BASSLINK INTEGRATED IMPACT ASSESSMENT STATEMENT

POTENTIAL EFFECTS OF CHANGES TO HYDRO POWER GENERATION

APPENDIX 11:

GORDON RIVER MEROMICTIC LAKES ASSESSMENT

Tyler, P.A.[1], Terry, C.[2] & Howland, M.B.[3]

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1. Limnologist - School of Ecology and Environment, Deakin University, PO Box 423 Warrnambool, Victoria 3280.
2. Consultant – Colin Terry and Associates, 2/129 Carr St, West Perth, WA 6005.
3. Senior Environmental Consultant, Hydro-Electric Corporation, GPO Box 355D, Hobart, TAS 7001.

EXECUTIVE SUMMARY

A study was undertaken to evaluate the potential implications of changed Gordon Power Station operations predicted under Basslink on the meromictic lakes of the lower Gordon River floodplain.

Surveys of the current status of these lakes indicate that monimolimnion salinity is continuing to decline in Lake Fidler under the current river flow regime, and that Lake Morrison has lost its meromixis at the present time. Sulphide and Marble Pools were not investigated, however, Sulphide Pool is assumed to be of a similar status to Lake Morrison. The mechanisms by which these lakes receive saline water and hence retain meromixis are largely dependent on the intrusion of a tidal salt-wedge into the river during low freshwater flow periods which naturally occur most frequently during summer and autumn. The operation of the Gordon Power Station has been previously implicated in the disruption of this pattern and has resulted in high river flows for the majority of the time.

Modelling of salt-wedge intrusion in the Gordon estuary indicates that flows less than 50 cumecs sustained on average for 14 days would be required to promote salt-wedge migration to a point upstream of Lake Fidler. The results of the modelling are comparable to field observations in both the 1970's and with the present study. Intrusion is possible over shorter time scales but require lower freshwater flows.

Analysis of flow records indicate that suitable flow conditions for extensive salt-wedge intrusion have only been met on four occasions since the commissioning of the Gordon Power Station, each time associated with major maintenance or installation work. No shutdowns associated with historical operational patterns were identified during dry periods, and no periods of low flow have been experienced by the Gordon River estuary since 1996. This trend is expected to persist post-Basslink. Current shutdowns associated with major maintenance are already highly compressed and are unlikely to change post-Basslink, consequently, Basslink *per se* is not considered a threat to the integrity of the meromictic lakes and there are no impacts that could be attributed to Basslink that would require mitigation. Regardless of Basslink, it is likely that long-term degradation of the meromictic lakes will continue due principally to the year-round maintenance of high river flows under the present operating patterns. It is possible that Basslink may offer some flexibility in the operation of the Gordon Power Station such that positive mitigation of existing impacts can be achieved.

It is recommended however, that long-term river flow monitoring be continued such that any probabilities of salt-wedge intrusion can be compared before and after the commissioning of Basslink. Additionally, it is recommended regardless of Basslink, that the status of the lakes is monitored and strategies for mitigation of current impacts are developed as part of the Hydro-Electric Corporation's operating strategies.

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1 INTRODUCTION

This report is one of a series of reports dealing with the potential impacts of the proposed electricity inter-connector cable (Basslink) between Tasmania and Victoria. The Basslink cable itself does not have a direct impact on the Gordon River. However, the connection of the Tasmanian electricity grid to the National Electricity Market (NEM) is expected to alter the way in which Tasmanian hydro-electric power stations are operated. Appendix 1 of this report series - Scoping Report: Basslink Aquatic Environmental Project (Hydro Environmental Services, 2000) deals with the modelling of these new operating practices and highlights the Gordon River downstream from the Gordon Power Station as an area susceptible to environmental impact which may result from changes to operational practices.

1.1 Aims

The aims of this study are to evaluate the potential impacts of changed Gordon Power Station operations under Basslink on the meromictic lakes of the lower Gordon River floodplain. Specifically to:

- evaluate the current status of the lakes, using historical and existing information, concentrating on Lake Fidler as a indicator,
- understand timing and other thresholds relating to salt-wedge intrusion;
- assess current frequencies of salt wedge migration in relation to power station operations and compare these to predicted Basslink patterns;
- propose mitigation strategies for any predicted Basslink impacts; and
- propose a monitoring program if appropriate.

1.2 Background

Three small lakes came to the notice of the scientific community during the Hydro-Electric Commission's "Lower Gordon River Scientific survey" in the 1970s. The lakes lie beside the river in its lower reaches (Figure 1). A fourth waterbody, Marble Pool is a nearby ancient remnant of a meromictic lake that is not now generally regarded as one of the Gordon River meromictic lakes.

They were not on the available maps of the day, they had no names and they were hidden from all but the aerial traveller, though, without doubt, they would have been known to convict and piner. Today they are known as Lake Morrison, Lake Fidler and Sulphide Pool (Figures 2-4). They are a special kind of lake, with rare and unusual properties.

1.2.1 The properties of meromictic lakes

Most lakes in the World are holomictic, that is for at least one period in each year wind driven currents circulate throughout, to their greatest depths. As a consequence of this the entire body of water is oxygenated. The three lakes along the Gordon River are not holomictic but meromictic (mixis =mixing, meros =part), that is they remain permanently stratified, by virtue of denser, saltier water in the bottom strata. Less than 150 such lakes are known in the World (Walker & Likens 1975) and only about 4 others occur in Australia. The Gordon River examples have considerable personage in the slim annals of meromixis (Tyler & Vyverman 1995).

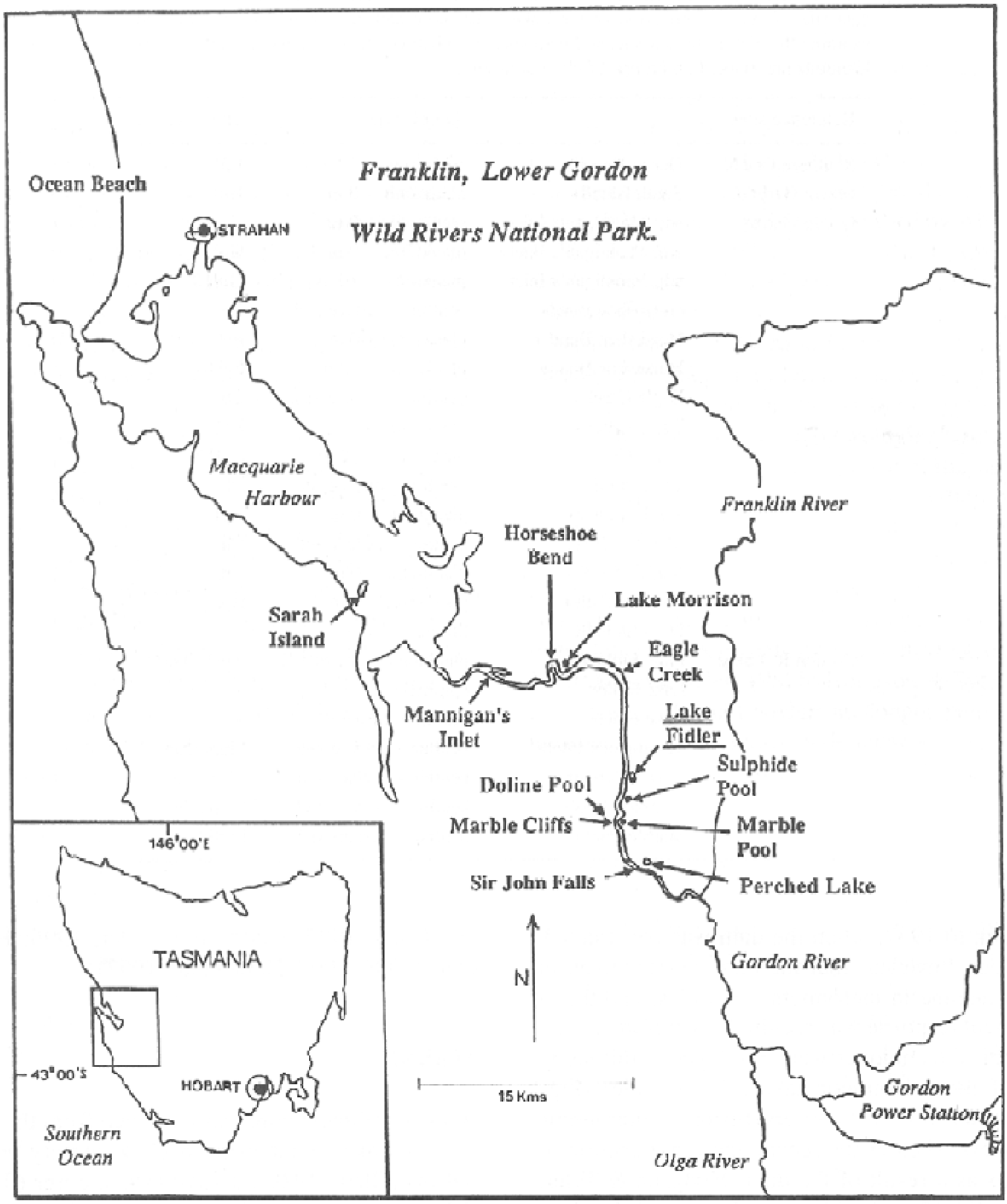

Figure 1: Map showing location of meromictic lakes and other locations on the river.

Figure 2: Lake Morrison from the air. The large bend in the river is at the Barbers Pole. The encroachment of peripheral vegetation, the process of terrestrialisation, is clearly evident.

Figure 3: Lake Fidler from the air, showing the herbfield encroaching on the lake at the edge.

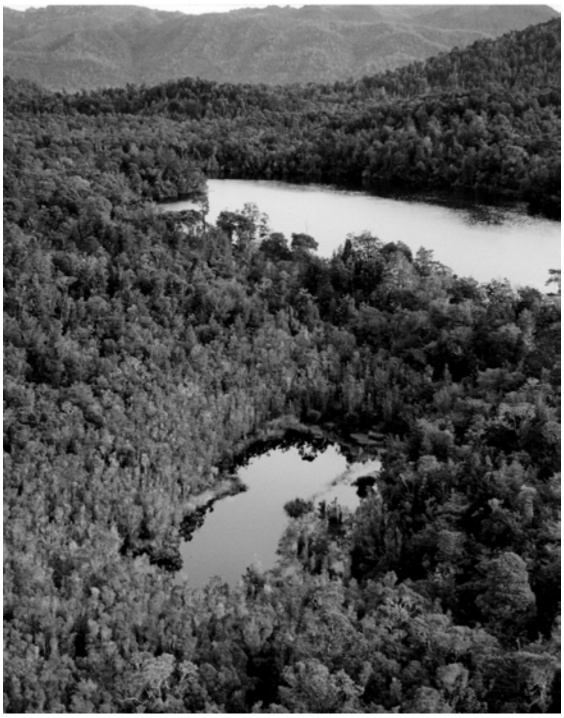

Figure 4: Sulphide Pool from the air, showing zonation of vegetation as the lake becomes terrestrialised.

Characteristically, the lower strata of meromictic lakes, collectively the monimolimnion, are devoid of oxygen and charged with hydrogen sulphide and other compounds, conditions which may exist unbroken for thousands of years. This stratum represents an abrupt change from the overlying layers (Figure 5). As well as the sudden diminution of oxygen and appearance of hydrogen sulphide, concentrations of other substances, especially mineral salts, suddenly increase. Physical conditions may, and usually do, also change abruptly. The generic word cline describes such gradients in conditions, be they abrupt or gentle. In meromictic lakes the salt gradient is the halocline, the oxygen gradient the oxycline and the temperature gradient the thermocline. Another cline is the redoxcline, across which redox (oxidation-reduction) potentials (Eh) change by as much as 500mV, from positive to negative. The redoxcline defines the plane where the last traces of oxygen, beyond the detection limits of modern field meters, disappear. It marks the boundary between an oxidised and oxidising world on the one hand, and a reduced and reducing world on the other. These zones of change in the various conditions, which may be congruent to greater or lesser extent, are embraced by the collective term chemocline—the cline of chemical change. The halocline, by virtue of the formidable density gradient it engenders, separates the circulating mixolimnion from a stagnant monimolimnion where natural chemical and microbiological processes progressively lead to a highly reducing milieu.

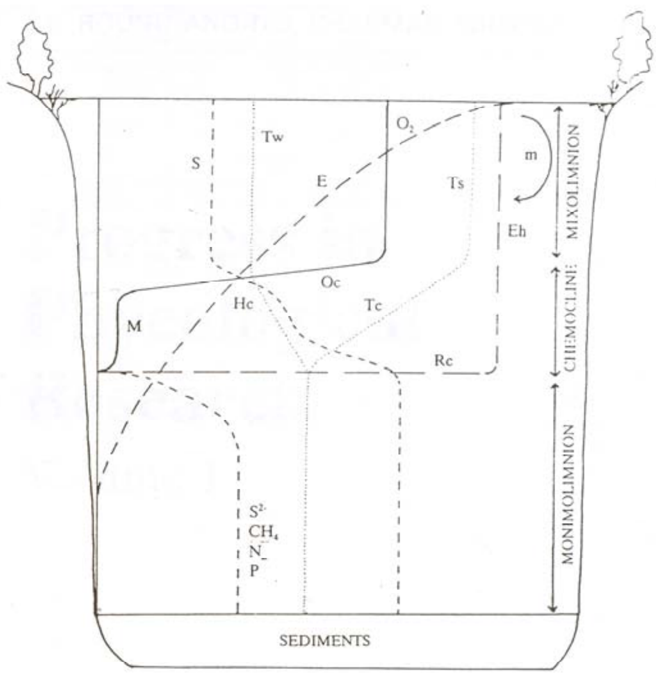

Figure 5: Diagram showing stylised vertical profiles of physicochemical parameters of meromictic lakes. S=salinity, Tw=winter thermocline, Ts=summer thermocline, 02=dissolved oxygen, Oc=Oxycline, E=downwelling photosynthetically-active radiation, Eh=redox potential, Rc=redoxcline, Hc=halocline, Tc=thermocline, M=microaerobic zone, m=wind-driven mixing. From Tyler & Vyverman (1995). Note vertical scale exaggerated.

The definitive arbiter, the redoxcline, stands as a knife edge divide (Figure 5) between the circulating, oxygenated mixolimnion, today’s world, and the dark, sulphuretted monimolimnion, harking back to the Precambrian and populated by microbes with Precambrian propensities (Croome & Tyler 1984, 1985, 1988; Baker *et al.* 1985; Miracle *et al.* 1991; Tyler & Vyverman 1995). Also characteristic of meromictic lakes, the vertical chemical and physical structure at the chemocline finds complementary expression in the intimate array of microbes, finely zoned in response to the physicochemical gradients. The chemocline is densely thronged by a diverse array of bacteria, algae, ciliates and other microscopic organisms, straddling the sharp, horizontal transition in thin wafers, a veritable microbial market place (Tyler & Vyverman 1995). The Gordon lakes have an unusual and enigmatic microbiological feature, the occurrence at the chemocline of eukaryotic photosynthetic flagellates, including one of bacterial dimensions (Figure 6), as well as the photosynthetic bacteria that occur at the chemocline of most meromictic lakes.

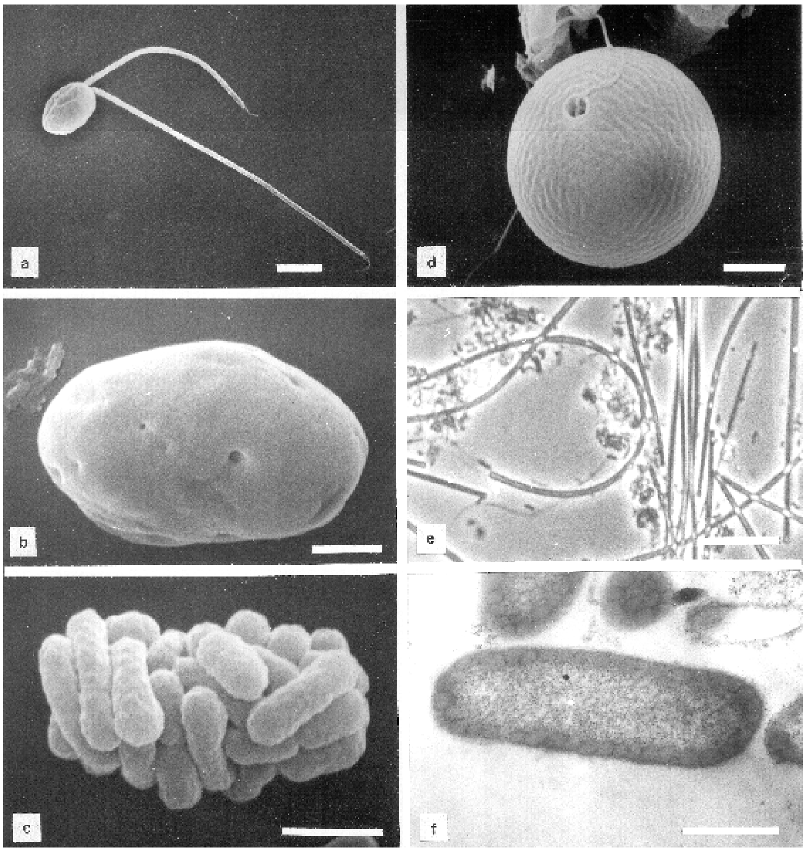

Figure 6: The microbial market place at the chemocline of Lake Fidler. a=*Scourfieldia cordiformis,* a green flagellate of bacterial dimensions (bar =2µm), b=the motile bacterium *Achromatium* (bar=1µm), c=the consortium of photosynthetic bacteria known as *Chlorochromatium aggregatum* (the swellings are the chlorobium vesicles that hold the photosynthetic pigment bacteriochlorophyll) (bar=1µm), d=the euglenoid flagellate *Trachelemonas volvocina* (bar=5µm), e=a filamentous suphur bacterium (*Beggiatoa* or *Chloroflexus*) (bar=20µm), f=the numerous photosynthetic bacterium *Chlorobium limicola* with peripheral chlorobium vesicles (bar=0.5µm). From Croome & Tyler (1984b).

The enigma surrounding the flagellates is that they are highly motile yet they assemble in thin planes adjacent to the redoxclines which, at the depths they occupy in the brown waters of these lakes, are in almost total darkness so that the normal and expected profession of the flagellates, photosynthesis, is impossible.

The final biological drawcard of the Gordon lakes is the most dramatic one and concerns the anoxic waters of the monimolimnion. Anoxic waters are invariably inhabited by bacteria that live a Precambrian lifestyle that does not involve gaseous or dissolved molecular oxygen. Only one group of eukaryotic organisms, a few genera of ciliates (motile, single-celled protozoa), can tolerate such lethal conditions. To do so they have undergone considerable biochemical readjustment. Their metabolism begins with the ingestion of bacteria, including particularly the photosynthetic bacteria that dwell at the redoxcline in vast numbers. The bacteria are digested by fermentative metabolism to release low molecular weight carbohydrates that are passed to the ciliate's hydrogenosomes. These unique organelles are modified mitochondria. Instead of performing oxidative metabolism, as mitochondria, the power houses of the cell, do in aerobic organisms, hydrogenosomes catalyze the breakdown of carbohydrates to yield fatty acids and hydrogen. The latter is passed to endosymbiotic methanogenic bacteria that live in the cytoplasm of the host ciliate as a halo around each hydrogenosome. This unique, syntrophic cascade is the key to the ability of descendants of aerobic ciliates to live their entire life cycle in anaerobic environments. Anaerobic ciliates are known from such nooks and crannies of the World as anoxic landfill sites, stratified and meromictic lakes and marine sediments. They have been particularly well studied in Europe (Fenchel & Finlay 1994, 1995; Guhl & Finlay 1993; Finlay & Fenchel 1991; Finlay *et al.* 1991; Miracle *et al.*1992). In the southern hemisphere they are known only from two lakes, one in Victoria (Finlay *et al.* 1999; Esteban *et al.* 2000) and Lake Fidler, where, so far, only 2 species have been observed.

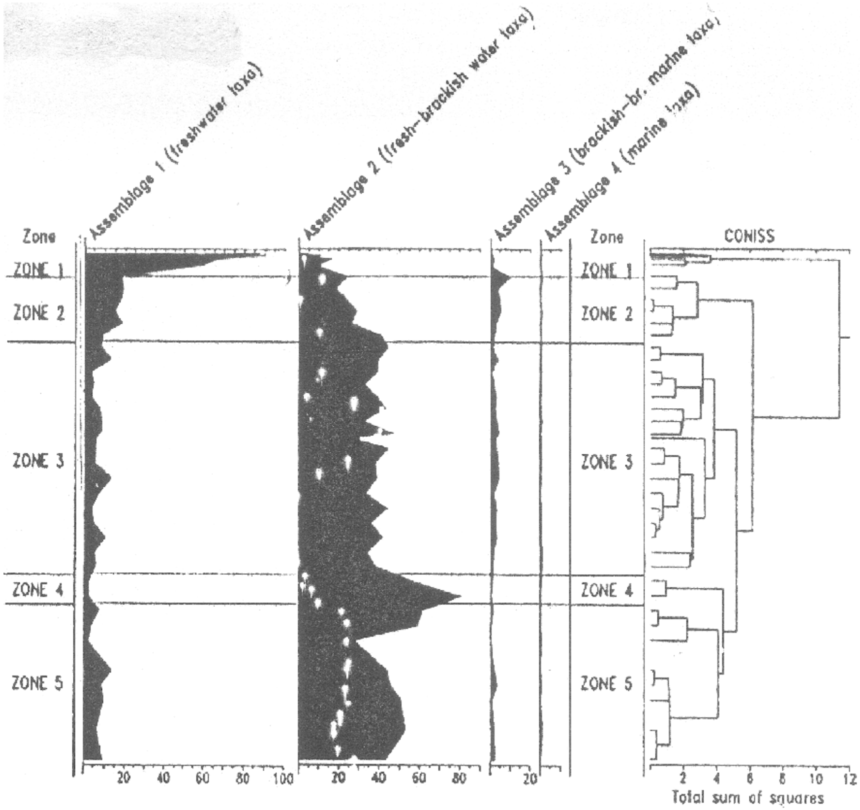

Figure 7: Percentage relative abundance of freshwater, marine and brackish species of diatoms in a sediment core of Lake Fidler. The freshwater species assume total dominance in Zone 1 when the lake becomes isolated from the river about 2,100 years ago. From Hodgson *et al.* (1996).

The origin of the Gordon lakes was by the familiar fluvial processes that cut off oxbow lakes from meandering rivers. What is so unusual about the Gordon lakes is that they were cut off as meromictic lakes. No other examples of meromictic lakes formed in this way are known. Lake Fidler was isolated from the river as a backswamp (Hodgson & Tyler 1996; Hodgson *et al.* 1996; 1997), cut off by an encroaching levee (King & Tyler 1981; Hodgson *et al.*1996) to leave the umbilical creek as the only remaining connection with the river, today permitting the flow of water in both directions. The evidence is fossilised in the sediments. By about 7,800 years ago the alluvial bar was in place and diatoms characteristic of lakes rather than rivers began to appear. Periodic laminae of clay indicate (Hodgson 1999) that there was still influx of salt water, probably by overtopping the levee in the manner that occurs today at Mannigans Inlet. By about 2070 years ago the lake was isolated from the river to the extent that it is today. This is clearly shown by the change from riverine diatoms to domination by lacustrine species, principally the typically lake dwelling *Cyclotella stelligera* (Figure 7). The contemporaneous accumulation of specific photosynthetic pigments, diagnostic for the bacteria that habitually dwell at chemoclines, indicates (Figure 8) that as Lake Fidler evolved so did meromixis.

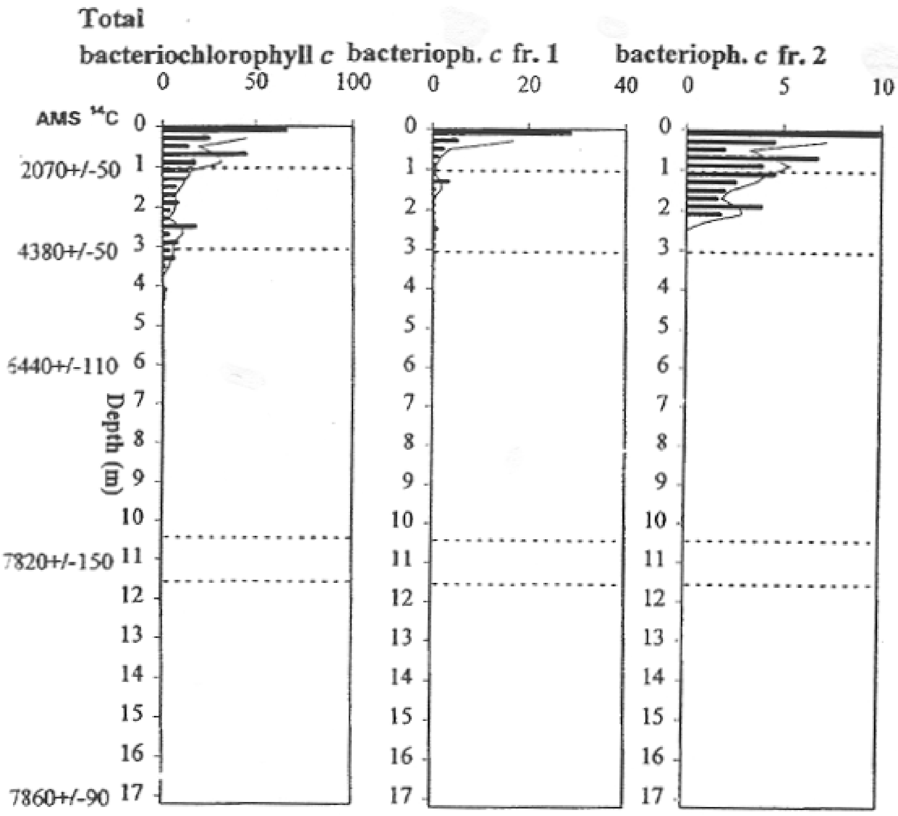

Figure 8: Fossil bacteriochlorophyll and its derivatives in the sediment core of Lake Fidler showing its origin as a meromictic lake at the top of the core. From Hodgson *et al.* (1998).

Lake Fidler has two meromictic neighbours, Lake Morrison and Sulphide Pool. The latter lies close to the present river course, as does Lake Fidler, but Lake Morrison is now considerably further inland (Figure 2). Sulphide Pool and also Marble Pool are believed to have arisen in the same manner as Lake Fidler, by the process that can be seen in action today along the Gordon River at Mannigans Inlet (King & Tyler 1981; Hodgson & Tyler 1996). The processes leading to the formation of Lake Morrison are less clear, but are not discussed here. Once formed, each lake gradually evolves towards extinction as fringing aquatic vegetation, followed by herbfield, shrubland and, eventually, forest, encroach on the lake like the closing of an iris diaphragm. This process of terrestrialisation is particularly apparent at Sulphide Pool, now a mere remnant of its former self (Figure 4) and is almost complete in Marble Pool (Hodgson and Tyler, 1996). Marble Pool is now not considered as one of the Gordon River meromictic lakes.

1.2.2 The maintenance of meromixis

The meromictic state of the three lakes was first reported in 1981 (King and Tyler, 1981), after the Gordon Power Station was already operating. No studies of the lakes had been undertaken prior to regulation of the Gordon River. The origin of the saltier water in the monimolimnia was not obvious until an undercutting salt wedge was detected in the river, far upstream. The resulting theory (King & Tyler 1981; Tyler 1986), that brackish water from the estuarine salt wedge somehow made its way to the lakes, rendering them meromictic, is now confirmed (Hodgson & Tyler 1996). However, the story is considerably more complex than that. A common ailment of meromictic lakes is that they naturally devolve towards or to the antithetic state of holomixis. Wind generated water currents in the mixolimnion entrain salty water as they skitter along the interface, thereby progressively paring away at the boundary and gradually driving the plane of the chemocline deeper and deeper in the water column. The deeper the chemocline is driven, progressively more energy is required to drive water currents to that vicinity and erosion of the boundary slows becomes less and less likely. When driven to a certain depth in a given lake, further deepening requires a storm of greater strength than those prevailing. Thus in meromictic lakes of moderate to great depth an equilibrium condition eventually is set up and a stable meromixis may persist for centuries. In shallow lakes, like those of the Gordon, however, devolution will continue until the whole lake circulates, so becoming holomictic, unless there is a replenishment of the denser, salty water on which meromixis hinges. The survival of meromixis in the Gordon lakes, against the natural forces of devolution, depends (Hodgson & Tyler 1996) on such episodic top up from the estuarine salt wedge that, under favourable conditions, advances some 38 km upstream.

The events that govern the intrusion of salty water into the Gordon River lakes, maintaining the meromictic state, are complex but understood in principle (Tyler 1986; Hodgson & Tyler 1996). Each inflow requires the almost uncanny congruence of three sets of meteorological circumstances.

First, the undercutting salt wedge must push upstream some distance beyond the lake in question (Figure 9). This is favoured by high tides, strong north-westerly winds and, particularly, low flow in the river. The salt wedge has been observed on numerous occasions at the Big Eddy, above Butler Island, and well beyond the meromictic lakes.

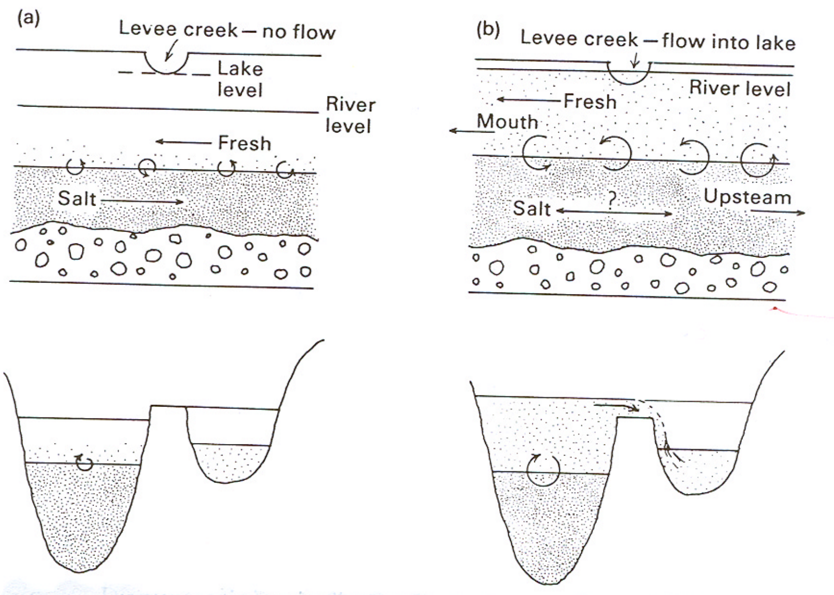

Figure 9: Diagrammatic longitudinal and cross sections of the river showing the mechanism of brackish water inflows into the lake. (a) low river flow, estuarine salt wedge intrudes upstream beyond lakes. (b) subsequent spate, with turbulent mixing at the interface, raising salinity in surface water which now enters the lake. From Tyler (1986).

Second, with the salt wedge well upstream of the lakes a spate is necessary in the Gordon River such that eddy diffusion at the boundary of the salt wedge and the strongly outflowing fresh water raises the salinity of surface water of the river to values well in excess of the surface waters of the lake. One such spate has been observed during previous surveys (Figure 10).

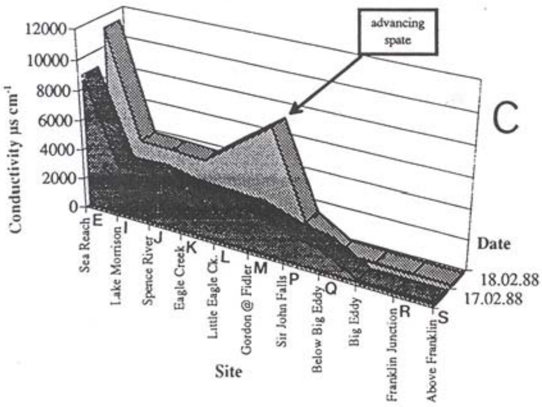

Figure 10: Surface water salinity of the Gordon River on two dates showing elevated levels in the vicinity of lake Fidler caused by the power station coming back into operation after a shutdown. From Hodgson & Tyler (1996).

The third and most demanding requirement is that the spate be of such magnitude as to elevate not only the surface water salinity but also the level of the river, such that salty water flows into the lakes, either via the connecting creek or by overtopping the levee banks.

Although the probability of such a fickle alliance of three independent variables would seem to be low, all three events have been observed, either *in situ* or remotely, and the flow of salty water into Lake Fidler has been recorded. The appearance of periodic clay laminae in the sediments is further, mineralogical evidence for regular intrusions of salt water over several thousand years (Hodgson 1999).

There is no doubt about the mechanism of maintenance of meromixis but there is scant information about the magnitude of the collective events necessary to recharge the lakes, nor about the necessary duration of them.

1.2.3 The value of the Gordon River meromictic lakes

The three meromictic lakes and their relationship with the Gordon River have been well studied and chronicled (King & Tyler 1981, 1982a,b, 1983; Bowling & Tyler 1984, 1986; Bowling et al 1986; Croome & Tyler 1984a,b, 1985, 1986, 1988a,b; Baker *et al.* 1985a-c; Tyler 1986, 1992; Tyler & Bowling 1990, Tyler & Vyverman 1995; Kirkpatrick & Tyler 1987; Miracle *et al.*1991; Hodgson & Tyler 1996; Hodgson *et al.* 1996, 1997; Harle *et al.* 1999). When south-west Tasmania was presented for World Heritage listing it met all four criteria for "outstanding universal value" as a Natural Property. Meeting one only would have guaranteed acceptance. The lakes were part of that property. Their limnological value lay first in the uncommon state of meromixis, of which they stood as graphic examples, with unique biological features. Secondly, all three lakes are excellent examples of the process of terrestrialisation by the gradually closing iris diaphragm of a circumferential herbfield (Tallis 1973), thereby meeting another World Heritage criterion as outstanding examples of ongoing processes in the development of plants and animals and of freshwater bodies (Mulvaney 1983). If that were not enough, it was believed that they also held archaeological and anthropological significance (Tyler 1986). The discovery that Aboriginal people inhabited the Gordon basin while the glaciers were still at work on the mountains ranks as the most exciting event in Australian archaeology, assuming prominent currency in the global view of the development of Mankind (Jones 1982). The sediments of the three meromictic lakes were seen as a chronicle of Aboriginal fortunes and adaptability as post Glacial climatic amelioration saw the spread of dense forest across their open hunting grounds. Meromixis spells, perhaps for millennia, stagnant and anoxic conditions in the bottom waters where pollen and other fossils accumulate as lake sediments. Under these circumstances the sediment surface is unwafted by water currents, undisturbed by the burrowing of aerobic aquatic larvae, both of which would redistribute and confuse the historical record mummified there. Meromictic lakes therefore preserve a particularly fine-grained and uncorrupted record of past events.

For all these reasons, the significance of the lakes is as ones of renown and as outstanding attributes in the scientific and cultural landscape of an outstanding World Heritage Area (Mulvaney 1983; Whitlam 1993). Kriwoken (2001) in Appendix 14 of this report series – Gordon River World Heritage Area Values Assessment - discusses World Heritage Area values in detail. Their relevance to considerations of Basslink is that their chance of survival in a state of meromixis is linked to hydro-electric operations on the Gordon River and that these in turn may be influenced, for better or for worse, by the changed operating regimes that Basslink would bring.

2 METHODS

2.1 Investigation of current status

Investigations of the present state of meromixis in the lakes, and of the dynamics of penetration of the salt wedge in the river, were undertaken during two periods of shutdown of the Gordon Power Station, in December 1999 and in March 2000.

Of the full suite of analyses and investigations used to establish the nature of the meromictic lakes only those that were necessary to determine their present status were employed in this study. Vertical profiles of selected physicochemical parameters in the water columns of the lakes were measured *in situ* by drawing (with a peristaltic pump) samples from selected depths through a flow-through cell furnished (Figure 11) with the necessary electrodes for electrometric measurement of temperature, salinity, oxygen and redox potential. The value of the redox potential is overwhelmingly influenced by the oxygen potential. Even traces of oxygen, way beyond the detection limits of modern electrodes, will maintain positive redox values. The change from positive to negative values of Eh, then, is a cardinal arbiter, the definitive and influential watershed between oxidised and reduced worlds, with their different metabolic systems. Salinity was measured in the flow through cell as its surrogate, electrical conductivity, using the same meter and electrode as in all previous studies. Measurement of the conductivity of potassium chloride standards showed that the instrument/electrode combination had not changed its performance characteristics since previous studies and that it was in near perfect agreement with standards. Therefore all conductivity values, past and present, are highly reliable. Full details of all methodology are given by Tyler & Buckney (1974), Miracle *et al.* (1992) and Tyler & Vyverman (1995).

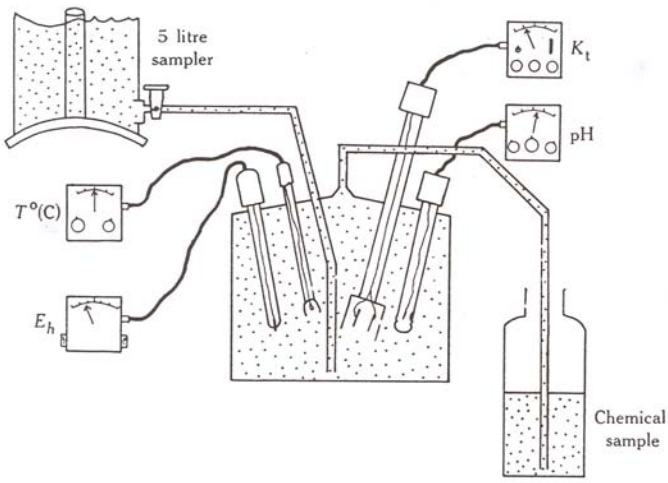

Figure 11: Diagram of a flow-through cell used for electrometric measurement of several physicochemical parameters without permitting contact with the atmosphere. From Tyler & Buckney (1974).

To determine the behaviour of the salt wedge in the river vertical profiles of salinity and temperature at selected depths, along relevant stretches of the river, were determined, periodically, with a Hydrolab salinity meter. River and lake levels were determined by reference to fixed gauge boards installed harmoniously with those that were used in previous studies. In addition, solar-powered data loggers provided continuous records of temperature, salinity, direction and velocity of flows into or out of Lake Fidler. The intent of these measurements was to quantify the model of salt wedge penetration of the river and the subsequent mechanisms leading to replenishment of salt in the lakes. The existing relationship (Figure 12) gave only the distance to which the salt travelled under different flow conditions. To predict the likelihood of recharge of the lakes requires also the time scale of advance of the salt wedge under different outflow regimes and the river levels reached with different discharge rates from power station and natural tributaries. Power station discharge or, particularly, its absence for various periods of time, becomes a major determining factor in the fortunes of the lakes. Because of this, the changes to the hydrology of the river that Basslink may bring needs to be evaluated in terms of the duration, frequency and timing of low flows.

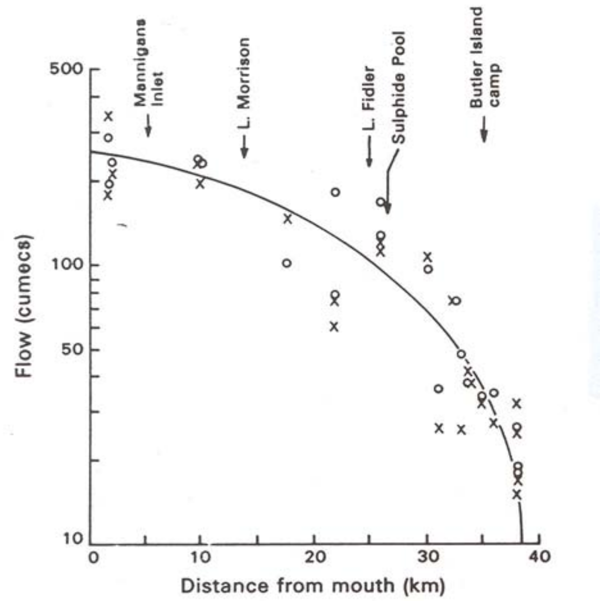

Figure 12: Curve showing relationship between river flow and the distance to which the salt wedge penetrates. From Kearsley (1978, 1982). Crosses are average flow over previous 5 days, open circles over the previous 10 days. Flow in this diagram is the sum of the Gordon u/s Franklin and the Franklin d/s Jane gauge sites.

2.2 Prediction of Basslink Changes

A relationship between river flow and salt wedge intrusion was developed by Kearsley (1978) as shown in Figure 12. The time taken for the salt-wedge to reach various positions within the estuary, could not be determined from this relationship. Consequently, a modelling approach was undertaken to combine the predictions of Basslink operating scenarios with modelled salt-wedge behaviour. Natural flows downstream of the Gordon and Serpentine Dams were modelled using the methods detailed in Appendix 2 of this report series - Gordon River Hydrology Assessment (Palmer *et al*, 2001). These were combined with the Gordon Power Station discharge predictions as produced by the TEMSIM model (Appendix 29 of this report series (Connarty, 2001) to estimate freshwater discharges to the Gordon estuary. Actual flow records, combined with the natural flow model (to correct for flow gauging location) were used to provide the 'current' or actual flows experienced by the estuary. Comparison of freshwater discharge predictions pre- and post-Basslink were then undertaken as described more fully in section 4.1.

The behaviour of the Gordon River salt-wedge in relation to such flows was undertaken as an extension of the Macquarie Harbour circulation modelling that is described in Appendix 26 of this report series - Macquarie Harbour Water Quality Assessment (Koehnken, 2001).

2.2.1 Salt-wedge model description

Salt water that forms the salt-wedge in the Gordon estuary comes from Macquarie Harbour. The model used in this study simulates the entire Macquarie Harbour system at once due to the interrelationships that exist between the rivers and the harbour. The model is a computer program that is fed information about the system, such as the river flow rates and salinity concentrations and was developed as part of a PhD project as described in Terry (1998).

The Macquarie Harbour system model includes:

- the harbour proper;
- Gordon River for 40 km from the harbour (ie. to the top of the estuary);
- King River for 10 km from the harbour;
- the sea “river” extending for 20 km out into the ocean from the harbour;

Birchs Inlet is ignored but is unlikely to affect the prediction of salt wedge dynamics in the Gordon River.

While the harbour proper is modelled in three-dimensions (based on the Princeton Oceanographic Model - POM, Blumberg and Mellor 1987), the three “rivers” are modelled in two-dimensions (laterally averaged, that is parameters across the river channel are assumed to be uniform). The model is run by a FORTRAN 77 computer program that produces output data files, which in turn are post-processed to be used by the Vis5D visualisation program (Vis5D, 2000) to produce outputs such as shown in Figure 13.

Figure 13. Example of salt-wedge model output (Time= 23 tides (11.90 d) with Gordon River flow of 25 cumecs). Intruding salt-wedge can be seen as lighter colouration to the left at the river entrance to Macquarie Harbour. Lines are 1 ppt isohalines.

The model uses a 250 m square horizontal grid and 23 non-dimensional vertical (sigma) coordinates, and steps forward in time at 3 second intervals. The sigma coordinates mean that within every water column of the harbour and river system there are 23 vertical levels - irrespective of the depth. Parameters modelled include: velocity, salinity, temperature, pollutant concentration, surface elevation and turbulence energy. Pollution is included as the King River discharges contain pollutants, primarily heavy metals from the Mount Lyell Copper Mine Lease (see Appendix 26 of this report series). Density is a function of salinity, temperature and pollution. The inputs for the model include: bathymetry, initial conditions and boundary conditions (such as river inflow and water quality, wind in harbour, air temperature and solar radiation).

Model runs were undertaken such that the relationship between river flow and salt-wedge dynamics could be interpreted. Some of the boundary conditions were held constant, including:

- Wind (none);
- Tidal forcing on sea 'river' (using a 12.42 h = 0.5175 d tidal period);
- Diurnal variation of air temperature (11°C to 18°C) and heat input (0 to 502 W/m^2); and
- Pollution concentration (zero for Gordon and 0.01 ppt for King River).

The base case for each model was for 15 tidal cycles with present average summer Gordon River flows (212 cumecs), after which the model continued for an additional 12 days at the low flow.

2.2.2 Application of the model

An important component of the model was the inclusion of a bathymetric profile that reflected the bottom contours of the Gordon River estuary. Given the numerical constraints of the model with using a 250 m grid only certain features could be described. A smaller grid could have been used, but there is a link between the grid size and the time step. So decreasing the grid size would have decreased the time step and increased the run times, which were already very long (with the model running at only twelve times real-time). There was also a difficulty in finding a consistent version of the bathymetry and in the end the bathymetry used is a combination of several as shown in Figure 14 (the bathymetry used is called "Colin"): taking the depths from a lead plumb bobbed version ("Christian") and spatial locations of the features from a recent sonar version ("Jackie"). Note that the very deep river holes have not been included, although this will not cause much inaccuracy as these holes are filled with dense saline water that the salt-wedge is expected to flow over due to sharp density differences.

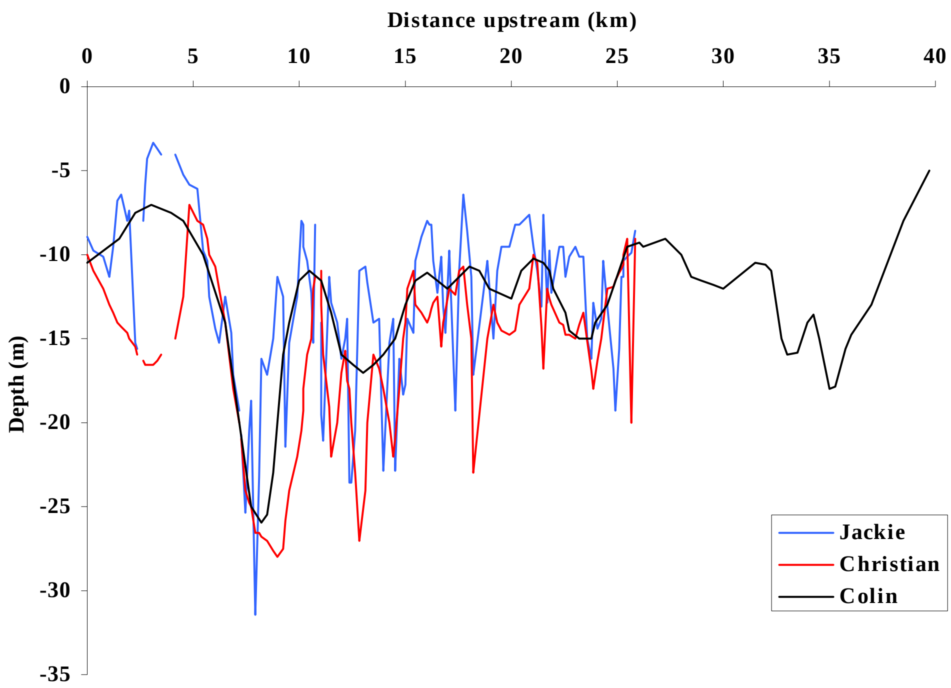

Figure 14. Lower Gordon River bathymetry from three sources, the one used is called "Colin". Lake Fidler lies at approximately 26 km upstream.

2.2.3 Calibration and comparison to previous relationships

The aim of calibration is to ensure the model calculates the position of the Gordon River salt wedge correctly. The main parameter which affects the speed of salt wedge is the river's bed roughness. Using measurements of the movement of the salt wedge under low Gordon River flow obtained during power station shutdowns in March 2000 and September 2000, the bottom roughness parameter was adjusted. Four roughness values were tested to get the closest fit using the September flow and salinity data, then the calibrated model was checked successfully against the March data. The model therefore is biased towards the data collected during the recent field surveys and show less salt wedge intrusion for given flows than the relationship presented by Kearsley (1978). The differences are possibly a result of the salinity thresholds used to determine salt-wedge distance, but may also be a result of different salinity characteristics of Macquarie Harbour (ie. the salt source) between the two periods of study. The 2 ppt isohaline was used as the threshold in the current study, but it is unknown what was used in Kearsley's analysis. The implications of using the relationship modelled in the current study are that only periods where a high probability of salt wedge penetration were likely are included in the analysis.

3 CURRENT CONDITIONS

The lakes were first investigated, and found to be meromictic, in 1977. By this time the dam at Strathgordon was complete. During the filling of the dam, between 1974 and 1977, the flows in the Gordon River would have been substantially reduced compared to natural. The lakes had not been discovered at this time, and no monitoring was undertaken, however, the incidence of low flows associated with dam filling would have increased the likelihood of saline recharge of the meromictic lakes. It is possible that the lakes were at an artificially high state of meromictic stability due to these low flows.

The first turbine in the Gordon Power Station was commissioned late in 1977 and the Gordon River was highly regulated from this period onward. The power station was operated almost continuously from then on and the constant discharge from the tailrace maintained flows in the river during the drier months at far higher than natural.

The likelihood of salt wedge intrusion was now remote, and devolution of the meromictic state of the lakes almost certain. Almost immediately the decline of meromixis, as measured by deepening of the chemocline and a decline in meromictic stability (see Hutchison, 1957 and Walker, 1974 for methods), commenced (King & Tyler 1982b; Bowling and Tyler 1984, 1986a: Croome & Tyler 1988b; Miracle *et al.* 1991; Tyler 1986). The decline continued (Figure 15) and by 1983 Lake Morrison and Sulphide Pool had become holomictic. In the deeper Lake Fidler the chemocline stabilised at a depth of about 3.5 m and, when the last measurements were made (in 1993), before the present investigations, it remained in a state of "precarious meromixis" (Hodgson & Tyler 1996).

Lake Morrison and Sulphide Pool are considerably shallower than Lake Fidler and are therefore more likely to proceed all the way to holomixis by wind-induced devolution. Lake Morrison, however, is considerably closer to the mouth of the river than the other two lakes. Therefore, the salt wedge is more likely to intrude upstream of it and may be likely to receive salt intrusions more frequently. It is possible that Lake Morrison, and perhaps also Sulphide Pool, vacillated between holomixis and meromixis under natural conditions, the periods of holomixis between successive restorations of meromixis being dependent on the frequency of salt wedge intrusion. This possibility was never tested because devolution under the conditions of the regulated river was already in progress when meromixis was first discovered.

In the case of wind-induced mixing, this would require a storm of considerable ferocity to set up circulation in the lakes to a depth where this would be detrimental to meromixis, particularly in Lake Fidler. The effects of freshwater input from either the local catchment of the lakes themselves or from flood waters of the Gordon has not been fully explored. Lake Fidler has a significant catchment including a small creek that drains a swampy area to the south, and the lake has been observed to fluctuate in level by over 1 metre in response to local catchment rain. Under these conditions this water exits the lake via the connecting creek to the Gordon River. During floods in the Gordon River, the flows are reversed and freshwater spills over to the meromictic lakes frequently either via the connecting creeks, or far more rarely over the levee banks themselves. The presence of the Gordon and Serpentine Dams upstream do regulate the maximum size of these floods, but this is not likely to be to a significant extent as far as the meromictic lakes are concerned. Hence, the regular mixing and freshwater dilution of these lakes is retained, yet the saline recharge necessary to balance these processes has been largely lost.

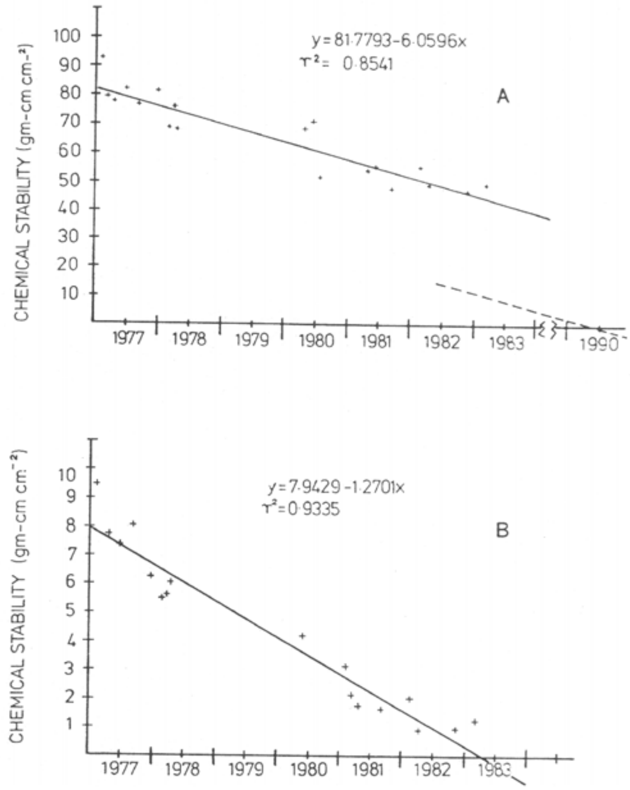

Figure 15: The decline in meromictic stabilities of Lake Fidler (A) and Sulphide Pool (B) after operation of the Gordon Power Station commenced to 1983. From Bowling & Tyler (1984).

Whatever the case, since 1977 Lake Morrison has alternated between holomixis and meromixis. In 1994 it displayed typical features of meromixis (Hodgson & Tyler 1996); on the same date Sulphide Pool was meromictic but not with the same abruptness of former times. During the present investigations, Lake Morrison had the veriest remnant of meromixis. Sulphide Pool was not investigated. It was considered that the focus of the present study should be Lake Fidler as it was thought that this lake still retained all the meromictic features that make these lakes of value. The data gained concerning potential implications of Basslink would be applicable to all three lakes.

A full suite of microbiological investigations was not undertaken during the present studies but samples were examined from key strata where, in the past, diagnostic microbes would be found in stable array. On this occasion the microbiology was muddled. Key eukaryotic flagellates were absent and photosynthetic bacteria were present above their usual position with respect to the chemocline.

This points to disturbance of the chemocline before sampling commenced and, in fact, other measurements indicated that equilibration was taking place. The halocline was tight and stable at a depth of a little over 3 metres (Figure 16) during a 5-day period from 17-22 December, 1999, but the redoxcline was in a state of flux (Figure 17).

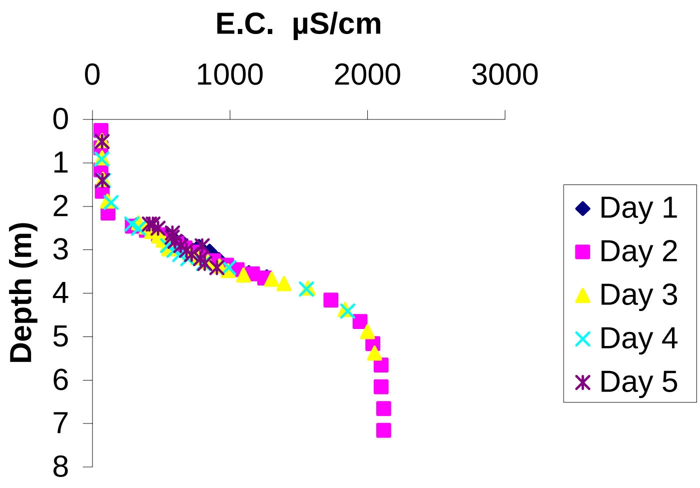

Figure 16: Vertical profiles of conductivity (E.C.) in Lake Fidler from 17/12/99 to 22/12/99. Depths are corrected to datum of previous studies.

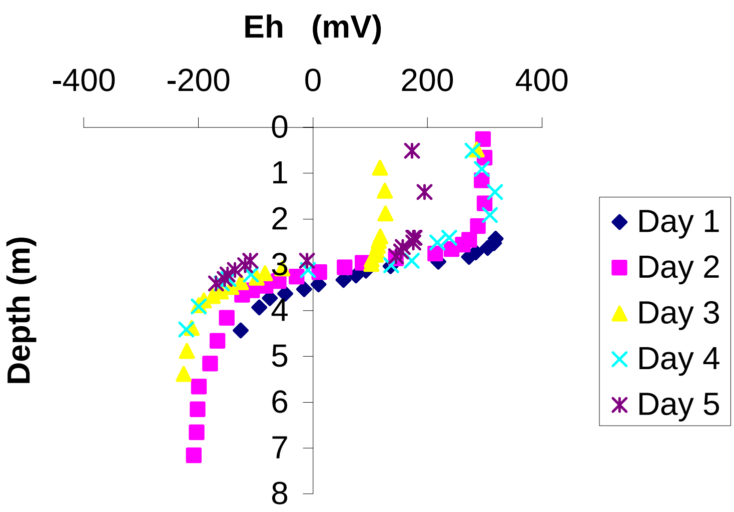

Figure 17: Vertical profiles of redox potential (Eh) in Lake Fidler from 17/12/99 to 22/12/99. Depths are corrected to datum of previous studies. Variation from day to day in the positive values of Eh result from failure to allow the lengthy equilibration period that a platinum electrode requires, and can be ignored. The important factor is the plane of change from positive to negative values.

Despite the stable halocline the Eh values indicate that the redox layering was changing over this five-day period (the variation in the horizontal axis are calibration errors and can be ignored; the diagnostic data are the vertical changes). The sequence of measurements shows a progressive upward migration of the redoxcline (Figure 17). There is no contradiction in the two sets of data. The halocline, predicated upon considerable density differences, would stabilise rapidly after disturbance. The redoxcline, dependent upon chemical and biological reactions, would certainly take longer.

The salinity of the monimolimnion of Lake Fidler remained approximately constant from 1977 to 1994, at 3,500-4,000 μScm^{-1}. Since the last previous measurements and the present study, major changes have taken place in Lake Fidler. The salinity of the monimolimnion is now only half of its previous value, which had remained more or less constant for 20 years. Any suspicion of faulty instrumentation was removed by daily calibration in the field and the inescapable conclusion is that the lake has either been flushed completely, with the former monimolimnion being replaced by new water of lower salinity, or the old monimolimnion has been diluted by intrusion of fresh water.

For the present study, the meromictic stability for Lake Fidler was calculated as 29.13 and 30.19 for the periods corresponding to the December 1999 and March 2000 field trips respectively. The short-term variability in meromictic stability both prior to and post-regulation is unknown, however, these figures indicate that the level of meromixis in Lake Fidler is now around the same minimum stability values calculated from the last measurements in 1993 (Figure 18). Importantly, the devolution towards permanent holomixis as predicted in Figure 15 is not apparent.

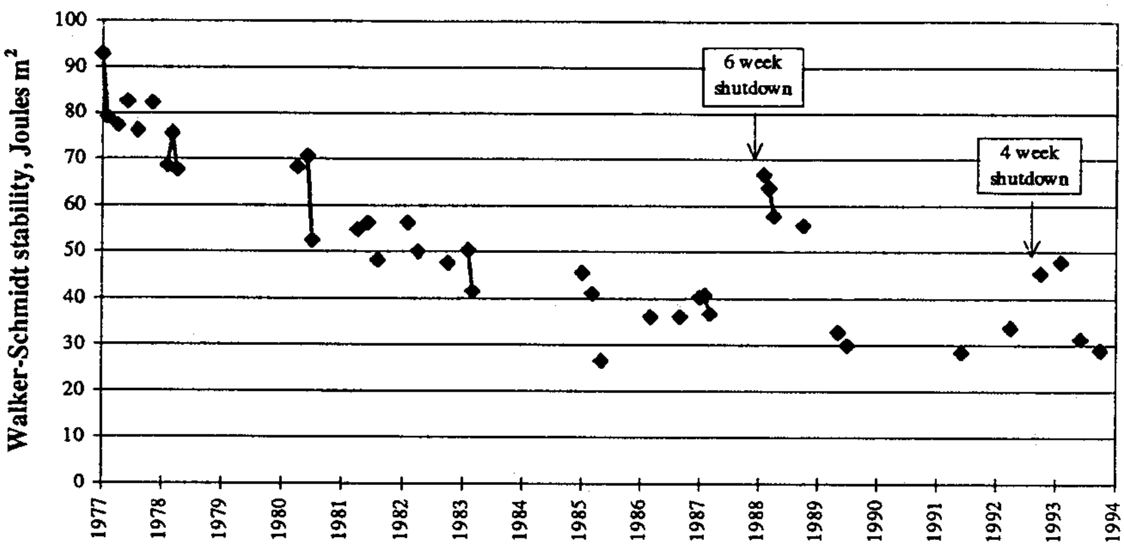

Figure 18. Meromictic stability for Lake Fidler 1997 – 1994. From Hodgson and Tyler (1996).

Despite the decline in monimolimnion salinity, Lake Fidler is still meromictic, with many of the essential features of meromixis. Because meromixis is, *sui generis*, an attribute of scientific significance, Lake Fidler and its neighbours still meet the criteria of World Heritage denomination. The change in the monimolimnion has potentially, however, compromised the sediments as a finely layered historical record. Because of the potential for circulation at the sediment interface, and hence the potential for oxygenation and subsequent bioturbation, the surface integrity of the sediments as a palaeolimnological repository of exceptionally fine grain must now be questioned. Close inspection of the conductivity values between 1977 and 1993 indicates that even during this period of relative stability there was probably a more dynamic state of affairs in the monimolimnion than previously admitted. This does not alter the fact that the lake is still meromictic and, in fact, the dynamism is of interest in its own right.

4 IMPLICATIONS OF BASSLINK

Based on historical trends and the salt-wedge and river flow modelling discussed below, it appears that the probability of saline recharge to the meromictic lakes has been greatly reduced since the operation of the Gordon Power Station. To understand the potential implications of Basslink on these lakes, a study combining the modelled natural Gordon catchment hydrology and actual gauged data for the Gordon valley was undertaken to relate the flow regimes in the Gordon River with the potential for saline recharge of the meromictic lakes.

4.1 The influence of power station discharges on river level

River level fluctuations in the lower Gordon are primarily driven by tidal and rainfall patterns. Figure 19 shows the overwhelming influence of heavy rainfall in the catchment on river discharge to the estuary. It is only during dry periods that the power station influence becomes a dominant influence on freshwater discharge.

Despite the significant effect that the power station can have on river discharge during dry times, the influence of the Gordon Power Station on river level in the region of the meromictic lakes is negligible. During wet periods, the discharge of the river is dominated by natural flows, particularly from the Franklin River. The corresponding changes in river level are far larger than any fluctuations attributable to the power station. During dry periods, the power station influence on flows is more significant, however, the changes in river level associated with these flows is then outweighed by tidal variations. Figure 20 shows the variation in river level at three sites in the Gordon River in response to experimental switching of the power station between off and ‘full-gate’ during a relatively dry period. The most upstream site (75 km) is within kilometres of the power station. Water level fluctuations are almost entirely driven by power station operation. The site downstream of the Franklin River, 36 km downstream shows that the flow pulses are significantly attenuated and the range of fluctuations is much reduced. By the time these flows reach the estuary, the much larger cross-sectional area of the river channel leads to a minimal response to power station flows. The fluctuations in the river level at Lake Fidler shown in Figure 20 are due almost entirely to the diurnal tidal variation experienced in Macquarie Harbour.

It can be seen therefore, that the power station has minimal influence on the water level fluctuations in the lower reaches of the Gordon River. Hence any changes to operational patterns induced by Basslink, particularly those related to short-term hydro-peaking will have virtually no effect on river level variations in this area. This is due to the attenuation of the power station flows, the large cross-sectional area of the estuary, and the relative dominance of rainfall and tidal patterns.

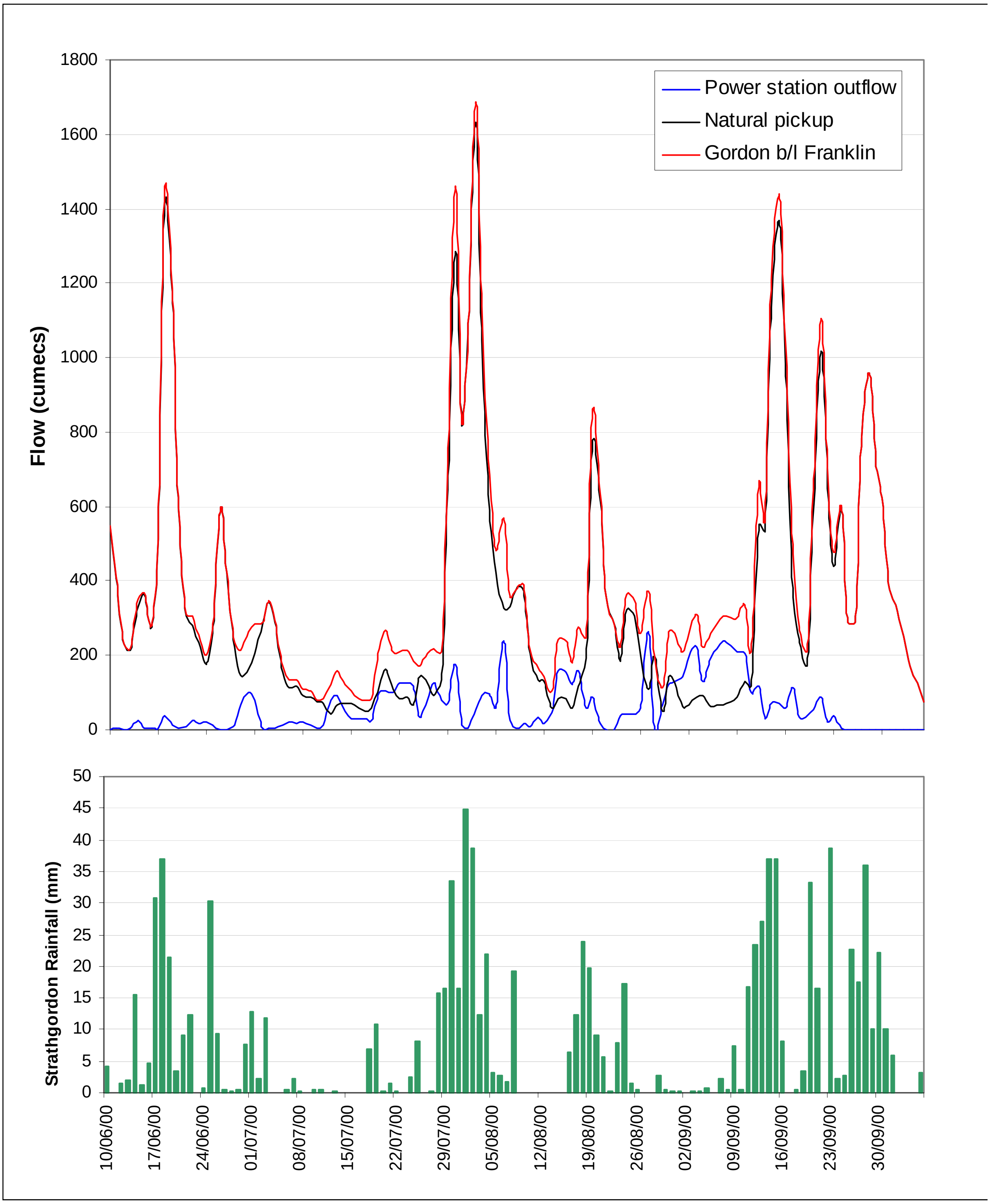

Figure 19. Relative influence of rainfall and power station discharge in the Gordon River below Franklin.

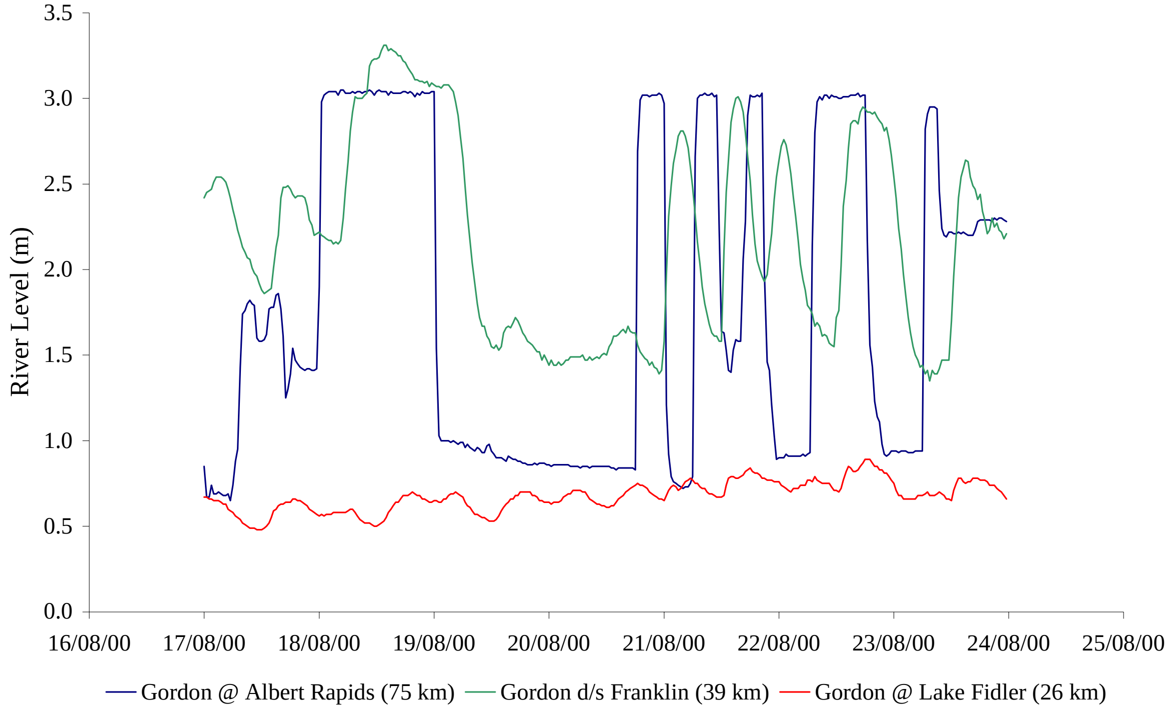

Figure 20. Water level variation in the Gordon River at Lake Fidler in contrast to riverine sites upstream during hydro-peaking in dry weather.

4.2 The relationship between river flow and salt wedge intrusion

The studies on Lake Fidler and Lake Morrison had the purpose of determining their present state of meromixis. Because the dimensions of flow in the river are the prime determinants of whether or not the lakes remain meromictic the behaviour of the salt wedge was closely monitored during the two periods of power station shutdown. The objective was to add temporal dimension to the spatial model (Figure 12) of salt wedge penetration. From the large electronic data set that resulted a few examples have been selected to illustrate the main findings. The sampling points are shown in Figure 21.

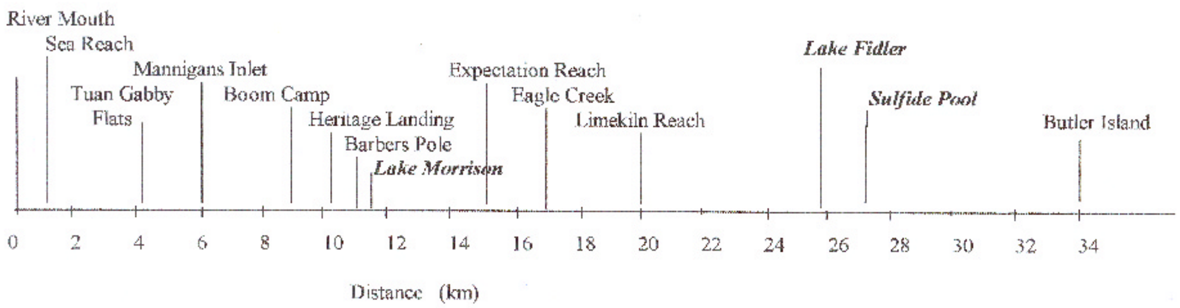

Figure 21. Sampling localities along the Gordon River and their distances from its mouth.

When flow into a salt wedge estuary is slight, and tidal influence strong, the salt wedge intrudes well upstream, in the case of the Gordon River to beyond Butler Island during dry times (Figure 12). If flow in the river increases, however, the salt wedge is pushed downstream. With very strong flows it may be all but expelled from the river, but with moderate flows it may be swept only some of the distance downstream. Further, in the latter case, remnants of the wedge may be left in the deepest holes of the riverbed. If such residual saltwater remains in the river for considerable time, microbial activity may render it anoxic. The next incursion of salt water may, depending on its density, flow over this older salt or undercut it and displace it upwards. This is unlikely to have much significance to recharge dynamics, but validates the bottom bathymetry adopted for the modelling study (Figure 14). Where two or more separate episodes of incursion of saltwater, each with different density and perhaps temperature, have occurred in this manner it will be recognised by more than one vertical discontinuity in salinity, temperature and other properties, that is a stepped profile. These have been observed many times in the Gordon. Such profiles confirm that saltwater enters and penetrates the river regularly, only to be partially or completely expelled by the next high flow (Figure 22).

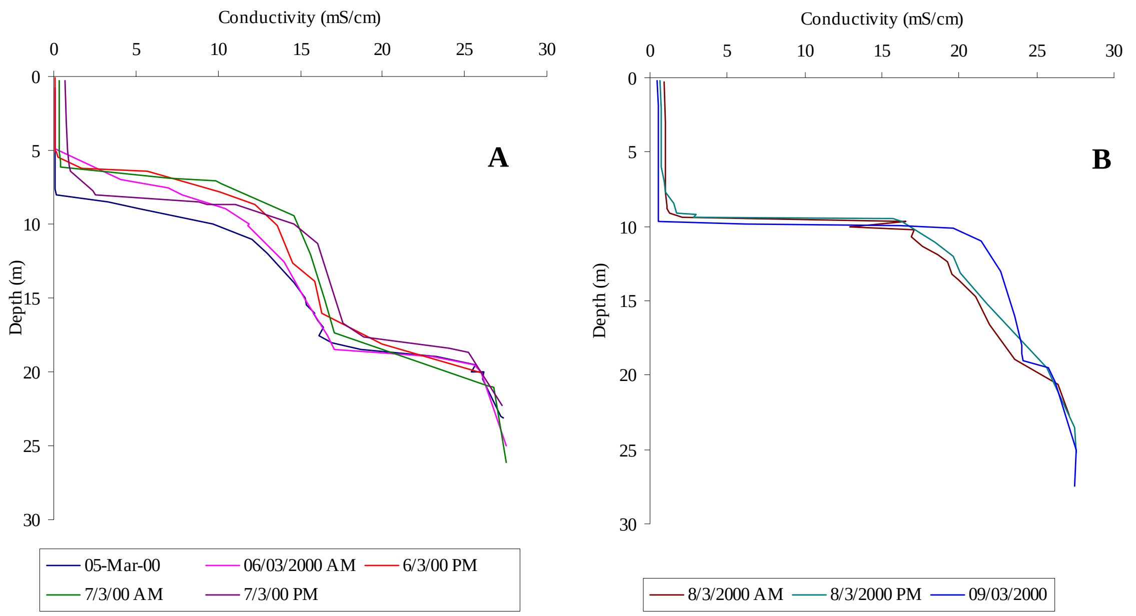

Figure 22: Conductivity profile in the Gordon River adjacent to Lake Morrison, between the 5th and 9th of March 2000 during a shutdown (A) and after the arrival of power station waters (B). Note the continued intrusion of the salt wedge at depth after power station startup, but deepening of the halocline. Remnant salt layer lies below 20 m.

The cardinal significance of the Gordon Power Station is that its discharge has a considerable influence on total flow in the river, at all times, so that whether it is in full flight or shut down is a prime determinant of the properties and dimensions of the salt wedge, and hence of the likelihood of survival of meromixis. Typically, the Gordon Power Station operates almost continuously through the drier summer-autumn months, particularly during ‘dry’ years. Hence the natural flows that would have occurred during these times are reversed with unseasonally high discharges. During a wet year, the Gordon Power Station is less likely to operate continuously during these months. Unfortunately, however, the natural catchment yield (particularly from the Franklin River) will provide flows high enough to prevent salt wedge intrusion. Hence the Gordon Power Station through its seasonal inversion of the flows for approximately half of the lower Gordon River catchment serves to ensure high flows to the estuary throughout any given year.

In order to provide low flow thresholds on which probabilities of salt-wedge intrusion could be calculated a modelling exercise was undertaken as part of the Basslink investigations to determine the time for salt-wedge penetration under various flow regimes. Initial trials using a time-series of variable flows as input to the model did not significantly change the results when compared to a steady flow assumption equating to the same average flow. Hence for all further investigations, steady average flows were used as model inputs to provide indicative times for salt-wedge intrusion rates.

Figure 23 shows the smoothed relationship between the flow rate in the Gordon River (below the Franklin) and the number of days required to reach points in the River upstream of Lake Fidler. It was found that it would take on average 7 days for the salt-wedge to reach 28 km up the river (ie. 2 km upstream from Lake Fidler) at a river flow of 31 cumecs. At higher flows, the time taken was increased (eg. 14 days at 50 cumecs), until an asymptote was reached which described the maximum expected salt-wedge intrusion distance for any given flow. At flows higher than 50 cumecs, the salt-wedge would never reach 28 km upstream no matter how much time this low flow was sustained (Figure 24). The results are more conservative than those reported by Kearsley but correlate well with recent field surveys.

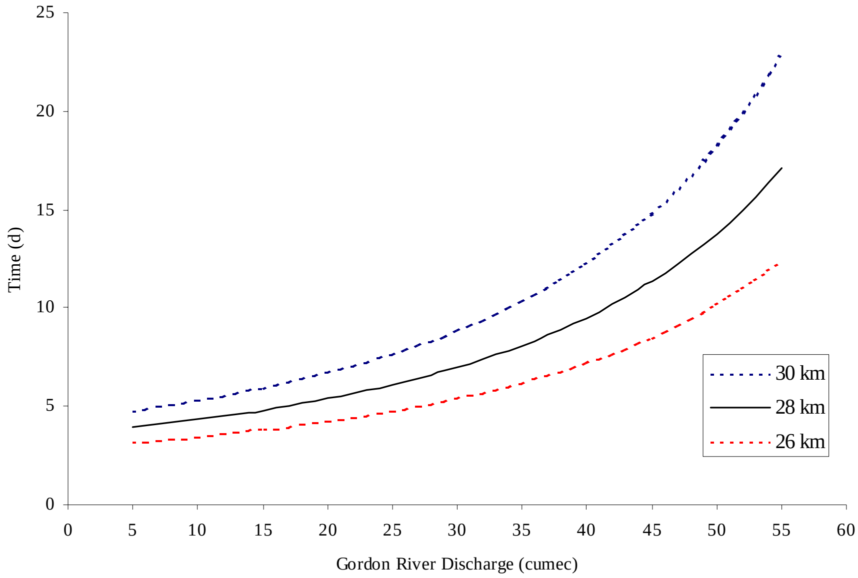

Figure 23. Relationship between Gordon River discharge and average time for salt-wedge to reach Lake Fidler (26 km) and 2km upstream of Lake Fidler (28 km).

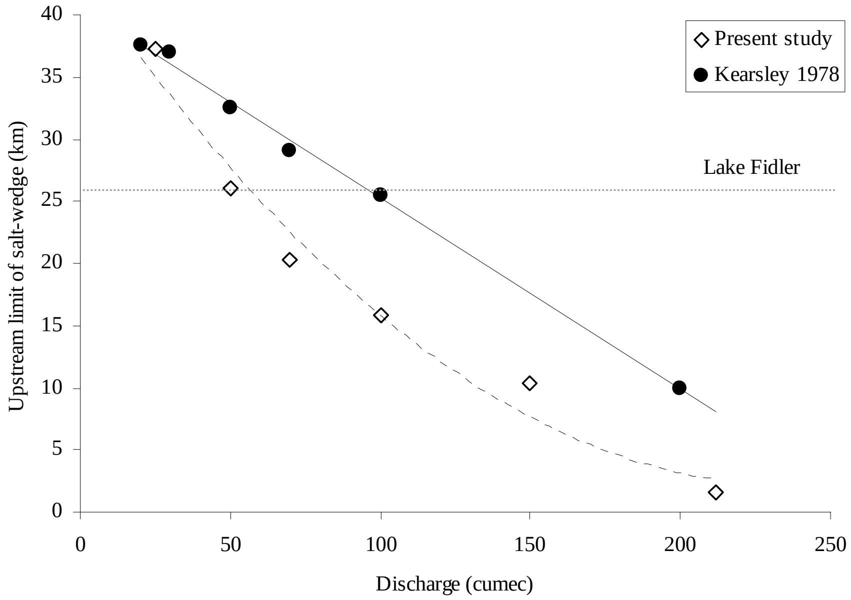

Figure 24. Limit of upstream salt-wedge as predicted by the present study and Kearsley (1978). Differences are possibly a result of the salinity thresholds used to determine salt-wedge distance or salinity conditions in Macquarie Harbour.

4.3 Probability of salt-wedge intrusion

The Gordon Dam was closed in April 1974 and initially filling of the storage occurred until 1977 (Figure 25). During this period, the incidence of low flows in the Gordon River was increased and the probability of salt-wedge intrusion in the estuary would have been comparatively high. The Gordon Power Station came on line in November 1977 with one turbine and was followed by the commissioning of a second turbine in 1979. During this time, the station operated primarily as a baseload station, discharging the bulk of its water during the dry summer-autumn months. Throughout this time, there appears to have been some opportunities for salt-wedge intrusion, although Tasmania's demand for electricity was steadily increasing and the probability of recharge was already significantly reduced from natural. In 1988 works were undertaken at the power station to install a third turbine, though, during much of this time, the power station continued to operate with its two existing turbines. Significantly, the power station was shutdown for the first 6 weeks in 1988, to finalise construction of the tailrace surge chamber and again for 4 weeks in October 1992. It was during these major shutdowns, that Hodgson and Tyler (1996) conducted extensive field work on the meromictic lakes and recorded increased meromictic stability in Lake Fidler associated with saline recharge. It is notable that the highest inflow channel salinities reported by Hodgson and Tyler (1996) occurred late March 1993 following a period with minimal power generation from the Gordon Power Station.

It is significant that during these shutdowns, despite the seemingly short odds of getting salt-wedge intrusion *and* the necessary flow events to spill brackish water into the lakes, recharge *was* observed. It would appear, therefore, that the major pre-requisite for recharge is the intrusion of the salt-wedge and that the other events to facilitate recharge, which are still far less understood (ie. transfer to the lakes themselves), occur with a reasonable regularity to allow recharge to occur at these times.

Hence, the focus of determining the potential impact of Basslink was centred on estimating the probabilities of salt-wedge intrusion in the Gordon River. These were estimated through modelling of intrusion rates under different flow rates and subsequent analysis of actual and modelled hydrological data to estimate the change in the percentage occurrence of low flows.

Time series data of actual flow discharges from the Gordon Power Station were coupled with the natural flow model for the catchment below the dams (ie. catchment pickup – Palmer *et al*, 2001) to generate a time series of flows between 1970 and 1998 (Figure 25). Data for 1999 and 2000 were not incorporated as power station operations were significantly affected during these years by the need to have shutdowns for the Basslink environmental investigations and represented atypical operational strategies. The resulting flow series, gives a realistic estimate of actual flows that would have been experienced at the head of the estuary (ie. Gordon below Franklin).

An analysis of extended low-flow periods that match the criteria discussed in section 4.1, (ie. flows of less or equal to 31 cumecs for at least 7 days, or 50 cumecs for 14 days) revealed four years of significance: 1981, 1988, 1993 and 1996 (Table 1; Figure 25). These four years were the only years that were predicted by the model to have a significant chance of salt-wedge intrusion upstream of Lake Fidler. Other low flow events extending below the 50 cumec threshold since the commissioning of the Gordon Power Station in 1977 were predicted by the model to not be of sufficient duration to allow salt-wedge intrusion past Lake Fidler.

Table 1. Months of current low flows: Percentage occurrence of 14-day average flows ≤50 cumecs (7-day average flows ≤31 cumecs in brackets) for the Gordon River downstream of the Franklin for the years 1988 to 1998 inclusive. Years with no occurrences are not shown.

Month	1981	1988	1993	1996
January	0	48.4 (41.9)	0	22.6 (29.0)
February	0	69.0 (20.7)	0	0
March	0	0	29.0 (6.5)	0
April	0	0	0	0
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	0	0	0	0
November	0	0	0	0
December	22.6 (19.4)	0	0	0

So, since the installation of the third turbine in 1988 there have been only 2 years (1993 and 1996) where low flows have occurred in the estuary. As discussed previously, 1988 was an extraordinary year, with the installation of a third turbine and significant shutdowns to allow the works associated with this new plant. Such an event is unique in the history of the operation of the Gordon Power Station. Such work would only be repeated in the event of further capital works, or in the event of major failure of the station, such as collapse of the tailrace tunnel. Clearly, such events do not form part of the day to day operation of the Gordon Power Station.

The low flow period in March 1993 is due to maintenance carried out at the Gordon Power Station following the commissioning of the John Butters Power Station. The contribution of an additional 143 MW of installed plant in the hydro system provided some flexibility, and this coupled with reasonable rainfall in other parts of the state allowed this outage to occur. It was a low flow period prior to this in 1992 and associated with the shutdowns in 1993 that Hodgson and Tyler (1996) monitored salt-wedge intrusion and partial water exchange with Lake Fidler.

In 1996 a power station outage occurred during January to permit transmission line maintenance. The latter part of 1995 and most of 1996 was classified as a particularly ‘wet’ year for the hydro system. The water availability in the other parts of the state provided some flexibility by allowing the Gordon Power Station to come off line during this time and allow the transmission line maintenance to occur. It should be noted that the inflows to the Gordon catchment were reasonably low during the summer of 95/96, indicating that much of the State’s rainfall during this period occurred in other parts of the State.

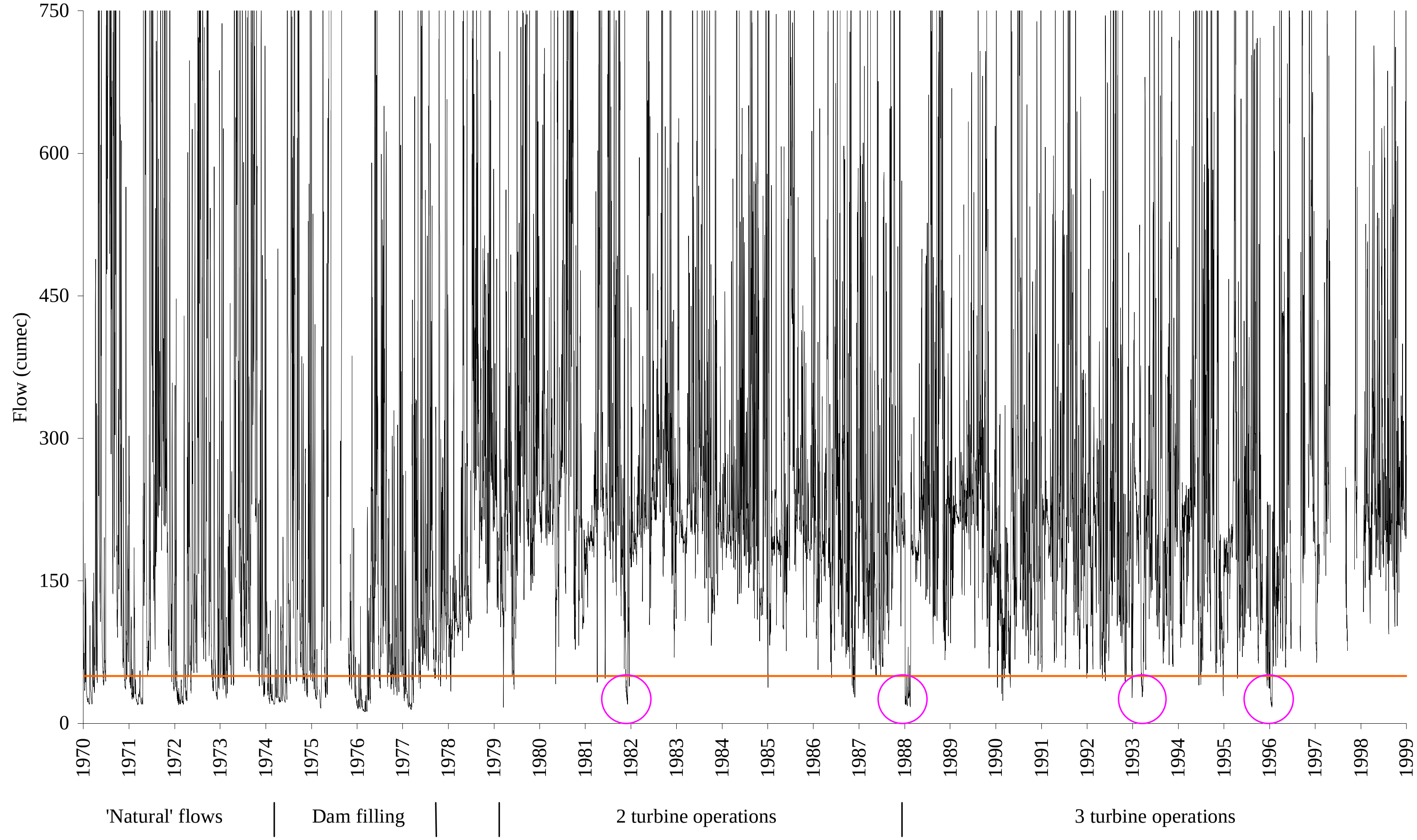

Figure 25. Daily flow time-series for the Gordon River d/s of the Franklin River confluence. The events circled in late 1981 and early 1988, 1993 and 1996 signify the low flow events since the operation of the Gordon Power Station where salt-wedge intrusion was predicted to be successful by the hydrological modelling. Other low flow events extending below the 50 cumec threshold (orange line) since 1979 were predicted by the model to not be of sufficient duration to allow salt-wedge intrusion past Lake Fidler. Note Y-axis truncated at 750 cumecs.

Interestingly, it is not only water availability, but also air temperature that influences the operation of the Gordon Power Station. During hot weather, the transmission system in the Derwent valley cannot deliver its full electricity capacity to the main load centre, Hobart. Hence, under these conditions, even if water is available for the Derwent power stations, the Gordon Power Station still needs to run to ensure reliable supply to meet the southern load. In recent years, the introduction of an 'electricity code' and the nomination of a 'system controller' who is responsible for ensuring reliable operation of both the electricity generation and transmission system have meant that long shutdowns of the Gordon Power Station during dry or hot weather are virtually impossible. This more stringent operation of the system coupled with growing electricity demand has virtually ruled out long shutdowns of the Gordon Power Station during dry weather regardless of Basslink. Even to achieve the environmental studies undertaken by Hydro Tasmania during 1999-2000, it was necessary to restrict shutdown duration to weekends with low power demand or to wetter cooler weather when transmission or water availability constraints allowed reliable operation of the hydro-electric system.

Due largely to the increasing electricity demand and the increasingly constrained generation and transmission system, maintenance practices at the Gordon Power Station and associated infrastructure are heavily constrained in order to minimise downtime at critical times of the year. The maintenance practices associated with long shutdowns over the last three years for instance, are about as compressed as is possible and it unlikely that this will change significantly after Basslink (Allan Rogers, Hydro Tasmania, pers. comm.). Hence it is unlikely that the probability or the timing of shutdowns will change after the commissioning of Basslink. Consequently, the meromictic lakes which are reliant on such shutdowns for the possibility of natural saline recharge, are unlikely to be affected any further by Basslink. Ironically, the flexibility that Basslink will introduce to the electricity system, in association with the upgrades of the Tasmanian transmission system pre-Basslink may allow for water management opportunities that are not currently available.

It is concluded therefore, that whilst there have been opportunities for low Gordon River flows in the past, these have been associated with extraordinary events such as the commissioning of new plant or essential maintenance which could not be deferred and was possible under a less constrained electricity system compared to present. It is likely that the current maintenance practices associated with long shutdowns and hence scheduled power station shutdown patterns will not change markedly under Basslink and will not affect the probability of saline recharge of the meromictic lakes compared to present.

4.4 Mechanisms for lake recharge

The second and third steps of meromictic lake recharge as described in Hodgson and Tyler (1996), are by far the less understood mechanisms of the recharge process. The 3-dimensional mixing of the salt-wedge such that it is entrained in surface waters is suspected to be initiated by eddies upstream of Lake Fidler, in particular at Snag Point. This has not been fully confirmed through field surveys or modelling, however, it is possible that the more turbulent flows from pulsed power station operations under Basslink will provide more mixing that solid 'blocks' of generation.

Two-dimensional modelling of the estuary was undertaken to investigate salt-wedge behaviour at power station startup. The results indicated that the freshwater spate behaved more like a piston, pushing the salt wedge out of the estuary, rather than entraining it in the surface waters. This is similar to what was observed during recent field studies but is contrary to the field observations of Hodgson and Tyler (1996) and highlights the limitations of modelling such a complex phenomenon. It is reasonable to expect that, given intrusion of saline water to a point upstream of the meromictic lakes, it is possible, if not probable that some entrainment would occur, raising surface waters to the necessary salinities to augment the chemocline if intruded into the lake.

Of a less predictable nature is the process by which saline water enters the meromictic lakes. The rise in river level associated with the power station discharge is in the order of 30 cm and by itself is not enough to raise the river level sufficiently from a low flow level (required for salt-wedge intrusion) to a point that will overcome the crest in the connecting creek bathymetry and allow brackish water to flow into the lake.

It has been previously been postulated that sub-surface exchange may allow direct transfer of salt-wedge waters through permeable sediments to the lower levels of the meromictic lakes. It is unlikely that this mechanism of exchange is significant, because:

- the lakes are all highly organic and the bottom layers are likely to form a relatively impervious layer which effectively seals the lake from the surrounding ground water, reminiscent of perched lakes in coastal sand dunes. Some hydrostatic 'pumping' between the groundwater and the lakes may still occur without actual water exchange taking place.

- it is probable that if the lakes were open to significant ground water exchange, that the monimolimnion would be diluted far quicker than has been observed as the river water is now dominantly fresh and the groundwaters of the local catchment would serve to further dilute the monimolimnion;

- the salinity of groundwater in the region was investigated by Kearsley (1978). Few data were available, although it was concluded that groundwater salinity was generally very low.

- only Lake Fidler would be of sufficient depth to allow direct exchange of saline water. Lake Morrison and Sulphide Pool are both relatively shallow and would lie above the normal salt-wedge depth; and

- data have been collected that show brackish water inflow via the connecting creek to Lake Fidler, thereby confirming without doubt this method of delivery (eg. Hodgson and Tyler 1996).

Consequently, the standing theory of meromictic recharge as described in Hodgson and Tyler (1996), despite the 'uncanny congruence of events' that is required for this to occur still appears to be the best model for this complex phenomenon. As has been described earlier, it appears that the probability of recharge is high as long as sufficient salt-wedge intrusion has taken place in the river. It is unlikely that Basslink will have any further negative effects on these processes.

4.5 Probability of freshwater flushing during floods

Flooding in the catchment is likely to increase the dilution of the mixolimnion and possibly the monimolimnion through exchange of freshwater between the river and the meromictic lakes. No data are available on the heights of the levee banks surrounding the lakes in relation to flood heights, however, it is possible that large floods still overtop the levee banks and therefore allow direct flow of floodwaters into the lakes. This type of disturbance would have been relatively common under natural conditions, but is now less likely because of the regulation of the upper Gordon catchment.

It is assumed that overtopping of the levee banks is currently a rare event, however, water exchange is still common between the lakes and the river via their respective connecting channels. Despite this, flows of freshwater to the lakes via the connecting channels have far less potential for producing meromictic instability due mainly to the lower flood volumes involved and less turbulence associated with flows through a single constricted channel.

It has been predicted that Basslink will result in higher median flows from the Gordon Power Station than are currently experienced (Palmer *et al*, 2001). This is due largely to a higher predicted incidence of full-gate flows to meet higher peak electricity demand. The possibility that this pattern when combined with the natural catchment floods (excluding the dammed catchment) may increase flood volumes compared to present was investigated in order to assess any risk of major disturbance events due to Basslink. A duration curve for flow volumes is shown in Figure 26.

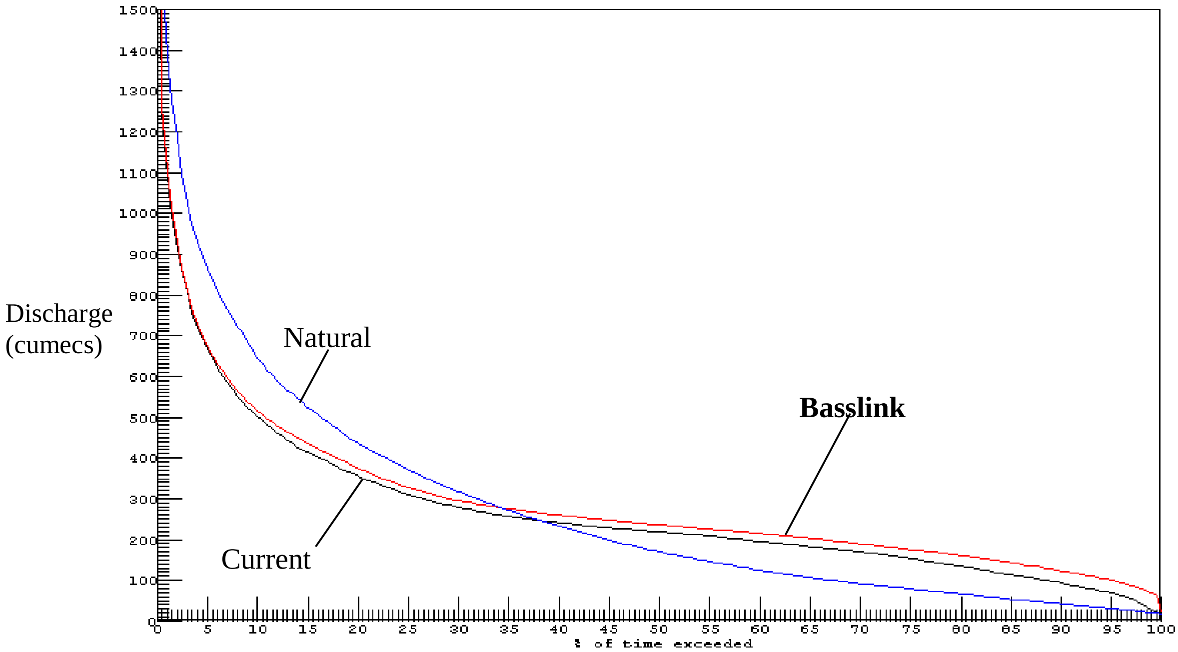

Figure 26. Discharge duration curve for the Gordon River below Franklin.

The curves relating to floods under current and Basslink scenarios are virtually identical and overlap entirely within the error boundaries of the estimates. The figures for Basslink also do not include maintenance and therefore tend to exaggerate the proportion of high flows. The reduction in flood heights compared with natural ones, by the Gordon and Serpentine dams is also clear. It is therefore concluded that the slight alteration in seasonal median flows from the Gordon Power Station will have no effect on flood volumes and therefore, no potentially negative effect on the meromictic lakes downstream.

4.6 Summary of Basslink implications

It is concluded that Basslink *per se* will not affect the probability of meromictic lake recharge. Similarly, Basslink will not increase the magnitude or duration of floods that may be significant to the disturbance of these lakes. It is also clear that the increase in short-term peaking of Gordon Power Station flows will not result in any significant river level variation issues in the lower reaches. Consequently, it can be concluded that Basslink will not affect the maintenance of meromixis in these unique waterbodies in comparison to the current situation.

Despite this, continued operations, in the pattern that has been evident particularly over the last decade represents a significant risk that long-term meromixis will be lost in Lake Fidler. Similarly, Lake Morrison and Sulphide Pool are also less likely to retain meromictic properties under the current regime. This poses a management issue that although not seen as a Basslink issue, does have implications for the operation of the Gordon Power Station and is discussed in the next section.

5 MANAGEMENT ISSUES AND MITIGATION OPTIONS

It is concluded that Basslink is unlikely to worsen the current trends towards loss of meromixis in the three Gordon meromictic lakes. Analysis of flow records indicate that suitable flow conditions for extensive salt-wedge intrusion have only been met on four occasions since the commissioning of the Gordon Power Station, each time associated with major maintenance or installation work. No shutdowns associated with historical operational patterns were identified during dry periods, and no periods of low flow have been experienced by the Gordon River estuary since 1996. This trend is expected to persist post-Basslink. Current shutdowns associated with major maintenance are already highly compressed and are unlikely to change post-Basslink, consequently, Basslink *per se* is not considered a threat to the integrity of the meromictic lakes and there are no impacts that could be attributed to Basslink that would require mitigation.

Regardless of Basslink, it is likely that long-term degradation of the meromictic lakes will continue due principally to the year-round maintenance of high river flows under the present operating patterns. The lack of saline recharge under the current situation is of great concern and should be investigated more fully with respect to the operation of the Gordon Power Station. Such investigations would by necessity run for a number of years and hence are ideally suited to Hydro Tasmania’s Water Management Review process. This process is well advanced for two of the six Hydro Tasmania catchments.

Despite the long-term (ie. non-Basslink) nature of this issue, a general discussion of the three most obvious mitigation options and issues is presented below.

5.1 Scheduled Power Station shutdowns

Under natural conditions, there would have been some probability of salt wedge intrusion due to low flows for 7 months of the year (Table 2), with June to October being too wet. Referring to the same table, it can be seen that under current operations, only 2 months of an average year have any chance of intrusion. Significantly, if the power station were to be shutdown all the time, the chances are markedly increased to 10 months per year, which has important implications for mitigation. The increase in probability compared to natural is due to the storage of the upper catchment and hence flows into Lake Gordon and Lake Pedder.

Despite the failure to achieve saline replenishment during two experimental shutdowns during 1999-2000 there is no doubt that it has occurred in the past. It is clear that some operating strategies minimise the probability of it happening whilst others would maximise the probability. Present evidence gives two clear criteria. First, shutdowns in summer-autumn, when natural river flows are at their lowest, would maximise penetration of the salt wedge in the Gordon River. Second, the longer the period of shutdown the greater the distance to which the salt wedge will penetrate, and the greater the chance of this coinciding with the subsequent high flows necessary to spill salt water into the lakes.

Power station operations after shutdown may be useful in “priming” the estuary by entraining salt into the surface waters through a series of pulses, before predicted rainfall. The possibility of low flows for ten months of the year, means that it may be possible to time shutdowns such that barometric pressure, wind speed and direction as well as rainfall patterns are the most favourable, not only during summer and autumn.

Table 2. Comparison of low flow periods between natural, current and with hypothetical power station shutdown: Percentage occurrence of 14-day average flows ≤50 cumecs (7-day average flows ≤31 cumecs in brackets) for the Gordon River downstream of the Franklin for the years 1979 to 1998 inclusive.

Month	Natural	Current	Powerstation shutdown
January	20.8 (11.4)	3.7 (3.6)	39.2 (24.7)
February	37.5 (19.7)	3.4 (1.1)	52.6 (35.6)
March	25.8 (13.6)	1.4 (0.3)	43.2 (26.6)
April	8.0 (4.2)	0	18.1 (8.7)
May	1.1 (0.0)	0	3.2 (2.6)
June	0	0	2.5 (0.0)
July	0	0	0.9 (0.0)
August	0	0	0
September	0	0	0
October	0	0	0.5 (0.0)
November	0.7 (0.0)	0	3.8 (0.8)
December	8.1 (4.7)	1.1 (1.0)	19.8 (10.6)
Full year	8.3 (4.4)	0.8 (0.5)	15.1 (9.0)

During dry periods or power station shutdown, the crucial factors are the distance to which the wedge penetrates, the salinity achieved in surface waters of the river as a result of turbulent entrainment at the salt-fresh interface, whether the accompanying rise in river level is sufficient to intrude water into the lakes, and the time it takes for the wedge to reach upstream during periods of low flow. Under the correct set of circumstances the power station discharge could be turned to advantage. With the salt wedge well upstream, the renewed discharge after a period of shutdown could augment the natural flow sufficiently to provide the spate necessary to intrude saline water into the lakes. Just such an event in 1988 (Hodgson & Tyler 1996) raised the surface salinity of the river to 8,000 $\mu S.cm^{-1}$ (Figure 10). It is not known what salinities are optimal, although it is assumed that any input of saline water will be beneficial. The benefits of any recharges will obviously be linked to their frequency and duration as well as the salinity and total volume of brackish water intruded.

The necessity for a temporal dimension to the model of wedge penetration boils down to a single consideration, the need to predict whether a planned shutdown of the power station of a given duration will permit recharge of the lakes by salt from the estuarine wedge. If posed in a connotative way, the model would be at its predictive best if it could say this for the complete range of natural conditions likely to be encountered during shutdown, or, if it could say how long a shutdown needed to continue under the conditions of the time.

Due to the complexity of this approach, it was decided instead to investigate thresholds relating to probable intrusions of the salt wedge. As shown earlier in Figure 23, it was found through modelling that there is a clear relationship between the distance of salt wedge intrusion in the river and the magnitude and duration of flows in the river. This relationship is indicative and does not take into account the sequence of flows throughout the time period. However, it has been demonstrated that the average flow during the period is far more important than the flow sequence in determining how far the salt wedge penetrates and hence is of considerable utility in investigating power station shutdown requirements.

In addition to the modelling approach, the two experimental shutdowns that were undertaken in conjunction with other field-work, were used to validate the predictions of the model. Both were extensively monitored. The full data sets show that each day during shutdowns the salt wedge crept further upstream and at any given site along the river the wedge approached progressively closer to the river surface, ie. the thickness of the wedge increased. In December 1999 the power station was shut down at 14.00hrs on the 17th. Between then and 18.00hrs on the 22nd the salt wedge failed to advance as far as Eagle Creek, about 10 km short of Lake Fidler. In March 2000, between 20.00 hrs on the 3rd and 21.00 hrs on the 6th it advanced to within 0.5 km of the lake, reaching there on the last day before the discharge from the reinstated power station was due to arrive. The salt-fresh interface, however, lay at a depth of 15m below the surface, under which conditions replenishment of salt in Lake Fidler was utterly impossible. Although failure to achieve recharge was disappointing, the data gathered on the salt wedge migration during this time were invaluable.

Failure to achieve replenishment of salt in Lake Fidler during two periods of shutdown should not occasion surprise. The two periods of closure had been chosen long in advance, without any means of ensuring that they occurred when tide, flow and wind conditions would be propitious. Clearly, in order to encourage salt wedge intrusion to a point upstream of Lake Fidler shutdowns need to be planned either to coincide with very favourable hydrological and meteorological conditions, or to persist for longer periods such that the probability of such a meteorological congruence is increased.

The modelling results indicate that salt wedge intrusion should be achievable within 7 days of power station shutdown during a very dry period (ie. 31 cumec average flow in the Gordon River downstream of the Franklin) or over a longer period (14 days) with higher flows (50 cumecs). If power station shutdowns were to be seriously considered as a mitigation measure, it would be necessary to:

- ensure that hydrographic recorders were maintained in the Gordon River downstream of the Franklin River and that data could be telemetered from this site to assess the real level of inflows to the estuary at any time;

- develop a network of stream and/or rain gauges coupled with hydrological modelling that could be utilised to predict catchment yield to some probability, such that power station operations could be timed (to account for lag times) for maximum benefit without undue (and expensive) restriction.

- undertake monitoring of salt wedge behaviour and the flows and water quality of the connecting channels of the meromictic lakes;

- monitor the stratification in the lakes through an array of salinity and redox probes that ideally would be permanently installed and telemetered; and

- ensure a realisation is created that recharge may not occur on any given occasion, due largely to the need for several events to take place that may not be under the influence of the power station. Consequently, several opportunities may need to be exploited before success is achieved.

A consideration in shutting down the Gordon Power Station is the role that it plays in maintaining freshwater flows in Macquarie Harbour during dry periods. There is some risk of disrupting circulation patterns near the aquaculture leases in Macquarie Harbour during long shutdowns (discussed in Appendix 26; Koehnken, 2001). The risk of exposing the fish cages to polluted water from the King River is a potential drawback to any shutdown related mitigation measures. Further research is necessary to ensure appropriate mitigation measures for the meromictic lakes can be planned to also minimise risk to aquaculture in Macquarie Harbour.

5.2 Direct injection of saline water

A less probabilistic approach is to deliver water at the appropriate salinity directly to the lakes, either via their respective inflow channels or into the lakes themselves. Such an approach gives exact control over the salinity of the inflowing waters, the volume delivered and the rate of delivery. This approach does have a major drawback in that intervention of this nature is counter to World Heritage Area management guidelines, which state that natural processes are important in the management of the WHA. Therefore the acceptability of such an approach would need to be determined through consultation with the relevant organisations.

If this approach was taken, direct injection would probably be best achieved by mixing saline water to the required salinity in a barge or boat mounted tanks. The saline water would best be sourced from the Gordon River itself, by utilising any salt wedge that is present, or from Macquarie Harbour. Water derived from the deeper sections of the Gordon River estuary may be suitable as this remnant salt water may share many chemical attributes with that of the monimolimnion of the meromictic lakes (refer to page 25). Water derived in this way would be superior to artificial seawater as it would contain organisms that would be likely to naturally flow into the lakes and would contain trace elements not found in commercial sea-salt mixes. Suitably mixed water could then be pumped to either the inflow channel, where recharge would occur through natural flow into the lake, or pumped directly to the appropriate depth of the lake determined by matching water densities. Detailed study would be required to determine the suitability and any potential negative effects of saline water derived in this way.

In either case, strict monitoring of the operation would be necessary to ensure that the rate of delivery was such that mixing of the lake was not occurring and that the meromictic stability of the lake was being maintained. Such recharges would probably pose the least risk if undertaken incrementally rather than during one operation.

5.3 Salt dosing

It would be possible to maintain the density of the monimolimnion and hence meromictic stability through direct dosing with crystalline salt or concentrated brine. This approach has the advantages of necessitating less equipment and hence disturbance of the natural environment compared with direct injection, but is limited to the considerations listed for direct injection and the fact that some trace elements as well as biological material would be absent in such a recharge.

5.4 Summary of mitigation options

Basslink does not pose an additional risk to the meromictic lakes of the Gordon River and hence no mitigation specifically aimed at incremental Basslink impacts is required.

The continued operation of the Gordon Power Station does pose risks for the sustained meromixis of these lakes, and an investigation of mitigation options is currently being investigated. Of the options identified to date, the scheduling of power station shutdowns is the least intrusive and capitalises on the natural processes that have been important in sustaining these lakes prior to regulation. This method does, however, have no absolute guarantee of success and has potentially adverse implications for the Macquarie Harbour aquaculture industry that would need to be investigated. Conversely, whilst direct delivery of saline water to the lakes is very likely to succeed, the method is more intrusive on the lakes themselves, may have unknown consequences and is in conflict with World Heritage Area management guidelines. Formulation of acceptable and effective strategies to reverse the current impacts of the Gordon Power Station will be a focus of the Gordon Water Management Review process.

6 MONITORING CONSIDERATIONS

Any further monitoring of Gordon River meromictic lakes should consider the following.

It is recommended that monitoring is undertaken post-Basslink in order to assess any changes in likelihood of salt-wedge intrusion in the lower Gordon River. The relationship between salt-wedge intrusion and river flows is now understood enough such that monitoring of river flows will provide an effective surrogate for salt-wedge monitoring. Hence it is recommended that:

- the Gordon below Franklin river level gauge (site 729) is retained on a long-term basis and that appropriate ratings to allow conversion to river discharge are maintained; and

- analysis of these river flow data are conducted such that the probability of occurrence of flow periods corresponding to a 14-day average of 50 cumecs and 7-day average of 31 cumecs can be compared pre- and post-Basslink. It will be necessary to make allowance for extreme natural events and/or emergency maintenance in this analysis and investigations should be conducted over a period of at least five years. Operational patterns since the corporatisation of the Hydro-Electric Commission in July 1998 are suggested as a realistic baseline.

In addition to the above monitoring that is strictly geared to Basslink, it is also recommended that future monitoring should address two additional components to ensure that long-term knowledge is gained for the effective management of these lakes, with or without Basslink:

- The status of Lake Fidler. This requires periodic measuring of vertical profiles of the physicochemical parameters that define meromixis. At its simplest this could be electrical conductivity (or salinity), temperature and oxygen measured *in situ* with a probe. This ideally is achieved through the installation of a temperature, salinity and redox array that would provide continuous long-term data that could be correlated with river flows and other environmental variables. Additional information could be gained from samples taken at close interval. From these the presence of hydrogen sulphide could be confirmed by smell. The most diagnostic indicator of meromixis, and of the depth at which the true metabolic watershed lies, would be a profile of redox potential. The instrumentation currently installed at Lake Fidler would provide evidence for any future inflows into the lake through measurement of channel flow, surface salinity and temperature. Monitoring of Lake Fidler should provide an appropriate reference for the other meromictic lakes although it will be necessary to determine this the suitability of this approach after further investigation.

- Penetration of the salt wedge. The main desideratum here is to monitor penetration of the salt wedge in the river under a wide range of conditions in order refine the predictive models developed as part of this study. Permanent vertical arrays of conductivity probes at a number of sites in the estuary would provide excellent data that could be supplemented by monitoring of the type carried out during the present studies.

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