 2004

Centre for Environmental Applied Hydrology
University of Melbourne

1963-

Gippsland Lakes Flood Level Modelling Project

Bibliography
ISSN 0 7340 3029 0

Centre for Environmental Applied Hydrology Report Series

This report presents the results from an extensive investigation into design flood level throughout the Gippsland Lakes. The work was undertaken as part of an Australian Research Council "Strategic Partnerships with Industry" project (C00106804) supported by the East and West Gippsland Catchment Management Authorities, the Gippsland Coastal Board, Deptartment of Sutainability and Environment's Floodplain Management Unit, Gippsland Ports, Lawson and Treloar Pty, Ltd. and the Wellington Shire.

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West Gippsland Catchment Management Authority:
Gippsland Coastal Board:
Gippsland Ports:
D.S.E. Floodplain Unit:
University of Melbourne:
Science Team:

Keywords:
Modelling (Hydrological, Hydrodynamic, Statistical)
Design Floods
Stochastic methods
Estuaries

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Preface

The Gippsland Lakes Flood Level Modelling project is a very challenging multi-disciplinary problem. Flood levels in the Lakes are the joint result of a number of complex physical processes, which are to varying degrees dependent on one another. This is a type of problem that has received little attention in the past, primarily because of its difficulty. The work undertaken in this project is breaking new ground, not just for flood-ocean problems, but also for joint probability work more generally. Many of the methods developed have the potential to be applied to a wide range of applications.

The project team has been particularly diligent in collating data sets from different sources, particularly with respect to the collation of survey information and time series data. These data have proved to be of suitable accuracy and extent for the requirements of the project. These data will also be a useful resource for the region for some time to come.

The project assessed several different approaches to establishing design flood levels. The approach adopted for deriving the final recommended levels is appropriate and the manner in which the different components are integrated is consistent with (and in part at the forefront of) current international research. The project team is to be commended for this accomplishment. The adopted approach takes full advantage of the available data – indeed, it is considered that the manner in which the data has been assembled and analysed represents the most comprehensive, thoughtful, and well-integrated treatment of a complex hydrological problem that could be practically achieved given our current levels of understanding and computing power.

Overall, this panel concludes that the estimates of flood levels for the Gippsland Lakes with annual exceedence probabilities of 1 in 20, 1 in 50 and 1 in 100 years provide a sound and defensible basis for planning.

May, 2004

Executive Summary

This project presents a new method for estimating "exceedence probabilities" for flood levels in estuaries and coastal lagoons, using the Gippsland Lakes as a case study. The Gippsland Lakes are a large system that has been subject to major floods, affecting fringing communities. Inundation of estuary fringes is a complex problem resulting from the interaction between river flows, tidal and sea level effects, and, if the estuary is large, local wind-effects within the estuary itself. These various physical influences are not independent. To determine the probability of a particular flood level occurring, as is necessary for design purposes, these various factors have to be combined in a manner that accounts for their partial dependence. There are no standard methods for doing this from Australian or International practice. In some places around the world, there may be sufficiently long data records to use direct measurements to determine exceedence probabilities for flood levels. This is not the case in Australia.

Current Australian flood planning policy requires that the 1% Annual Exceedence Probability (AEP), more commonly known as the 1:100 year event, is used for design purposes. Present levels for the Gippsland Lakes were established by the State Rivers and Water Supply Commission using information from a large flood in 1952, but accompanying their estimation was a call for a more thorough analysis of the influences on Lake water levels, in order to establish a more rigorous and defensible methodology. This project provides such a methodology and applies it to the Gippsland Lakes.

An overview of the methods and testing is provided in this report and an extensive list of supporting scientific publications provide details on various aspects of the approach used. The techniques required to undertake this work are at the cutting edge of statistical hydrology and consequently a thorough scientific review was needed.

On two occasions throughout the project, a team of Australia's leading experts in statistical hydrology and hydrodynamics reviewed the project to provide independent assessment of the rigour and quality of the work. The first review focussed on the proposed methods and ways of testing the results. The second review focussed on the implementation of methods and interpretation of the results. Their overview is presented as a preface to this report, where it is noted that:

> *"…..The approach adopted for deriving the final recommended levels is appropriate and the manner in which the different components are integrated is consistent with (and in part at the forefront of) current international research. The project team is to be commended for this accomplishment. The adopted approach takes full advantage of the available data – indeed it is considered that the manner in which the data has been assembled and analysed represents the most comprehensive, thoughtful, and well-integrated treatment of a complex hydrological problem that could be practically achieved given our current levels of understanding and computing power.*
>
> *Overall, this panel concludes that the estimates of flood levels for the Gippsland Lakes with annual exceedance probabilities of 1 in 20, 1 in 50 and 1 in 100 years provide a sound and defensible basis for planning."*

The final results from the project are new estimates for the 1 in 100, 1 in 50 and 1 in 20 year flood levels for the Gippsland Lakes. The results are based on methods that use available meteorological and river flow records. They therefore do not account for any future influences such as may be caused by climate change. The results are summarised in Table A below.

Table A Recommended 1% (1:100yr), 2% (1:50yr) and 5% (1:20yr) annual exceedence levels for the Gippsland Lakes

	Lake Wellington	Loch Sport (L.Vic.)	Mid Lake Victoria	Lake King (North)	Paynesville	Metung	Lakes Entrance
5% (1:20yr)	1.7	1.4	1.4	1.6	1.5	1.5	1.3
2% (1:50yr)	2.0	1.7	1.7	1.8	1.7	1.8	1.6
1% (1:100yr)	2.2*	1.9	1.9	2.0	2.0	2.1	1.8

* This is for the centre of Lake Wellington. For the land around Lake Wellington near the river inputs, levels should be higher to account for the gradients between the rivers and the lake. The current 1% level of 2.5m is consistent with the work undertaken in this project for the land around Lake Wellington near the river inputs.

In addition to the AEP water levels, there are a number of outputs from this project that will be useful to local agencies and other researchers. These include:

- The Digital Elevation Model: The DEM is being used already by several agencies and is available on CD or can be downloaded over the web.
- A large data base of climatic and hydrological information. This includes over 100 years of daily rainfall data presented as 5x5 km grids over the whole area, flows for all the rivers, daily and hourly (where available) wind and atmospheric pressure; Lakes Entrance water level observations; derived coastal ocean level and 25 years of water levels for locations through the Lakes simulated from the forcing data.
- A hydrological model for each major river that provides daily flows (tuned to provide accurate flood flows) for the period covering the rainfall data (over 100 years).
- A calibrated hydrodynamic model of the Gippsland Lakes and statistical methods which can be used as a basis for studies into the effects of climate change on water levels in the Lakes. The methodology is ideal for a comprehensive assessment of climate change scenarios because it integrates the effects of changes in rainfall, sea level, atmospheric pressure and wind, however detailed information on expected changes in these forcings would be needed.
- The suite of models would also be useful for studies into altered entrance conditions and potentially real-time forecasting of flood levels.

Background

Australia's population is clustered around the coastal fringe and development pressures on estuary areas are steadily growing. Inundation of estuary fringes is a complex problem resulting from the interaction between river flows, tidal and sea level effects, and, if the estuary is large, local wind-effects within the estuary itself. These various physical influences are not independent. Weather conditions that cause floods tend to cause particular ocean-level responses and may be associated with particular wind events. It is therefore not appropriate to determine, for example, the 1 in 100 year water level in an estuary based on combination of the 1:100 year flood in all in-flowing rivers along with the 1:100 year wind event and 1:100 year high water-level in the ocean. This would result in an estuary water-level with a different (much lower) probability of occurrence than 1:100 years and, if the value were used for design purposes (1:100 year levels being required by Government as a basis for prescribed flood levels for planning), would entail a large additional cost to the community. Of course, underestimating design flood levels has potentially large effects also. In order to realistically define the probability of inundation, the relationship between all of these factors, as well as the hydrodynamic behaviour of the estuary itself, must be taken into consideration in a physically realistic manner.

The Gippsland Lakes Flood Modelling Project (GLFMP) was established through the Australian Research Council's "Strategic Partnerships with Industry" scheme, which includes funding from the Federal Government ($170,000) and local organisations (approximately $335,000). It is a joint effort by the University of Melbourne's Centre for Environmental Applied Hydrology, the East Gippsland Catchment Management Authority, Gippsland Ports, Lawson and Treloar Pty. Ltd., the Gippsland Coastal Board and the West Gippsland Catchment Management Authority. Additional funding was provided by the DSE Floodplain Management Unit and the Wellington Shire.

The Gippsland Lakes are one of the largest coastal lakes systems in Australia. The catchments contain major industry including the Latrobe Valley brown coal and power generation plants, extensive harvesting of native and plantation timber, a paper mill, agricultural development including irrigation, horticulture and grazing, as well as major water storages. Since 1889 an artificial entrance to the sea has been maintained. The Lakes also contain internationally listed (RAMSAR) wetlands, are one of Victoria's premier tourist destinations and host the largest fishing fleet in southern Australia. Several of the region's large towns are in close proximity to the lake waters edge and significant flooding of commercial and residential properties has occurred, most recently in June 1998 when large parts of Lakes Entrance and Paynesville were inundated.

The key objective for the GLFMP is to establish new design flood levels (and Annual Exceedence Probabilities – AEPs) for the Gippsland Lakes that account for the range of physical influences on water levels in a large estuarine system. These physical influences include streamflows, wind and ocean levels. There are no methods presently available for combining the effects of these influences in a comprehensive manner so a significant amount of new science was developed through this project. The present design flood-levels for the Gippsland Lakes are interim estimates derived via an analysis of historical flood-levels, with some empirical allowance for wind and tidal effects (SRWSC, 1981). Accompanying their estimation was a call for a more thorough analysis of the influences on Lake water levels in order to establish a more rigorous and defensible methodology.

The project developed and tested several generic methodologies for application to any estuary system, but based the application on data from the Gippsland Lakes. The Lakes are an ideal case study because they are a relatively complex series of water bodies, yet there is good data available to establish and test the new methodologies. The new methodologies developed are conceptually quite simple, but their application was complex and required several new methods in stochastic data generation to be developed. The details of these developments are outlined in a series of journal publications and reports (see Bibliography). This report presents the overall concepts applied, providing an overview of each of the main project components and their key assumptions, and then present results, interpretations, overall conclusions, and a consideration of uncertainty.

Overview of the Gippsland Lakes

The Gippsland Lakes, have a water surface area of almost 400km^2 and a contributing catchment area of over 20,000km^2, and are one of the largest coastal lagoon systems in Australia. Since 1889, an artificial entrance to the Lakes has been maintained.

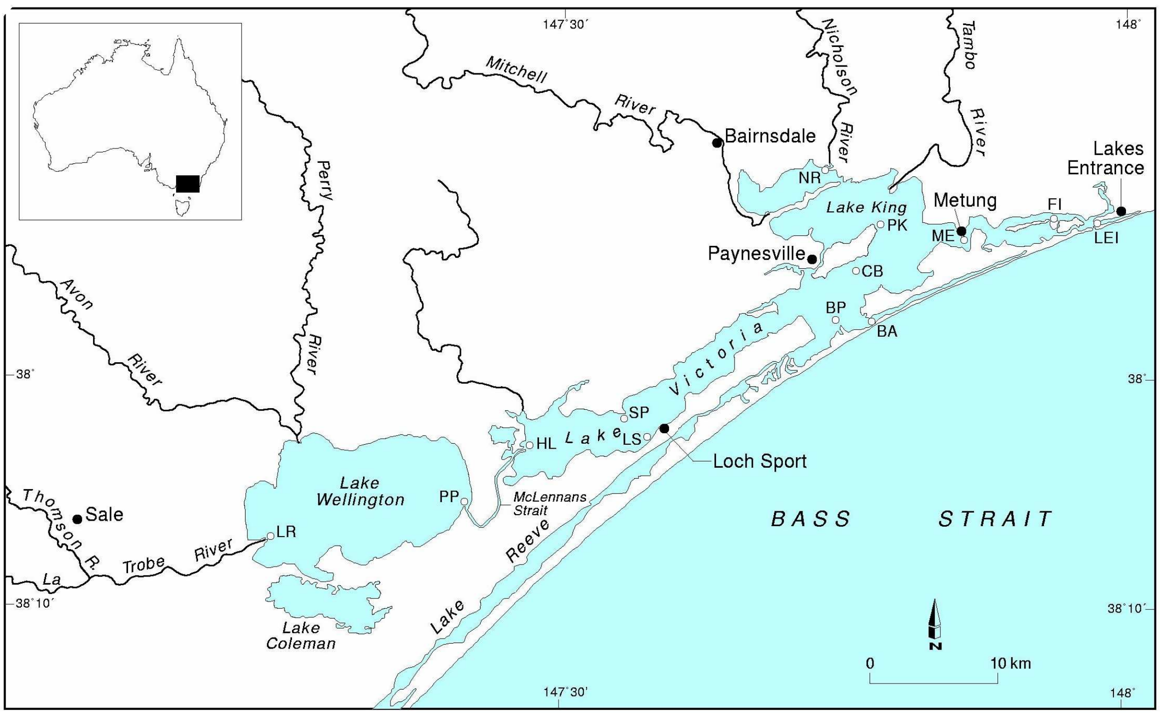

Figure 1 Location map of the Gippsland Lakes. The points marked within the Lakes are the locations of water level recorders that were used for model development and testing.

The Gippsland Lakes system comprises three major water bodies interconnected with complex channels, six river basins that are large enough for floods not to occur simultaneously, a maximum wind fetch of about 50 km exposed to frequent strong wind events, and a connection to the Bass Strait subject to significant coastal ocean level variations, due to atmospheric effects and coastally trapped waves. Tan et al. (2002, 2004e) studied the water level fluctuations in the Gippsland Lakes and the following summarises the general magnitudes and time scales of the main forcings:

(a) Streamflow is the dominant forcing affecting the extreme water level in the Lakes. For example, the June 1998 flood was dominated by the eastern rivers with a combined peak flow of 320,000 ML/day and resulted in the highest water level in the last 25 years at 1.3 m AHD (sustained above 0.8 m AHD for 3 days) inside Lakes Entrance (mean water level is approx. 0.1m). The event coincided with a low pressure system that began to move into the region about 3 days before with concurrent high winds of about 10 m/s. Streamflows change on the order of hours to days, but take the order of days to pass through into the Lakes system.

(b) Prevailing wind directions are west/southwest and east/southeast and these exert a significant influence on the lakes level. In December 1998, a westerly storm event recorded wind exceeding 20 m/s during the passage of a low pressure system of almost 990 hPa. The event resulted in maximum water level difference of over 1 m across Lake Wellington, and also between Hollands Landing (HL) and Fraser Island (FI) in Lake Victoria-Lake King. Wind events occur on time scales of hours to days. Wind, can also cause wave set-up at the entrance to the Lakes, temporarily raising mean offshore water levels for periods of several hours to a day.

(c) Low frequency coastal ocean level fluctuations are highly correlated with Mean Sea Level Pressure (MSLP) and penetrate as far up as Lake Wellington with some attenuation. The low frequency signals are due to the combined effects of inverse barometric pressure (BP variations are up to 50 hPa ~ ±0.25 m) and coastal trapped waves. Attenuation of the signal through the Lakes system is moderate, e.g. a 0.1 m drop was detected in Lake Wellington, but with 2 days lag, in response to a 0.2 m drop in ocean level over a 5-day period. High frequency coastal ocean level variations comprising astronomical tides with a spring range of about 0.8 m attenuate to about 0.3 m just inside the entrance and diminish quickly along the lagoon to less than 0.05 m some 20 km upstream from the entrance. Tides are thus important in the eastern part of the Lakes system. Coastal ocean levels change on time scales of hours to weeks in response to MSLP changes on time scales ranging from days to weeks, storm surges from hours to days and the predominantly semi-diurnal tides.

Overview of Project Methodology

The approach to estimating the AEP of high water levels involves two key steps. The first is to build a well-tested model of the estuary that captures the key hydrodynamics of the system. The model must accommodate the incoming river flows, represent the "throttling" effects at the coastal ocean boundary and simulate the wind effects within the estuary. The model must be complex enough to represent the key components of the system dynamics, yet simple enough to allow for computationally intensive Monte-Carlo type simulations[1]. A hydrodynamic model (SOBEK, Verwey, 2001) was developed and tested against several data sources (McMaster et al., 2003): high-resolution water level measurements (Grayson et al., 2000), 25 years of historic data (Tan et al., 2002; Tan and Grayson, 2002b, also described below), and available (but limited) information from historic flood events. The hydrodynamic model and testing are described in detail in McMaster (2004).

The second key step is to use this model to predict water levels throughout the estuary system and use these to estimate AEPs for design purposes. This second step was approached in three different ways, each based on a different set of underlying assumptions. These three approaches were then compared and contrasted to define both the optimum approach, and to gain more confidence in setting the final design levels. These three methods are outlined in the following section.

Because of the complexity of the various tasks and numerous judgements and decisions that had to be made regarding the methodologies, as well as the likelihood that at some stage in the future we

[1] Monte-Carlo simulations are where a model is run many times with sets of input information that have the same statistical properties. In the context of this project, these sets can be thought of as representing possible flood and weather conditions over a long period of time – i.e. not exactly what was observed historically, but what **could** have been observed, given the statistical properties of the recorded data.

may be called on to defend the work, an ongoing process of peer review was undertaken. There were three forms of peer review:

- publication of research work in refereed conferences and journals;
- involvement of independent experts in supervising postgraduate work on the project; and
- formal review of methodologies by independent experts on two occasions. This review panel concluded that:

"….The approach adopted for deriving the final recommended levels is appropriate and the manner in which the different components are integrated is consistent with (and in part at the forefront of) current international research. The project team is to be commended for this accomplishment. The adopted approach takes full advantage of the available data – indeed it is considered that the manner in which the data has been assembled and analysed represents the most comprehensive, thoughtful, and well-integrated treatment of a complex hydrological problem that could be practically achieved given our current levels of understanding and computing power."

The details of the reviews and outcomes are discussed later in this report.

Summary of key project components

Hydrodynamic model of the estuary system

The hydrodynamic (HD) model was established using WL Delft's SOBEK modelling package. SOBEK is a combined one and two-dimensional modelling package that has been used in Australia for the last few years. Figure 2 shows the schematisation of the one-dimensional model. This model represents the major rivers flowing into the Lakes, the Latrobe, Avon, Mitchell, Nicholson and Tambo Rivers. The major lakes, Lake Wellington, Lake Victoria and Lake King are also represented, along with the narrow channels joining them, McLennans St. and McMillans St.. The entrance to Bass Strait is also represented. Being a one-dimensional model (to keep computational loads manageable), additional links were required to represent floodplain areas (Figure 2).

Cross sections were distributed along the length of each branch, to represent the geometry of each of the flow paths (white dots marked in Figure 2). These cross sections were derived from a comprehensive digital elevation model developed in the project (see below and in Wealands et al., 2002). Bed friction was applied separately to each reach section, with values chosen to represent the effects of different types of vegetation or substrate. This was one of the factors used in the calibration process. A wind field was applied to the entire model domain to represent the effects of wind "set up". This can be a significant source of water level variation. For example in the major wind event of Boxing Day 1998, water level variations of around 1 m occurred due to strong W/SW winds. This wind field was defined by a wind speed (m/s) and direction derived from nearby meteorological stations (Tan and Grayson, 2002b), and boundary data including discharges for the inflow points and water levels for the downstream boundary, was provided as time series. All these time series were based on either historical or stochastically generated data, depending on the approach being used (as discussed later in the report).

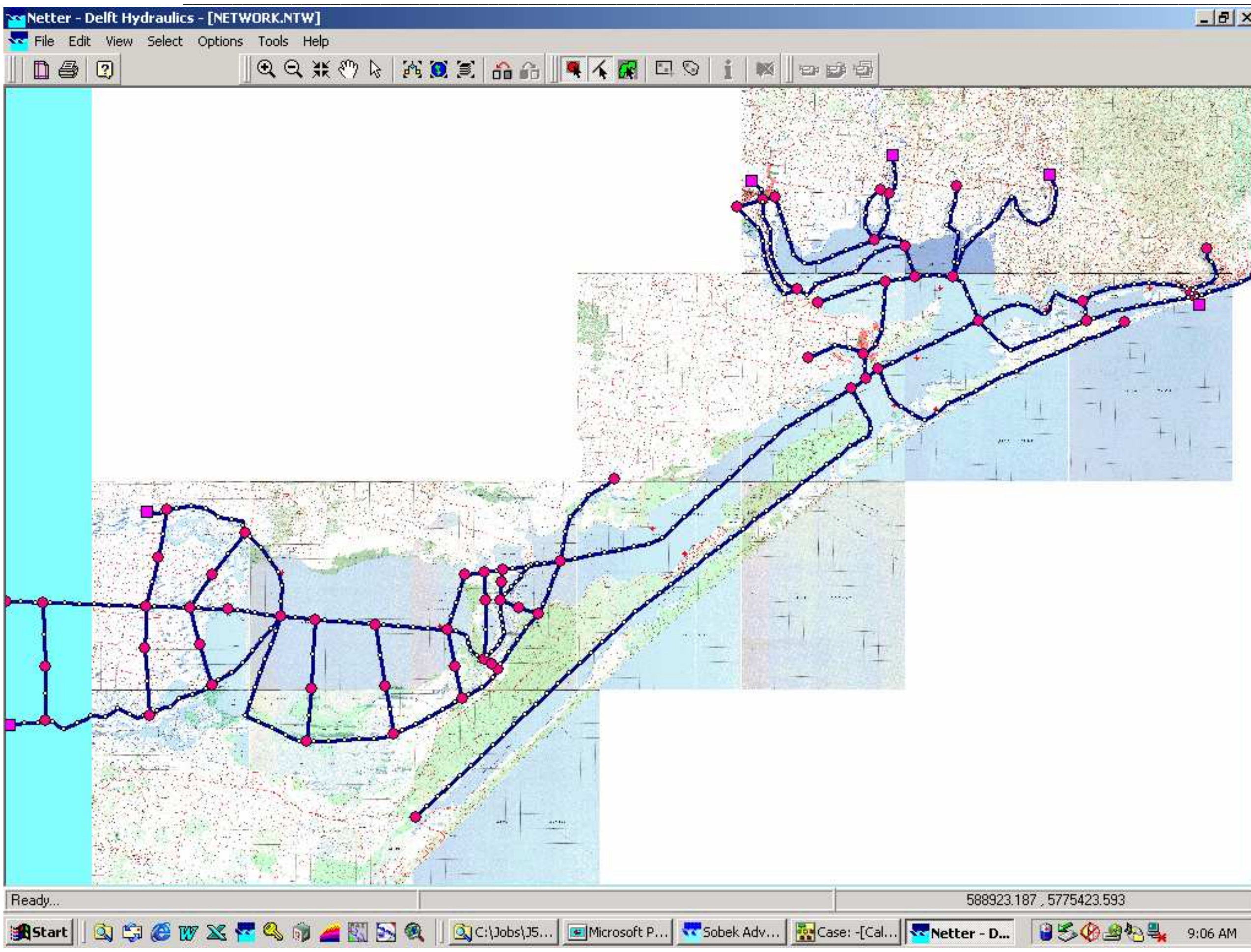

Figure 2 – One-dimensional model schematisation.

Model Calibration

The model was calibrated using data from a number of water-level recorders within the Lakes system that have been in place since late 1998 (Grayson et al., 1999). These water level recorders were installed and have been maintained by The University of Melbourne. These data consist of a time series of water levels referenced to AHD, and include a number of low to medium-sized flood events, and a major wind event on Boxing Day 1998. In addition to these water level recorders, Gippsland Ports maintain a water level recording gauge on Bullock Island. This has been recording water level data since the 1970's. Over the past 30 years there have been several other water level gauges within the lakes system for shorter periods. Only one set of data has been used, from a gauge operated by Thiess, in Lake Wellington, at the mouth of the Latrobe River. Other data has not been used as it was either unavailable, too short a record, or unreliable.

Twenty-five years of historic forcing data (described in more detail below) was used for model testing. Given the objectives of this project being to estimate 1% AEP levels accurately, the emphasis of the testing was on floods and high water-level events. Although the real entrance to the Lakes is dynamic (due to changing dredging over time and changes throughout an actual flood), the modelling approach required a single optimum set of model parameters to be defined that worked best "on average", since the history of actual entrance details is not available. The final set of parameters gave excellent results with over 90% of the highest 100 levels between 1976 and 2000 being within 10cm, and a mean bias of only 3cm. Major floods (over 1m AHD) are estimated within 10 cm, and in general the shape of the flood peaks was consistent with records. The 1998 event was the most difficult to reproduce, although the peak level (which is the key output required from this study) was still within 14cm. There appears to have been significant change in the entrance bathymetry during the 1998 event, probably caused by the major sand build up inside the entrance that was present at the time, but the entrance bathymetry appeared to recover to pre-event configuration some days later. Figures 3 and 4 show the results at Lakes Entrance (LEI) for the 1998 strong wind event and the 1990 flood wind event respectively, illustrating that the model is capturing the dynamics of extreme conditions well (McMaster et al., 2003).

The 25 year model run also produced estimates of water levels throughout the Lakes system. Points were chosen to represent levels across Lake Wellington, the western end of Lake Victoria (i.e. around Loch Sport), the eastern end of Lake Victoria and Paynesville, the northern and southern parts of Lake King, around Metung, and at Lakes Entrance.

Additional HD model testing was conducted to resolve a number of issues that are important to the later Monte-Carlo (MC) simulations (McMaster et al., 2003). These issues included :

a) the difference between 1-dimensional and 2-dimensional representations of the Lake Wellington/McLennan Strait and Entrance areas. *(to ensure that the 1-D simplification would be robust and accurate under the more extreme conditions experienced during MC simulations);*

b) the number of days of simulation needed to define an independent "event". *(this was important because the MC simulations are based on a continuous series of large events which require certainty that these events do not interact);* and,

c) the time resolution needed for stochastic forcing data. *(to ensure that the generated data sequences would be at fine enough resolution to represent to influence extreme levels in the Lakes system).*

It was found that the 1-D simplification necessary to make the duration of each HD model run acceptably short did not significantly alter levels at the locations where output information is being extracted. Fifteen days was found to be sufficient to ensure independence of events, and data was required to be provided on an hourly time step.

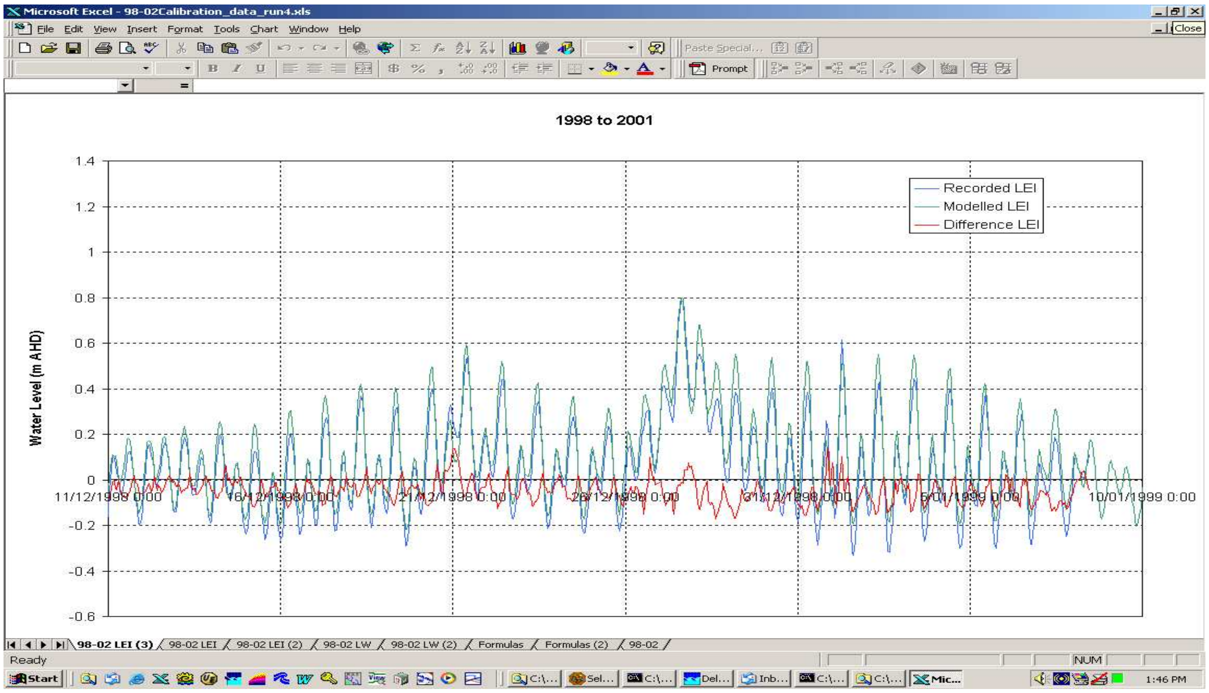

Figure 3. Simulated and observed water levels at Lakes Entrance (LEI) during the 1998 wind event. flood event

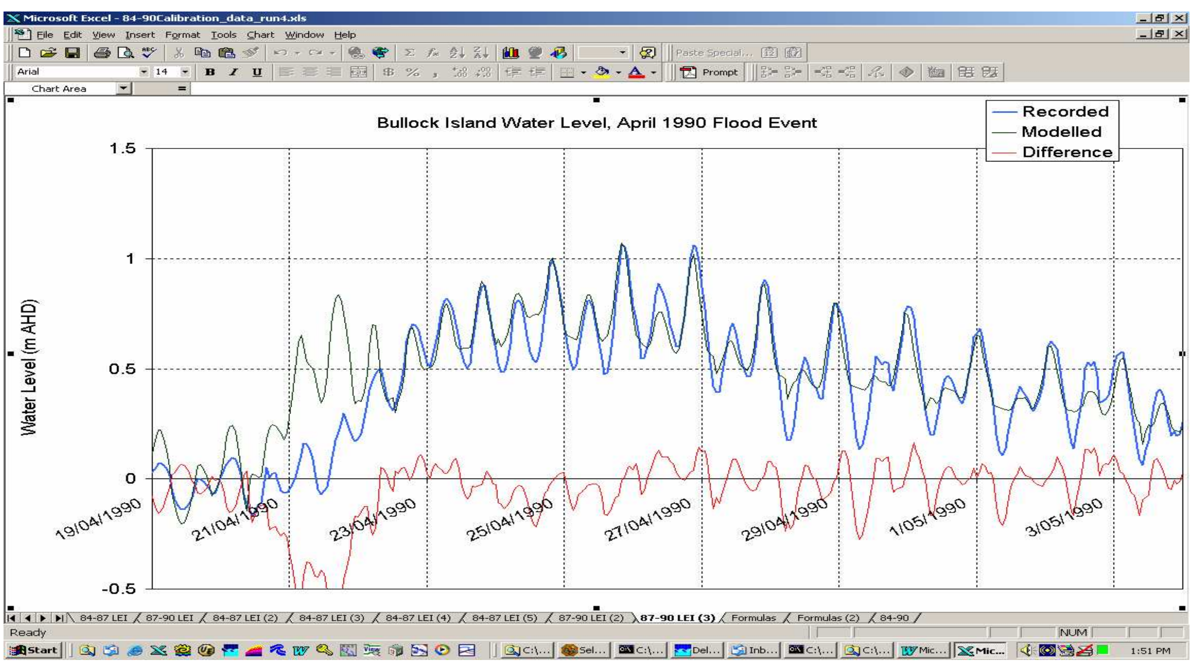

Figure 4. Simulated and observed water levels at Lakes Entrance (Bullock Island) during the 1990

Estimation of AEP levels

As discussed earlier, three different approaches to computing AEP levels were developed, based on different input data sets. In this section each of these methods is described and their advantages and disadvantages are discussed.

Method 1. Fitting of frequency distribution to observed (and simulated) lake level data;

This is the simplest approach and is basically the technique by which flood levels are derived for rivers where there is a reasonable length of observations. It consists of plotting peak water level data in a standard manner, fitting a curve (from a range of recommended distributions), and extrapolating to define a 1%AEP level (with uncertainty bounds).

There are three problems with this method in the context of this project. The first is that only 25 years of water level observations at Lakes Entrance are available. This does not preclude use of the method, but makes the uncertainty bounds large (of the order of +/- 0.5 m for the level at Lakes Entrance). This is too large to be of direct use for revising planning levels, nevertheless it does provide an "expected value" and so serves as a starting point for comparison. The second problem is that levels are required for many points around the Lakes, not just at Lakes Entrance where observations are available. This problem is overcome by using the calibrated hydrodynamic model and 25 years of forcing data (river flows, wind and ocean levels) to simulate levels for these locations, and then plot the data as if they were observations and extrapolate as is done with the data from Lakes Entrance. The third problem is that analysis of historical rainfall and streamflow data indicates that the last 25 years was considerably drier with fewer floods than over the last 100 years. This means that estimated levels based on the last 25 years will be underestimates of the long-term expected levels. This point is illustrated in Figure 5 which is a plot of 1 day, 3 day and 7 day AEP flows for the Mitchell River at Glenaladale. It shows that particularly the 3 day and 7 day total for the past 25 years are much lower than over the long term.

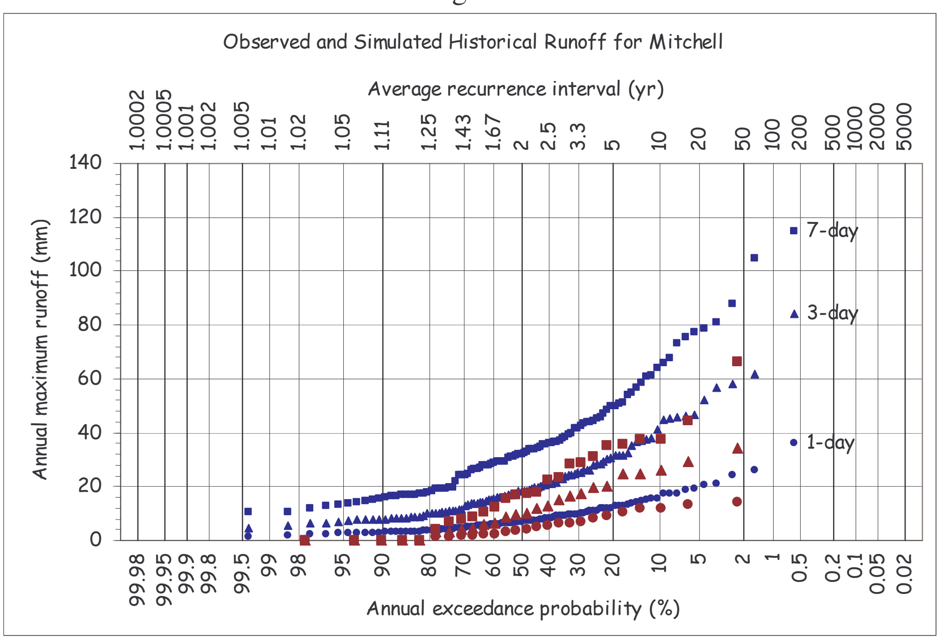

Figure 5. AEP plot of 1 day 3 day and 7 day flows for the Mitchell River at Glenaladale. Brown points are based on data from 1975 to 2000 and blue points are based on long term data.

Method 2. Stratified Monte-Carlo analysis based on joint flood frequency distributions of streamflow forcings.

This method was originally raised as a possibility in the initial stages of the project, but not fully explored because of limitations in jointly maintaining streamflow and other forcing factor correlations. The review panel however recommended that this method be pursued since it was expected to provide a somewhat independent check of other methods. The method is based on choosing a dominant river and undertaking a regional flood frequency analysis to enable extrapolation of flows, based on the maximum amount of data. All other inputs and forcing data are then related to this dominant input, based on functions derived from the observed correlations (eg. Tan et al., 2002). Monte-Carlo sampling is then used to select a value of flow from the distribution of flows from the "dominant input", and the other forcing derived from the data-driven functions. These input data series are then run through the HD model to give water level estimates throughout the Lakes.

The main assumptions are:

(i) that high lake levels are dominated by river floods;

(ii) that a particular river for each of the western (into Lake Wellington) and eastern (into Lake King) inputs can be chosen as dominant; and

(iii) that the relationships between the dominant input and other inputs/forcings are consistent (i.e. there is limited stochastic component to the preservation of correlations between the different forcings).

The implementation of this method proved to be substantially more difficult than was originally envisaged by the review panel. This method is fully described in Chiew et al., (2004). The method results in estimates based on "western dominant" and "eastern dominant" floods. Clearly the levels in Lake Wellington are primarily controlled by floods in the Western rivers, but high levels in Lakes Victoria and King and through to Lakes Entrance can be affected by major floods from both river systems so it is not clear which set of estimates is most relevant to these regions.

Like Method 1, Method 2 is also based on the last 25 years of data. As the historical rainfall and streamflow in the last 25 years was considerably drier with fewer floods than over the last 100 years, levels estimated by Method 2 based on the last 25 years will also be underestimates of the long-term expected levels. In the final review, the panel recommended that Method 2 not be pursued due to the data limitations and implementation difficulties.

Method 3. Stratified Monte-Carlo analysis based on spatial hydro-climatic simulation models.

This method has been followed since early in the project (Tan et al., 2001, 2004d). It is based on using historical data to define the relationships between rainfall, wind, and atmospheric pressure. These are the basic physical conditions that affect floods and ocean levels. Stochastic data generation methods are then used to provide long sequences of combined forcing data that preserve the statistical relationships between the key physical factors but that represent a much wider range of conditions than recorded historically. Conceptually this method is appealing because the early work on correlations between all the forcings showed that correlations were much stronger between rainfall and wind/ocean level, than were correlations for streamflow (Tan et al., 2001; Tan, 2004d). This is expected since the actual streamflow that occurs due to a weather pattern depends on the antecedent catchment conditions, wheras the rainfall, wind and pressure conditions are more closely related in time.

Detailed descriptions of the methods are provided in Tan (2004) and Tan et al. (2004a,b,c,d,e) and only an overview is provided here. The approach starts by stochastically generating rainfall, and then generating statistically reliable, correlated sequences of wind and ocean level. These input data series are then run through the HD model to give water level estimates throughout the Lakes. This method enables more comprehensive maintenance of all the correlations between forcing variables than does Method 2, but requires two additional modelling steps. Firstly a model to generate spatial patterns of rainfall, and secondly a calibrated runoff model to simulate streamflow from the generated rainfall. The review panel accepted that this method was the most sound conceptually, and that the proposed approach for implementation was appropriate, but noted that the extra modelling steps have the potential to introduce additional uncertainty.

The advantages and disadvantages of the three methods used to generate AEP water level estimates are described in Table 1. Figure 6 illustrates the basic steps in each of the methods.

Table 1. Advantages and disadvantages of the methods used in the project.

Method	*Advantages*	*Disadvantages*
Method 1	Simple to implement Standard methods available for extrapolation	Only 25 years of data available resulting in considerable uncertainty. In addition, last 25 years are drier than the long-term average.
Method 2	Similar to standard flood-frequency methods No modelling of rainfall-runoff required	Based on 25 years of data. Last 25 years are drier than the long-term average. Limited in the way correlations between forcings are maintained Must assume that a particular river in each of the West and East represents dominant floods, and controls peak water levels Moderate computational intensity
Method 3	Preserves correlations between important forcing variables Enables longer historical records to be used, providing more confidence in extrapolated results Is conceptually the most sound	Requires additional modelling steps (although these can be separately tested for accuracy) Computationally intensive

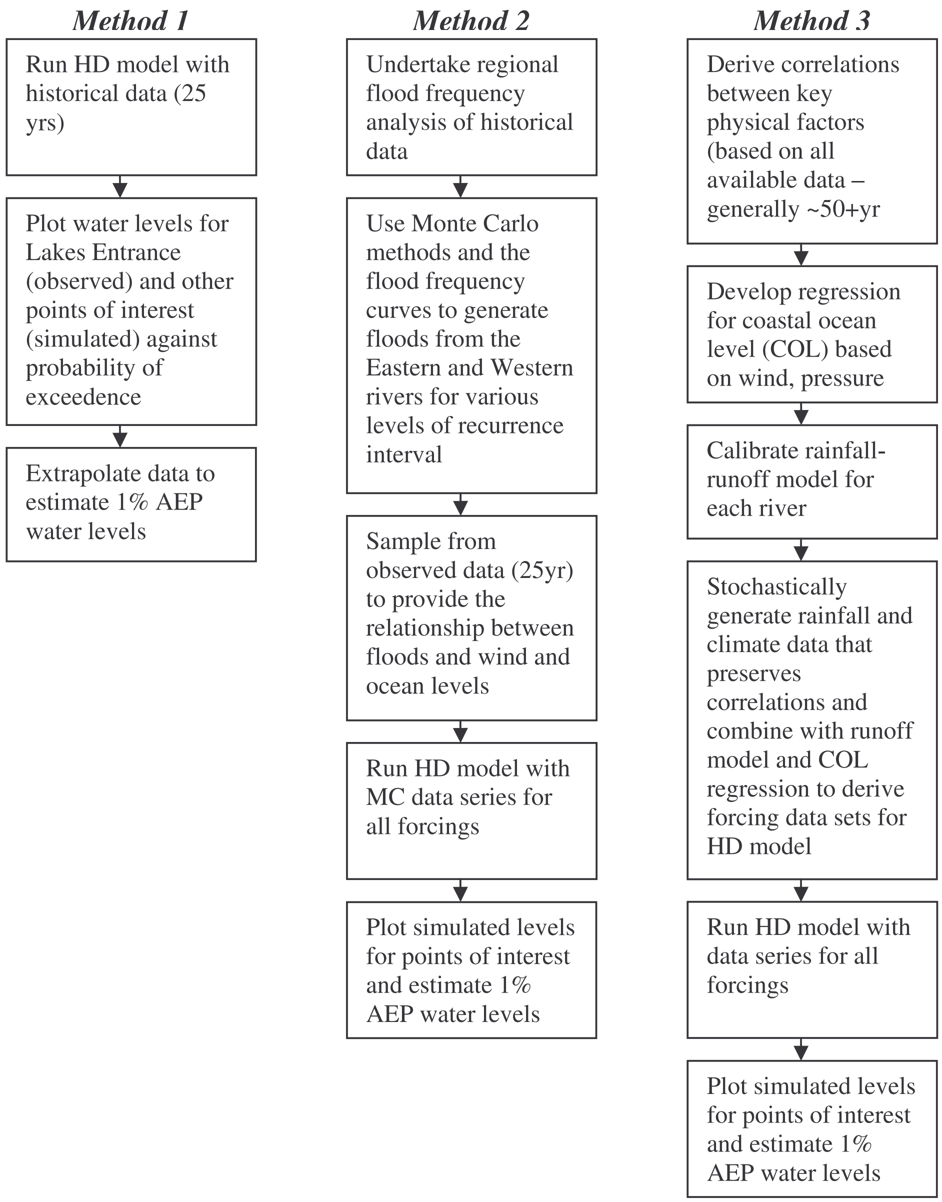

Figure 6. Basic steps in each of the methods.

In the following section, the data collated for the project are described. These data are in themselves an important outcome of the project and are already being used by other groups working in the region.

Data collation and analysis

This section summarises the data on dominant environmental forcings compiled for the project. The correlation analysis was conducted using the daily and hourly data for the 25-year period from 1976 to 2000. During this period, all required data were available. Some data types were available for longer periods. An extensive report details the methods used in compiling, checking and infilling the data sets (Tan et al., 2002).

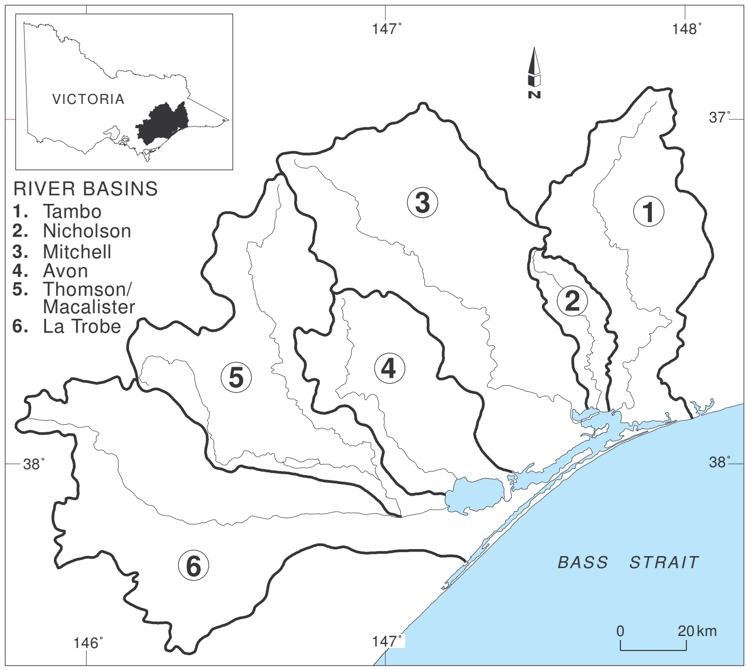

Figure 7 Major river catchments

River Discharge and Precipitation

The six major river basins are shown in Figure 7. The eastern rivers (Tambo, Nicholson, Mitchell) delivering a combined discharge of 1,100 GL/year are essentially unregulated, whereas the western rivers (Avon, Thomson/Macalister, Latrobe) contributing on average 1,600 GL/year are partly regulated except the Avon. Concurrent discharge data are available from 1976 (hourly) and 1961 (daily) to 2000. Precipitation data are available from around 10 daily rain gauge stations and 10 pluviograph stations selected across the catchments to enable a good spatial and temporal coverage. Both daily and hourly data are available for the 25-year concurrent period from 1976 to 2000. Gridded (5 km x 5 km) rainfall data prepared by QDNRM are available for the period 1900-2000.

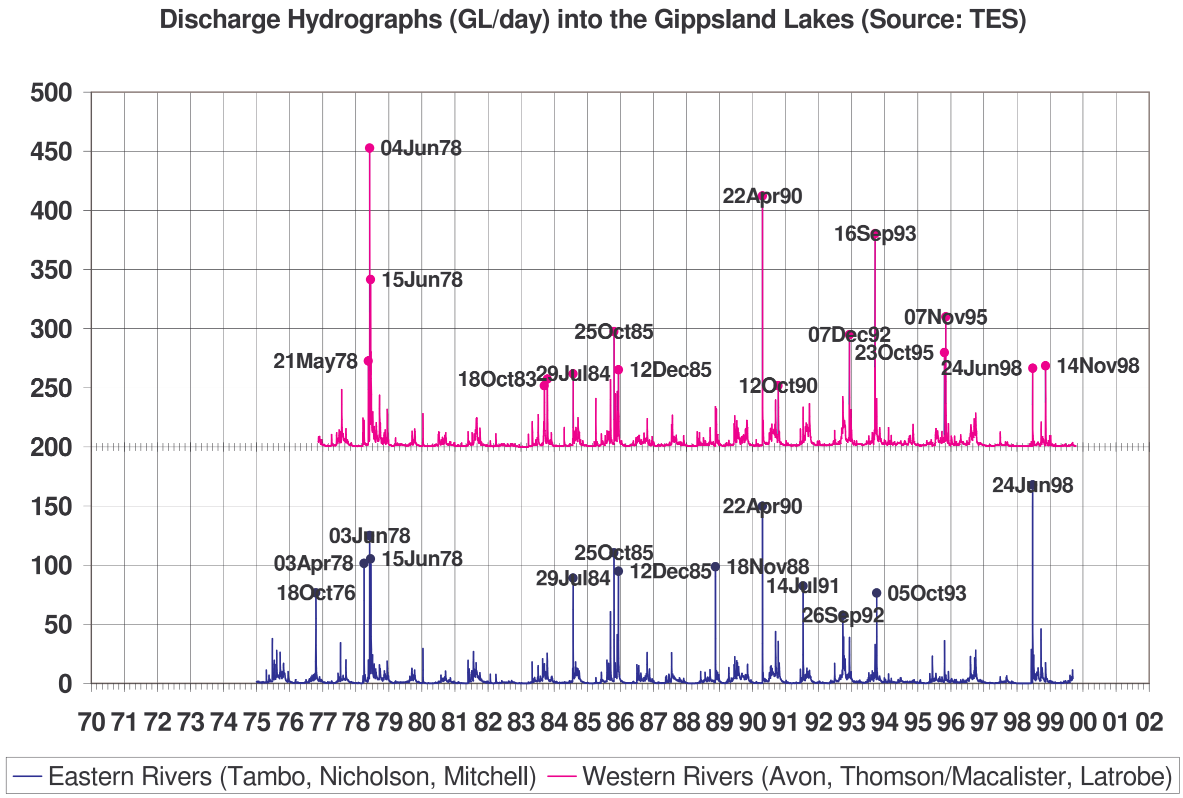

Figure 8. Combined Eastern and Western river discharges, illustrating dates of key floods.

Coastal Ocean Level

The hydrodynamic model requires coastal ocean levels to specify its downstream boundary conditions. These boundary conditions are critical to the levels at Lakes Entrance and as noted above influence levels throughout the Lakes system. Unfortunately, there is no coastal water level recording station in the vicinity of the entrance. The coastal ocean level data are therefore inferred from data gathered at four locations (Figure 8):

(a) A 2-year (July 1997-June 1999) simulated time series just offshore of Lakes Entrance (LEO) from the CSIRO Bass Strait model (Walker & Andrewartha, 2000).
(b) A 3-year (1998-2000) measured times series in the Lakes Entrance inlet channel located at the northern (inner) and southern (outer) locations, separated about 200m apart.
(c) A 23-year (1978-2000) measured time series at the Kingfish B platform (KFB) located approx. 80km offshore of Lakes Entrance.
(d) A 27-year (1974-2000) concatenated measured time series at the New Works Jetty (1974-1995) and Bullock Island Jetty (1995-2000), both located just inside the Lakes Entrance (LEI).

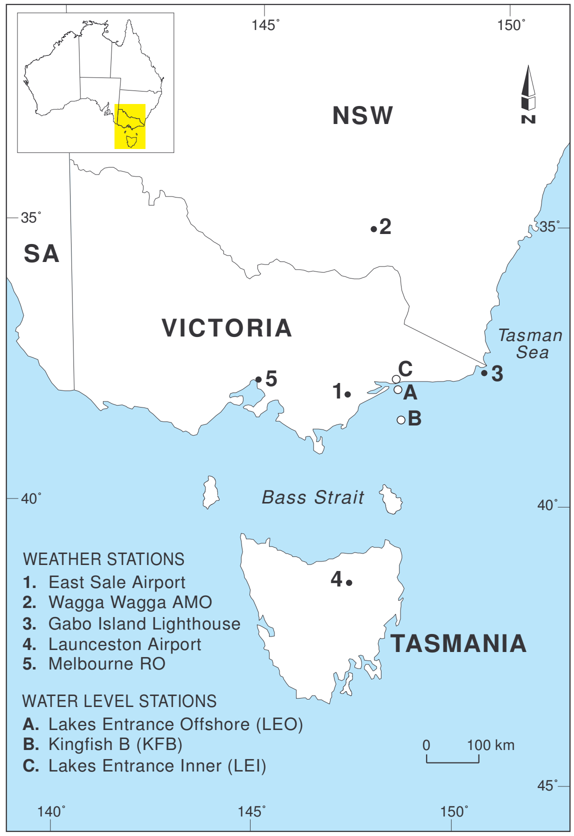

Figure 9 Water level and weather stations

Low frequency water level variations at LEI were obtained by subjecting the hourly water levels to a low-pass filter (Godin, 1972) to isolate frequencies that extend from 0 to 1 cycle/day. This low-pass data gave an estimate of offshore boundary conditions during non-flood conditions. To infill the data during times of significant river flows, periods of overlapping LEI and offshore data were used to develop a regression relationship between low-frequency offshore water level using the following approach (see also Tan and Grayson, 2002a):

(a) Concurrent low frequency signals at the entrance channel, LEO and KFB were compared against the low frequency signals at LEI, in order to ascertain the validity of using the low frequency signals at LEI (except during period of flood water pile-up inside the entrance) to represent those at LEO.
(b) The relationship between the low frequency signals at LEI and the met-ocean forcing variables (e.g. MSLP, along-shore wind stress and SOI) and seasonality were investigated.
(c) The historical low frequency coastal ocean variations at LEO were reconstructed using an empirical approach (multiple linear regression model) with the appropriate met-ocean forcings as the explanatory variables.
(d) The high frequency component of the coastal ocean levels is deterministic and is generated using a tidal prediction package based on the harmonic constants derived from the short-term LEO water level measurement in 1986.

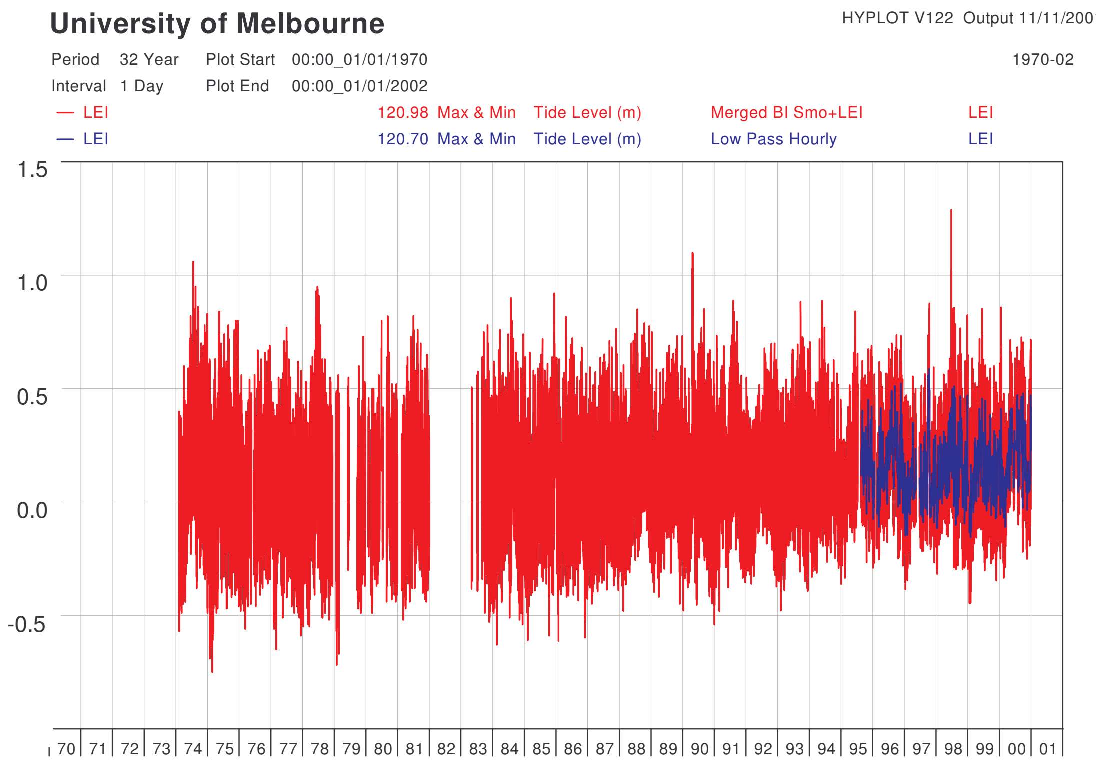

Figure 10. Water levels recorded at Lakes Entrance (Bullock Is., LEI) in m AHD (note there are some periods where the gauge failed).

(e) Historical coastal ocean levels at LEO are then reconstructed by linear superposition of the low frequency water level variations derived in (c) above, the high frequency deterministic astronomical tidal variations obtained from tidal prediction (d) and the wind set-up from (e).

(f) Only the low frequency component of the coastal ocean level variations, which is considered as the stochastic component, is generated in the synthetic data generation phase of the Project. The generated low frequency sequence is randomly superimposed onto the tidal series to form the boundary conditions for the Monte-Carlo simulations.

Wind

10-minute mean wind data are available at the East Sale Airport (Station 1, Figure 8), with hourly data since 1997 and 3-hourly data since 1943. 3-hourly wind data (1965-2000) are also available at Lakes Entrance (Station C). High resolution wind data (1978-2000) at KFB (Station B) was intermittent and used where possible for testing. Wind data is presented as speed and direction, resolved into cross-shore and along-shore directions. Wind stress is also part of the data base.

MSLP and MSLP Gradient

MSLP data were collated from five weather stations in the region (Figure 9). These stations were selected for their good temporal (1957 to date) and large spatial (synoptic) coverage. Both the regional MSLP (Station 1) and the synoptic MSLP gradients (expressed in hPa/100km) in the two major directions (east-west and north-south) are considered in the analysis. All stations have good data resolution with 7 to 8 readings/day, except Gabo Island Lighthouse (Station 2) which has 3 readings/day, thus allowing hourly data to be derived with reasonable accuracy.

Digital Elevation Model

The methods outlined above are designed to provide AEP water *levels*, but to be useful for management applications, these need to be presented as *maps of inundated area.* In addition, the hydrodynamic model requires information on cross-sections of inflowing streams and the broader bathymetry of the Lakes. An accurate digital elevation model of the Lakes and the surrounding area is therefore a critical element of this project and was one of the first tasks to be undertaken. Development and testing of the model is described in Wealands et al. (2002). A brief summary of the main data sources and testing results follow.

As part of work by SRWSC in the early 1980s, floodplain mapping for the Gippsland Lakes region was undertaken using analytical photogrammetry. A map series with 1m contours was produced at 1:10 000, with contour accuracy ranging from 0.25m to 0.5m in height (Personal communication, Photo-Mapping Services Pty Ltd, 10/12/2001, QASCO Victoria, 24/07/2001). This series provides coverage of the Lakes area, including many areas that would not otherwise have had a topographic survey.

The contour and spot height data obtained from the mapping series were the primary data sources for the DEM. They provide high quality definition of terrain shape and absolute elevation, being at a scale where important features are represented (eg. roads, levee banks). For much of the region this is a sufficient data source, however in the townships of Paynesville, Loch Sport, Lakes Entrance and Metung there have been significant changes since the early 1980s. Further terrain data was sourced from local authorities and integrated with the contour data.

For hydrodynamic flood modelling to be successful, accurate bathymetry of the system is also important. Over the past 25 years, there have been hydrographic surveys completed of most parts of the Lakes, with regular surveys conducted near the artificial entrance and main channels. A set of 51 survey maps with scales ranging from 1:500 to 1:25 000 were utilised for defining the bathymetry. A set of 1m contours (digitised from 1:10 000 mapping) for 60% of the Lakes was available in digital form. To improve detail between contours, spot depths were digitised from other source maps. Areas not represented in the contour set consist entirely of spot depths. In areas where no detailed survey data was available, channel descriptions from the Sailing Directions of Victoria have been used to supplement knowledge. All bathymetric surveys used for this study consist of spot depths with an accuracy of 0.1 metres (Personal communication, Victorian Channels Authority, 10/12/2001). In addition, surveys were commissioned by Gippsland Ports to cover the rivers as they enter the Lakes, the Carstairs Bank region, McLennan Straits, Jones Bay, Bandin/Spoon Bay and Lake Reeve.

Rainfall-Runoff modelling

Method 3 required the simulation of streamflow from rainfall data, requiring a rainfall-runoff model to be developed for each of the river catchments. The SIMHYD model (Peel et al., 2001) was used as a basis. This is a daily lumped conceptual model and was set up and calibrated using the daily discharge data available from 1974-2000 at the most downstream gauges in each of the six main catchments. Details of this modelling are given in Tan et al. (2004b) but key points are noted below:

- Because this is a flood study, calibration and simulation of extreme events was emphasised;
- SIMHYD was modified to suit the project requirements and catchment conditions by including internal routing for all catchments, and a snow module for the Mitchell catchment;
- Input data for model calibration and simulation were daily lumped catchment-averaged rainfall (estimated from the SILO 5km x 5km rainfall fields) and mean monthly areal potential evapotranspiration (and temperature for snow simulation for the Mitchell model);
- Instantaneous river discharge data measured at the most downstream locations within each catchment were extracted as mean daily discharge for model calibration;
- The calibrated models were used to simulate (reconstruct) daily runoff from 1901 to 2000 at the 6 catchment outlets into the HD model;
- Appropriate post-processing work was included to account for discharges from downstream of the calibrated gauges and other areas fringing the Lakes, as well as direct precipitation into the Lakes surface.

Summary of Peer Review process

The peer review process for the project was conducted in three stages. Very early in the project, a group of independent experts were convened to discuss the general approaches proposed. The second stage was the most rigorous and occurred at the end of 2002 when all the data preparation and a large amount of the analysis was completed, but there was still the opportunity for some changes should the panel deem this necessary. The third stage was at the end of the project when all results were presented to the panel for final comment. The main outcome of the final review was referred to in the Introduction.

The Review Brief for stage 2 called for the review panel to identify additional analyses that "must" be undertaken to ensure the integrity of the project– all of these were addressed. In early 2004, the review panel was reconvened to assess the final results and how the project team had addressed matters raised in the earlier review. The outcome of this was a full endorsement of the project methodology and implementation, and a confirmation that Method 3 is the only method that is capable of incorporating all of the key influences on water level in a sound manner. Their deliberations are summarised in the preface to this report.

Summary of Results

Table 2 summarises the results for the 5%, 2% and 1% AEP levels for key locations around the Gippsland Lakes using the three estimation methods described above. Where ranges are shown for Method 2, these reflect the levels predicted from the western and eastern dominated simulations. The Table also includes the 1% levels presented in SRWSC (1981) and levels currently used for planning purposes.

Methods 1 and 2 produce generally similar estimates for more common events with Method 2 giving generally higher results for locations closer to the entrance. Method 3 is similar for Lake Wellington but produces higher water level estimates for other sites, with differences generally increasing towards the entrance. The results of Method 3 are the most conceptually sound and defensible approach and therefore form the basis for the recommendations in this report. Method 3 more closely preserves the observed correlations between ocean water levels, wind and flood events than the other methods and does not suffer the biases introduced by approaches that can use only the last 25 years of data (which is a period that was considerably drier than the average for the last 100 years – see for example Figure 5). In Lake Wellington, the correlations between ocean water levels, wind and flood events are not so important because, although ocean level changes do affect water levels in Lake Wellington, it takes 2-5 days for this to occur, while the response of the rivers to heavy rain is much more rapid. Therefore, the coincidence of high river flows and high ocean levels (driven by Low pressure systems and associated winds) is greater closer to the entrance. These effects are not properly captured by methods 1 and 2.

An important result from the modelling is that 1% water levels in the section from Lake King/Metung to Flannagan Is are high compared to Lakes Entrance. This is the result of the "throttling" effects of shallow channels around Kalima that were noted by McMaster et al. (2001, 2003) – i.e. these shallows rather than the entrance itself can be a hydraulic control. These results indicate that the present declared levels for the section Paynesville/Lake King to Flannagan Is., should be raised to 2.0-2.1 m AHD. The 1% level for Method 3 at Lakes Entrance is 1.8 m AHD.

The SRWSC estimates were based primarily on information from the 1952 flood. This was a large event in the western catchment resulting in extreme levels being observed around Lake Wellington. The results of the present study indicate that the 1% levels for Lake Wellington derived from that event are conservative and that the 1% AEP level is more likely to be around 2.2m AHD (rather than 2.5 m). A complicating factor in the SRWSC estimate is that the location of measurement was not on the Lake itself but rather on the flats between Marlay Point and Sale. The actual level in Lake Wellington for the 1952 flood was not measured. Some additional analysis was undertaken to assess Method 3 estimates for water levels close to where the 1952 observations were made. This indicated that there are considerable gradients between the rivers and Lake Wellington and this causes levels in the area affected by river flows of up to 2.5m. This is consistent with observations in 1952.

The values for Loch Sport are for the Lake Victoria side of the town. The modelling did not account for components such as overflow from Merriman's Creek (affecting the Lake Reeve side of Loch Sport) so formal recommendations cannot be made for that side of the town. The current 1% AEP levels are assumed to be the same on both sides of the town.

As noted in the earlier discussion, Method 3 is the most conceptually sound approach. However, the additional modelling steps have the potential to introduce additional uncertainty into the results. This was recognised by the project team and noted by the review panel in their first major review. As a result, a comprehensive set of independent checks on each stage of the data analysis, modelling and data generation, were undertaken and presented to the final review panel meeting. There is no evidence to suggest that the results from Method 3 are biased upward. Each of the independent checks indicated that the modelling and data generation steps produce results that are consistent with the observed distributions from long term data, and the key correlations are preserved appropriately. The consistency of results in parts of the system where correlations between forcing variables are expected to be less significant provide strong support for the lack of overall bias in Method 3. The divergence between the methods towards Lakes Entrance is expected given the observed relationships between COL and floods and the fact that Method 3 preserves these better than the other methods. In addition, it is clear that Methods 1 and 2 will be biased low because the past 25 years of rainfall and streamflow data indicate that the period was significantly drier than over the longer term. As noted earlier, there are problems with the implementation of Method 2 that add uncertainty to the results from that method.

There is a final and completely independent consideration that further supports the use of estimates from Method 3. This is the limited historical observations of flood levels from locations around the Gippsland Lakes. During the 1952 flood event, water levels of 1.8m AHD were measured around Lakes Entrance with at least 3 occasions in the past century with levels around 1.6 to 1.7m AHD. In 1893 and again in 1978, levels of 1.7m AHD were observed around Paynesville. Levels of 1.7 to 1.8 m AHD have been observed on at least two occasions in the past century at Metung. These historic observations are entirely consistent with the results of Method 3. This is illustrated in Figure 11 which is a plot of AEP versus water levels for Lakes Entrance showing the results of Methods 1 and 3, along with a "hybrid" plot that incorporates the historic observations into the data from Method 1.

The information provided in this report and the supporting data sets will enable detailed mapping of expected inundated areas for various AEP levels around the Gippsland Lakes. The production of these maps is beyond the scope of this project, but it is understood will become the responsibility of the local Floodpalin Management Agencies (The East & West Gippsland Catchment Management Authorities).

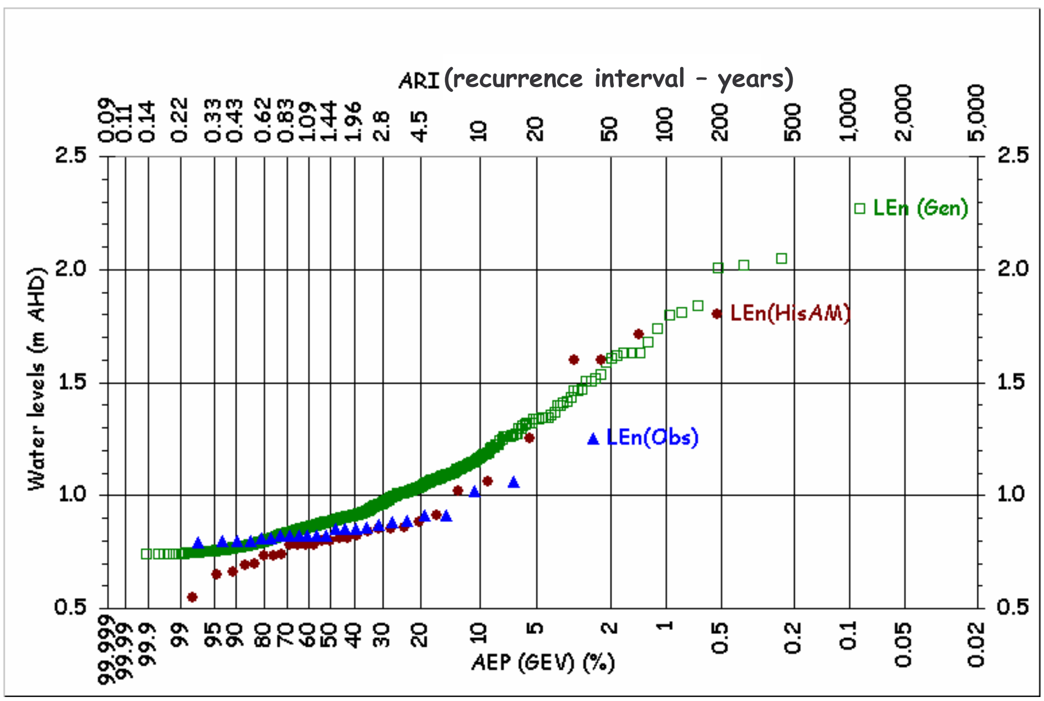

Figure 11. AEP versus water level for Lakes Entrance showing the results of Method 3 (green open squares), Method 1 (blue solid triangles) and hybrid plot combining historical observations with method 1 data (brown solid circles). This illustrates that the historic data is consistent with the results of Method 3 and highlights that Method 1 underestimates AEP levels significantly

Table 2. Summary of estimated 1%, 2%, and 3% AEP levels for locations around the Gippsland Lakes. Numbers in **bold** are recommended values

	Lake Wellington	Loch Sport (L. Vic.)	Mid Lake Victoria	Lake King (North)	Paynesville	Metung	Lakes Entrance
5% (1:20yr)							
Method 1	1.4	1.2	1.2	1.3	1.2	1.2	1.1
Method 2	1.6	1.2-1.3	1.2-1.3	1.3	1.2-1.3	1.2-1.3	1.0
Method 3	**1.7**	**1.4**	**1.4**	**1.6**	**1.5**	**1.5**	**1.3**
2% (1:50yr)							
Method 1	1.7	1.4	1.4	1.6	1.4	1.4	1.2
Method 2	1.9	1.4-1.6	1.4-1.6	1.6	1.4-1.6	1.4-1.6	1.1-1.2
Method 3	**2.0**	**1.7**	**1.7**	**1.8**	**1.7**	**1.8**	**1.6**
1% (1:100yr)							
Method 1	1.9	1.6	1.6	1.8	1.6	1.6	1.3
Method 2	2.1	1.6-1.9	1.6-1.9	1.7-1.9	1.6-1.8	1.6-1.8	1.3-1.4
Method 3	***2.2**	**1.9**	**1.9**	**2.0**	**2.0**	**2.1**	**1.8**
**SRWSC	2.5	1.5	1.5	1.5	1.5	1.5	1.5
***Currently used for planning	2.5	1.5	1.8	1.8	1.8	1.8	1.5

* This is for the centre of Lake Wellington. For the land around Lake Wellington near the river inputs, levels should be higher to account for the gradients between the rivers and the lake. The current 1% level of 2.5m is consistent with the work undertaken in this project for the land around Lake Wellington near the river inputs.

** these are the levels interpreted from the SRWSC (1981) excluding provision for waves and wind effects.

***these levels are those adopted for planning and do not include freeboard allowances (i.e. recommended floor levels are higher than these levels)

Overview of the relative influence of forcings on different locations around the Gippsland Lakes

The 1% AEP flood levels are influenced by all three major forcings – wind, ocean level and river floods. In general, a significant level of river flooding is required for extreme Lake water levels, however relatively frequent river floods can lead to extreme Lake levels when winds are strong and/or ocean levels are high. In particular, strong westerly and south-westerly winds cause both "pile-up" of water towards Lakes Entrance, as well as raising ocean levels in the vicinity of the entrance. These effects influence peak levels back as far as Lake King, Paynesville and eastern Lake Victoria, decreasing westward. Wind effects are particularly important on Lake Wellington, with river flooding being critical to water levels in the land between the major rivers and the Lake.

Tidal effects are critical considerations at Lakes Entrance and towards Metung. The peak levels indicated in Table 2 will only occur at high tide. This means that access around the town should be possible, even during rare floods, albeit intermittently. This sort of information will be important for emergency response and public education. Further analysis can be undertaken to elaborate on this issue if required.

Other project outputs

In addition to the AEP water levels, there are a number of outputs from this project that will be useful to local agencies and other researchers. These include:

- The Digital Elevation Model: The DEM is being used already by several agencies and is available on CD or can be downloaded over the web.
- A large amount of work went into collating, checking, "cleaning" and archiving all of the data that was required for this project. This includes over 100 years of daily rainfall data presented as 5x5 km grids over the whole area, flows for all the rivers, daily and hourly (where available) wind and atmospheric pressure; Lakes Entrance water level observations; derived coastal ocean level and 25 years of water levels for locations through the Lakes simulated from the forcing data. A report has been prepared on the data archive (Tan and Grayson, 2002b).
- The Hydrological Model (SIMHYD) provides daily flows for all rivers (tuned to provide accurate flood flows) for the period covering the rainfall data (over 100 years). These models could be used for many applications and can be made available directly to organisations – they will run on a PC. If it is intended to use them for streamflow management plans, the effect of pumping and diversions would have to be included for rivers where these are a significant volume – this is not particularly difficult, but would require some extra work.

Recommendations for further work

The procedures developed in this project have several important applications beyond the estimation of AEP levels under present conditions. The most important of these are:

- Investigation into the impacts of climate change by incorporating the recent projections of weather patterns from CSIRO under different change scenarios. The methodology is ideal for a comprehensive assessment of climate change scenarios because it integrates the effects of changes in rainfall, sea level, atmospheric pressure and wind, however detailed information on expected changes in these forcings would be needed.
- Development of a real-time water level forecasting system for the Gippsland Lakes. This would utilise real-time river flow and weather data, along with rainfall, wind and MSLP forecasts, to estimate water levels out to a few hours ahead (or as long as the rainfall wind and MSLP could be forecast). This could be used for emergency response.
- Maintenance and enhancement of relevant data collection. The availability of data made this project possible and it is vital that such records continue to be maintained to assess issues such as long-term changes in ocean levels, hydrodynamic effects of the entrance and other changes influencing water levels. The review panel recommended that an additional water level recorder be installed to measure coastal offshore water levels. Such data would minimise uncertainty related to influences on coastal ocean level such as strong winds and mean sea level pressure changes.

NB. Since completion of the project, the LEI site has been decommissioned. Reinstatement of this site should be a priority to maintain the only long-term water level record in the Gippsland Lakes

Data Archiving

This project involved the collation and analysis of a large amount of observed data, as well as the generation of a large number of stochastic data sets. Several models were also constructed and calibrated. All of this information will be archived at both the University of Melbourne and the East Gippsland Catchment Management Authority.

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