SCIENTIFIC REPORT

SCIENTIFIC INVESTIGATION INTO EEL DEATHS IN WESTERN VICTORIA

PAUL LEAHY, RENEE PATTEN, ALEX LEONARD

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EXECUTIVE SUMMARY

Prior to the onset of below-average rainfall in 1997, more than 10 inland south-west Victorian lakes held substantial short-finned eel (Anguilla australis) populations. As of autumn 2007 lakes Colac and Purrumbete are the only ones that have a large eel population. The remaining water bodies have either dried up or experienced large-scale eel deaths.

In Lake Modewarre, Lake Tooliorook and Lake Bolac sudden mass eel deaths have occurred. In early 2005 EPA Victoria began a scientific investigation into the cause of the deaths. Over the course of the investigation, a number of theories as to the cause of the deaths were examined. The available evidence did not support a number of theories that had been proposed, including pollution, disease and overpopulation.

EPA developed a further investigation for the summer of 2006–07 with the aid of the Eel Death Investigation Reference Group, which consisted of representatives from key stakeholder groups and technical experts. The key focus of the investigation was to examine whether eel physiology or age influences their response to declining water quality conditions in western lakes, particularly increased salinity.

Background

Between Spring 2006 and Autumn 2007 a monitoring program was designed to assess changes in water conditions and eels. The four lakes monitored were Lake Modewarre, Lake Colac, Lake Tooliorook and Lake Bolac. EPA collected information on the conditions in the lakes using water quality loggers, which recorded information at every hour throughout the period. Eel blood was analysed for salt content and their sexual maturity was determined. Water sampling for toxin-producing algae was also undertaken.

Two large eel death events occurred between spring 2006 and autumn 2007. In late November 2006 the salinity was one-third that of seawater, but by March 2007 the salinity had risen to over twice that of seawater.

Findings

Major outcomes of 2006–07 monitoring

- The common link between all eel deaths was a salinity rise of 20–40 per cent in the four weeks prior to the deaths and a pH of around 9–9.5.
- EPA sampled the blood plasma of eels to see if their salt levels were within normal ranges. This work showed that the blood plasma salt levels of dying eels in Lake Tooliorook and Lake Bolac was much higher than eels from two other western Victorian waterways.
- The blood plasma salt level found in dying eels from Lake Bolac is higher than any previously recorded for eels in scientific literature.
- The actual salinity does not appear to be as important as the rate of increase. Other factors also make the salinity rise lethal.
- Rising salinity is exacerbated by extremely high pH. When the water pH is over 9 eels are more susceptible to rising salinity. This is likely to be due to the combined role of the gills in regulating both salinity and pH.
- Other factors like dissolved oxygen and turbidity may play a role in the eel deaths but are not as critical as rising salinity and high pH.
- There is no evidence of toxic algae being the cause of the eel deaths.
- Metal contamination was investigated again at Lake Bolac and there is no evidence to suggest that this was the cause of the eel deaths.

Future

Major recreational fisheries and a large commercial eel industry have been affected by the changes to Victoria’s Western District lakes. Their recovery depends on a period of sustained higher rainfall. If sufficient rainfall occurs and some of the salt is flushed from the lakes, then there is no reason the lakes cannot recover.

Drying and associated high salt levels are a natural part of many lake systems in Australia historically. The return of a wetter climate has seen a rapid return by the plants and animals that inhabit the lakes.

Western District lakes and climate change

The greatest threat to the recovery of the Western District lakes in the long term is likely to be climate change. These lakes tend to act like large rainfall gauges, with lake levels heavily dependent on rainfall. Sustained below-average rainfall and low run-off into lakes leads to low water levels and, eventually, complete drying. The investigation into eel deaths has underlined the susceptibility of even hardy fish like eels to low rainfall conditions.
The effect of drought on south-west Victoria in the last 10 years has been an insight into the consequences of climate change on Victoria’s Western District lakes.

The potential for fish deaths in Lake Colac

Lake Colac is one of the last large inland lakes in south-western Victoria with a substantial fish population. In Autumn 2007 it was estimated that perhaps over 500 tonnes of fish were present in the lake. If the trends of increasing salinity and pH in Lake Colac continue as they have for the last three years, then it is likely that large-scale fish deaths will occur.

EPA’s research has shown that carp are most susceptible to the changes in salinity, followed by redfin and then eels. Unless there is substantial summer rainfall then we predict that deaths will occur in the 2007–08 summer. If pH remains low then we expect that carp and redfin deaths will be followed by eel deaths. If pH rises quickly then deaths may happen in quick succession.
1. INTRODUCTION

Since December 2004, EPA Victoria has been investigating large fish and eel deaths in southwestern Victoria. Previous reports by EPA have highlighted the extreme conditions present in the Western District lakes during eel deaths. Investigations over the 2006–07 summer centred on developing a better understanding of short-finned eel (*Anguilla australis*) populations in western lakes and a detailed knowledge of their response to water conditions in the lakes.

Leahy *et al* (2007) summarised EPA’s investigation to date and highlighted remaining questions to be answered in the 2006–07 summer. The key areas to be addressed were:

- the impact of eel maturity on eel mortality
- the nature of water quality changes in the lakes
- the physiological response of eels to changing water conditions
- the potential presence of algal toxins in the lakes.

A review of the causes of eel deaths in previous summers highlighted the likelihood of deaths occurring in Lake Bolac and Lake Tooliorook in the 2006–07 summer. In consultation with the Eel Death Investigation Reference Group, which consisted of representatives from key stakeholder groups and technical experts, a monitoring program was designed to investigate these issues. The program began in spring 2006 and involved continuous water quality measurement through deployed water quality loggers, monthly monitoring of the lakes for algae and water chemistry and sampling of eels for maturity and blood chemistry.

In late November to early December 2006 a large number of eels died in Lake Tooliorook, five kilometres south-west of Lismore. In March 2007, probably the largest number of eels so far died at Lake Bolac (Figures 1 and 2). These came after large eel deaths at Lake Modewarre and Lake Bolac in previous summers (Leahy *et al* 2007). This report provides an overview of EPA’s findings on the cause of eel deaths.

Monitoring in previous summer periods identified a relationship between rapidly rising salinity and the eel deaths, suggesting the eels were unable to regulate the rising salinity in their blood. Part of the 2006-07 sampling focused on collecting data to determine if this was the case.

Figure 1: Dead eels among seagrass mats at Lake Tooliorook, December 2006
Fish maintain salt and water balance internally through osmoregulation, which occurs within a range that permits normal physiological functioning. The major osmoregulatory organs in fish are the gills and kidneys and, to a lesser extent, the skin, urinary system and gut (Jobling 1995).

In freshwater, fish must avoid the loss of salts by reabsorbing them and by the production of large volumes of dilute urine (Martinez et al 2005). Conversely, in saline water, fish must remove excess salt and avoid the loss of water from their bodies (Shuttleworth and Freeman 1973).

Gills are the point of exchange between fish and the aquatic environment. This includes the regulation of the internal concentration of salts, removal of wastes and exchange of gases like oxygen and ammonia (Maetz 1971).

The plasma component of blood is the body’s major transport mechanism for salt. Vertebrates generally keep the salt concentration in their blood plasma within a relatively narrow range. Tight control of plasma salt levels is necessary for normal physiological functioning (Lutz 1972).

The salinity difference between freshwater and seawater is a factor of about 200. However, the difference between freshwater and seawater fish blood plasma salinity is only around 25 per cent (Jobling 1995). Numerous studies on several eel species have shown that eels maintain plasma sodium concentrations within a very narrow range, even when comparing eels adapted to freshwater or to seawater (for example Kirsch 1972a). Although research has found that freshwater and seawater-adapted eels have stable blood plasma concentrations, during the period when eels are adapting to seawater, they have elevated salt concentrations in their blood plasma, a phenomenon known as ‘hypermineralisation’ or ‘sea-shock’.

A review of the scientific literature found there have been no studies of the blood plasma ions of A. australis, nor A. reinhardtii, the other south-eastern Australian eel species. Given the rise in salinity and pH observed in western Victorian lakes (Leahy et al 2007), blood plasma may be an important indicator of the response of A. australis to changing water conditions.

The major ion salts regulated by osmoregulation are sodium (Na+) and chloride (Cl-), with much lower concentrations of potassium (K+), magnesium (Mg2+), calcium (Ca2+) and other ions including sulfate (SO42-), carbonate (CO32-) and bicarbonate (HCO3-). In saline water, the regulation of the monovalent ions (Na+, Cl- and K+) largely takes place in the gills; specifically, in
The chloride cells (Jobling 1995). The divalent ions (Mg\(^{2+}\), Ca\(^{2+}\) and SO\(_4^{2-}\)) are predominantly regulated through the kidney in saline waters (Cleveland and Trump 1969).

In considering the osmoregulation of fish, pH must also be considered. Water pH is an important consideration for fish health. At low pH, fish are susceptible to the high bioavailability of some metals like aluminium (Alabaster and Lloyd 1982). At high pH, like the levels recorded in western Victorian lakes (Leahy et al 2007), gill ammonia excretion can be blocked, leading to death (Eddy 2005). Ammonium can substitute for sodium and potassium, blocking the normal osmoregulation processes (McKenzie et al 2003). One consequence of this is that fish are susceptible to combined stress upon the gills: for example, high salinity and low dissolved oxygen or high salinity and high pH.

High salinity (greater than 50 per cent seawater) and high pH (9 to greater than 10) are common characteristics of the Western District lakes in this study. These conditions are similar to those that Wilkie and Wood (1996) describe as being inhospitable for all but a small number of fish able to tolerate extreme conditions because of their specialised adaptations. Another possible influence on the osmoregulatory ability of the eels is their stage of sexual maturation. Chan et al (1967) found that, in comparison with yellow, immature European eels (A. anguilla), silver, mature European eels showed a range of changes upon transfer to seawater, suggesting a better ability to cope with higher salinity.

As described in McKinnon (2006), eels of the genus Anguilla have complex life cycles, with both freshwater and marine phases. Eels undertake extensive seaward migrations to spawn, after spending much of their lives in freshwater. Eels undergo a process of morphological and physiological change, which enables them to prepare for a long migration and reproduction. Characteristic changes with the onset of migration include the initiation of sexual maturity and migratory behaviour. Such changes include shrinking of the gut, changes in colour, lengthening of the pectoral fins, enlargement of the eyes and development of sexual organs (Pease 2004, Tesch 2003). This process is known as ‘silvering’ due to the characteristic silver colour of migrating eels.
2. METHODS

Site location and description

Four lakes were monitored during the 2006–07 monitoring period: Modewarre, Colac, Tooliorook (also known as Ettrick Lake) and Bolac (Figure 3). Table 1 shows data collected during the 2006–07 monitoring period. The monitoring program is given in more detail in the following sections.

These lakes have been the focus of previous reports by Leahy et al (2007), with the exception of Lake Tooliorook, which is located five kilometres south-west of Lismore. Lake Tooliorook was added as a monitoring location because it had similar characteristics to Lake Modewarre and was predicted to be susceptible to eel deaths in the summer of 2006–07.

All four lakes have historically had large populations of short-finned eel (*A. australis*), supporting a commercial fishery. These lakes have also been important recreational fisheries, with redfin (*Perca fluviatilis*) and brown trout (*Salmo trutta*) the most important recreational species.

For comparison with the inland lakes, water quality, chemistry and eels were collected from Belfast Lough, the estuarine lake section of the Moyne River, Port Fairy, in February 2007. Belfast Lough is geographically close to the lakes, has a similar catchment geology and is kept open to the sea for boating. The salinity of Belfast Lough should remain relatively constant and similar to that of seawater. Therefore the condition of the eels from this location is of interest for comparison to the inland lakes that experienced large changes in salinity.

All four monitored lakes have a lunette-type formation, with sandy eastern shores and typically muddy western shores. The maximum depth of the lakes is less than four metres while, in recent times, none has been deeper than one metre.

Lakes Modewarre and Tooliorook are characterised by abundant growth of submerged seagrass (*Ruppia* sp.) and typically have low turbidity. In contrast, Lakes Bolac and Colac are historically turbid and have had high algal concentrations in their water columns (Leahy et al 2007).

Collection of in-situ water parameters

In-situ water quality was monitored by the use of two calibrated water quality loggers in each lake. Water temperature, dissolved oxygen, pH and electrical conductivity were measured and recorded by all loggers, with turbidity measured and recorded on selected loggers only. All measurements were
### Table 1: Overview of data collected from October 2006 – April 2007

<table>
<thead>
<tr>
<th>Location</th>
<th>Month</th>
<th>Eel Morphology</th>
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recorded hourly. The loggers were cleaned and recalibrated on average every three weeks, more frequently where biofouling was an issue. Water quality was checked independently using calibrated handheld meters.

Two loggers were located in each lake with deployment limited to the shores of the lakes due to shallow water. Although a logger was deployed in the centre of Lake Bolac, it had to be removed in November 2006 as boat access was prohibited by the lower water levels. The loggers were deployed by wading out to approximately 100 m from shore and positioned at a depth of 5–20 cm in a minimum of 30 cm of water.

Due to the soft sediments and difficulty in access on the western sides of the lakes, loggers were placed in the east and south-east sides at lakes Modewarre and Bolac and in the south-east and north east at Tooliorook. At Bolac, the logger situated in the east was relocated to the north-west shore, due to the receding waterline. In Lake Colac, loggers were placed on the eastern and western shores to avoid sabotage, as these were the most secure locations in this lake.

**Chemical analysis**

In addition to the continuous logging of water quality, water samples were collected for major ions and alkalinity. Samples were analysed by two National Association of Testing Authorities (NATA) accredited laboratories, both following *Standard Methods* (APHA 2005). Major ions analysed were sodium (Na⁺), calcium (Ca²⁺), magnesium (Mg²⁺), potassium (K⁺), chloride (Cl⁻), and sulfate (SO₄²⁻).

As reported in Leahy et al (2007) metals, particularly aluminium and selenium, were high in water samples collected from Lake Bolac in January 2006 during the eel deaths. This was presumed to be due to the high levels of suspended sediments in the water column (that is, clay and silts). The high suspended sediment levels during the January 2006 sampling prevented filtration of the water samples to determine if the metals were likely to be soluble and, hence, bioavailable.

During the Lake Bolac eel deaths in March 2007 metals sampling was repeated to determine whether there were high levels of bioavailable aluminium. Lower suspended sediment in March 2007 meant that water could be filtered through a cellulose acetate 0.45 μm filter. Filtered and unfiltered samples were acidified in the field with nitric acid to pH 1–2. Metals analysis was undertaken by a NATA-accredited laboratory, following *Standard Methods*.

**Algal analysis**

During the monthly algae sampling two samples were collected: one sample was preserved with Lugol’s solution and another was kept at 15 °C with no preservative, to keep the algae alive. Microscope cell concentration counts were performed on the Lugol’s preserved sample, while the unpreserved sample was used for confirmation of identifications. Algae were generally identified to the lowest practical level, generally genus.

**Eel collection**

Fleets of fyke nets were set in all lakes and Belfast Lough. Nets were set for two days to ‘fish in’, cleared and then left for 24 hours prior to fish collection. Fishermen chose locations most likely to yield fish. Nets were evenly distributed within Lake Tooliorook and Belfast Lough.

In lakes Bolac, Colac and Modewarre, the placement of nets was restricted to their eastern side because of constraints in depth and substrate type. Commercial fishermen report reduced net mortality on the eastern shores of these lakes. A random subsample of around 30 eels was taken from the fishermen’s nets, although the actual number analysed varied depending on fishing success and mortality in transit.

During the eel deaths at lakes Tooliorook and Bolac numerous eels were observed moving lethargically through the water. These eels were easily collected by hand nets and by seine netting and were also analysed.

**Blood plasma collection and analysis**

For blood analysis, 1–3 mL of blood was collected from the truncus arteriosus in euthanased eels using an 18-gauge syringe. Blood was expelled from the syringe with the needle removed, to avoid physical damage to the red blood cells. The blood was allowed to clot at room temperature for two hours, before being centrifuged at 6000 RPM until plasma was clear. The plasma was removed and stored at -20 °C until analysis.

Ion analysis was performed within a week of sample collection to avoid concentration of the plasma. Some red tainting of the plasma was observed, and clearly tainted plasma samples were not analysed. Plasma ions were analysed by two NATA-accredited laboratories.

**Eel measurements and maturity determination**

Each eel was weighed and external measurements were recorded for the left pectoral fin, left eye diameter (vertical and horizontal) and total body length. For each eel sampled at Bolac, Colac, Tooliorook and Belfast Lough (no eels were caught at Lake Modewarre), the stage of maturity was calculated using the silverting index developed by Van den Thillart et al (2005). The silverting index uses length, weight, mean eye diameter and pectoral fin length.
The Gonadosomatic Index (GSI = [gonad weight/body weight] x 100), a commonly used method of calculating sexual development in fish, was also calculated for a subsample of eels where gonads could be sampled and weighed.

**Estimation of eel mortality**

To estimate the number of dead eels, every visible eel was counted within 10 evenly distributed 100 m long lake edge segments. Eels were counted if visible from shore within the 100 m segment. The average number of eels counted per 100 m segment was then extrapolated to the whole lake using the length of the perimeter of the lake. This method is likely to underestimate the number of dead eels, as some may not be visible below the surface of the water or towards the centre of the lake.

### 3. RESULTS

#### Climate conditions in 2006–07

Previous reports by EPA have highlighted the relationship between the deaths and the low rainfall in south-western Victoria (Leahy et al 2007). Figure 4 shows the rainfall deficiency (difference from long-term average) in Victoria for the 12 months prior to April 2007.

Rainfall in south-west Victoria was in the lowest 5 to 10 per cent of records during this 12-month period. The consequence of this and the low rainfall since 1997 was that many lakes in the region dried up. By Autumn 2007 both Lake Modewarre and Lake Bolac were close to drying up, with the water depth less than 30 cm.

#### Fish deaths in the summer of 2006–07

Eel deaths occurred in Lake Tooliorook and Lake Bolac in the 2006–07 monitoring period. At Lake Tooliorook eels began dying around 23 November 2006. Sick and dying eels were observed up until around 18 December 2006. The number of dead eels by mid-December was estimated to be 75,000. Healthy galaxiids were observed during seine netting in late November 2006 during the eel deaths. No dead galaxiids were observed during the eel deaths, but this may have been due to their small size.

Because of the high eel mortality, the commercial eel fisherman ceased fishing the lake in mid-December 2006. It also became increasingly difficult to set nets in the lake due to lack of depth and dense seagrass.
beds and so no eel survey netting was undertaken after the eel deaths in December 2006.

At Lake Bolac an estimated 50 to 100 golden perch died in early February 2007, but this was not reported to EPA at the time of the deaths. High eel mortality rates of over 25 per cent in fyke nets were observed by commercial eelers from around 13 February 2007 onwards. However, other than dying in the nets, eels were not observed dead in the lake until 11 March 2007. Eels were then observed dying and dead over a two-week period. By 29 March 2007, no live eels were sighted and no eels were caught by commercial eelers in their nets. The estimated number of eels dead at Lake Bolac in March 2007 was 95,000.

Commercial eelers estimated that the number of eels in the lake at the start of summer 2006–07 was around 150,000. Given the heavy fishing prior to the deaths and the likely underestimate of death event size, it is unlikely that live eels remained in the lake at the end of the 2006–07 summer period.

Eels were observed attempting to burrow into sediments in Lake Bolac during the deaths. Eels have been known to burrow into sediments as a survival mechanism (Tesch 2003), and this may be one way that eels could survive in Lake Bolac. Up to 500 pelicans were observed at Lake Tooliorook in early December 2006 and many were observed feeding on eels. The consumption of eels is another reason why the actual number of dead eels may be higher than estimated.

Small numbers (fewer than 50) of European carp (Cyprinus carpio) died in Lake Colac in January and March 2007. Both incidents were linked to run-off from rainfall events. Carp were observed showing spawning behaviour, and dissection of the carp showed they were heavily laden with eggs or male gonads.

Carp mortality associated with spawning is frequently reported to EPA, particularly after rainfall events. The carp become lethargic and can get stranded at such times. In these cases, the carp deaths are considered to be due to a different process than the eel deaths at Lake Tooliorook and Lake Bolac.

**In-situ water quality**

The water quality monitoring results for lakes Modewarre, Bolac and Colac up until the start of the 2006–07 summer period have been presented in Leahy *et al* (2007). For comparison, longer-term electrical conductivity sourced from the Victorian Water Quality Monitoring Network (VWQMN) and earlier EPA investigations for Bolac and Tooliorook is presented in Figures 5 and 6. Water quality monitoring during the 2006–07 summer period for the four lakes is presented in Figures 7–18.

![Figure 5: Long-term electrical conductivity in Lake Bolac, 1977 – April 2007](Monitoring data from www.vicwaterdata.net)
Figure 6: Electrical conductivity in Lake Tooliorook, December 2005 – April 2007
(Monitoring data from www.vicwaterdata.net)

Figure 7: Electrical conductivity in Lake Bolac, October 2006 – March 2007
Figure 8: Electrical conductivity in Lake Tooliorook October 2006 – March 2007.

Figure 9: Electrical conductivity in Lake Modewarre, October 2006 – March 2007.
Figure 10: Electrical conductivity in Lake Colac, October 2006 – April 2007
(Different scales used for Lake Colac compared with other lakes)

Figure 11: Turbidity in Lake Bolac, October 2006 – March 2007
Electrical conductivity (a measure of salinity) increased at least twofold in all the monitored lakes over the course of the 2006–07 summer monitoring period (Figures 7 to 10). Although groundwater and surface run-off may add a small amount of salt to the lakes studied, a doubling of the conductivity equates roughly to a halving of the volume of the lakes.

The greatest increase in electrical conductivity was at Lake Bolac, which exhibited a fivefold increase between spring 2006 and autumn 2007. The electrical conductivity recorded in the lake was unprecedented in 30 years of water quality monitoring (VWQMN 2007).

In all the lakes studied, the increase in the summer of 2006–07 was greater than previously recorded summer rises (see Figures 5 and 6, and Leahy et al 2007). This is likely to relate to the severe rainfall deficiency for much of south-west Victoria (Figure 4) and the increasing rate of evaporation in shrinking water bodies, which heat up more readily.

Figures 7 and 8 show that the eel deaths at Lake Tooliorook and Lake Bolac were associated with a period of increasing salinity. In the four weeks preceding the eel deaths, the salinity rose as follows:

- 40 per cent at Lake Bolac in March 2007
- 20 per cent at Lake Tooliorook in November 2006
- 20 to 35 per cent at Lake Modewarre in January 2005 and January/February 2006
- 35 per cent at Lake Bolac in January 2006.

**Turbidity**

Turbidity was much higher in Lake Colac and Lake Bolac, which typically greatly exceeded 100 NTU (nephelometric turbidity units), compared with Lake Modewarre and Lake Tooliorook, which were normally less than 20 NTU (Figures 11 and 12). The turbidity of lakes Modewarre and Tooliorook are not shown, as these lakes display similar patterns to lakes Colac and Bolac respectively.

Although turbidity was high at lakes Bolac and Colac, both generally decreased through the monitoring period. This was particularly apparent at Lake Bolac, where average turbidity decreased from around 300–500 NTU in November and December 2006 to around 100 NTU in February 2007.

The decline in turbidity in Lake Colac was not as great, however, with the exception of periods of high turbidity in February and March 2007, average turbidity was clearly lower towards the end of the monitoring. In both Lake Bolac and Colac, declining turbidity appears inversely related to rising salinity, which is commonly seen in saline waters (Gregory 2006) (Figures 11 and 12).
pH

The pH in all four lakes was extremely high, especially at Lake Modewarre and Lake Tooliorook (Figures 13 to 16). In Lake Modewarre, pH was usually between 9.5 to 10.5, and exceeded 10 for much of the monitoring period. In Lake Tooliorook, logger and spot measurements taken around the lake on the same day showed a difference of up to 1 pH unit at different locations in the lake. This suggests a lack of mixing in the lake, probably because the sea grass, *Ruppia* sp., forms dense beds, restricting water movement in the lake. The pH declined through the monitoring period at both Lake Modewarre and Lake Tooliorook. A likely explanation for the high pH in Lake Modewarre and Lake Tooliorook is the abundant seagrass, which is likely to increase pH through high productivity. Although pH was lower in Lakes Bolac and Colac, generally between 8 and 9, pH rose in both lakes by over 1 pH unit within a two-month period during summer. In Lake Bolac, pH peaked at 9.86 in mid-February 2007, and in Lake Colac pH peaked at 9.6 in February and March 2007. At Lake Bolac, eel mortality in fishing nets rose following this high pH.

![Figure 13: pH in Lake Bolac, October 2006 – March 2007](image-url)
Figure 14: pH in Lake Tooliorook, October 2006 – March 2007

Figure 15: pH in Lake Modewarre, October 2006 – March 2007.
Dissolved oxygen

Figures 17 and 18 show dissolved oxygen data for lakes Bolac and Tooliorook. Dissolved oxygen data for Colac and Modewarre are not presented, as these lakes have dissolved oxygen patterns similar to Bolac and Tooliorook, respectively.

Hourly monitoring data has been presented as the daily average, maximum and minimum of two loggers in each lake. Inspection of the dissolved oxygen monitoring data showed diurnal patterns in all lakes (not shown), with the daily maximum typically corresponding to a mid-afternoon peak and the minimum to an early-morning trough.

In the first half of the monitoring period, dissolved oxygen fluctuation was greatest in the two macrophyte-dominated lakes, Modewarre and Tooliorook, ranging between 50 and 250 per cent saturation (see Figure 18 for Lake Tooliorook results).

In Colac and Bolac, dissolved oxygen was much more variable in the second half of the monitoring period, which relates to greater algal activity during this period, ranging between close to zero and 350 per cent saturation (see Figure 17 for Lake Bolac results). Algal concentrations were higher in these two lakes in March and April 2007 (Figure 23).

At Lake Tooliorook, minimum (that is, overnight) dissolved oxygen dropped substantially following the eel deaths. The combined effect of a large biomass of rotting eels and seagrass presumably acted to increase oxygen demand in the lake. Areas of stagnant anoxic water with purple sulphur bacteria were observed in patches in the lake.

At Lake Bolac dissolved oxygen declined before the eel deaths in March 2007. This is most apparent in the daily minimum dissolved oxygen, which declined in February 2007. High mortality was seen in nets at this time, indicating netted eels were subjected to multiple stressors. In the week before the widespread deaths, the daily minimum dissolved oxygen was close to zero. Minimum dissolved oxygen recovered to 20 to 50 per cent when eels were dying.

It is understood that eels can tolerate low and temporarily anoxic conditions (McKinnon 2006) and so low dissolved oxygen is not considered to be the sole cause of the eel deaths. However, the low oxygen prior to the deaths may have exacerbated the effect of other stressors in the lake such as high pH and salinity.
Figure 17: Dissolved oxygen (%) in Lake Bolac, October 2006 – March 2007

Figure 18: Dissolved oxygen (%) in Lake Tooliorook, October 2006 – March 2007
In situ water quality and major ions were assessed at Belfast Lough, Port Fairy in February 2007, during netting for eels. In situ measurements were collected at two locations in the estuary on 14 and 16 February 2007. Conditions were similar at both locations on both days and average in situ water quality measurements and major ion concentrations are presented in Table 2.

The pH and electrical conductivity suggest Belfast Lough is similar in composition to seawater. Salinity at Belfast Lough was around 40 ppt or 58,000 μs/cm, which is higher than the salinity of Lake Tooliorook at the time of the deaths, but lower than Lake Bolac during deaths there.

Electrical conductivity varied by less than 10 per cent in the different sampling events. The pH in Belfast Lough was around 8, and generally much lower than the values recorded for the four lakes. Dissolved oxygen in Belfast Lough was around 60 per cent saturation. This is not high, but was sufficient for fish survival.

**Major ion analysis of water**

Analysis of major ion proportions at lakes Bolac, Colac, Modewarre and Tooliorook showed that the ionic composition, calculated from molar concentrations, remained relatively stable throughout the 2006–07 sampling period (Table 3). Differences in average composition of the cations sodium (Na⁺), calcium (Ca²⁺), magnesium (Mg²⁺) and potassium (K⁺), in comparison to seawater composition as reported by Atkinson and Bingman (1998), are also shown in Table 3.

Samples collected in February 2007 showed that the ionic composition of Belfast Lough water is comparable to that of seawater (Table 3). The western lakes studied showed similar proportions of sodium in comparison with seawater, with most variation shown in proportions of magnesium, potassium and calcium.
Lake Tooliorook and Lake Bolac have significantly higher proportions of magnesium, with their recorded ranges clearly higher than that reported for seawater. This is indicative of the location of these lakes within volcanic plains. Lake Colac also has a greater proportion of magnesium in comparison to seawater, but not to the same degree as Bolac and Tooliorook.

The proportion of potassium in the western lakes studied is much lower than ranges reported for seawater or Belfast Lough.

Significantly lower proportions of calcium in Tooliorook and Modewarre in comparison to the other water bodies studied may be indicative of their macrophyte dominance. Calcium is a micronutrient required only by some algal species, whereas it is a universal requirement of macrophytes and other higher order plants for normal metabolic processes (Wetzel 2001).

The western lakes studied showed no significant changes in ionic composition during the 2006—07 summer. This suggests that change in proportions of ions was not a mechanism for the eel deaths.

**Eel maturity and sexual development**

On the basis of the silvering index of Van den Thillart et al (2005), five stages were identified in the 285 eels sampled at Lake Colac, Lake Bolac, Lake Tooliorook and Belfast Lough (Figure 19 and Table 4) The stages identified were: undifferentiated stage 1 eels; female stage 2, 3 and 4 (FII, FIII and FIV) eels; and male stage 2 (MII) eels.

Undifferentiated and FII eels are considered resident eels (immature growth phase), FIII are pre-migrant eels and FIV are migrant eels. Only one male was identified from the silvering index and was not considered in further analysis.

Table 4 shows the mean and 95 per cent confidence limits for the morphological variables measured for undifferentiated and female eels, grouped by the stages identified in the silvering index.

The silvering index was found to categorise eels into maturity stages with distinctive ranges in length, weight, eye diameter and pectoral fin length. The mean length and weight of migrant eels as determined by the silvering index in this study are comparable to values obtained for A. australis classified as migrant by De Silva et al (2002).

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**Figure 19: Relative abundance of silvering stages for eels sampled at lakes Colac, Bolac and Tooliorook and Belfast Lough.**
Further support for the applicability of the silvering index to *A. australis* is seen in the gonad development of the different stages. Gonad development (calculated from the gonadosomatic index, GSI = [gonad weight/bodyweight] x 100), increased with each class identified by the silvering index (Table 4). Mean GSI of females increased from 0.67 per cent ±0.16 (±95% CI) in resident stage II eels, to 1.03 per cent ±0.24 in pre-migrant stage III eels, and to 1.62 per cent ±0.19 in the migrant stage IV eels. These values are similar to those obtained by Van den Thillart et al (2005), who recorded a mean GSI of 0.54 per cent for stage II females, 0.8 per cent for stage III females and 1.5 per cent for stage IV females.

These results suggest that the use of the silvering index (Van den Thillart et al 2005), although based upon another species of eel, was appropriate to determine the maturity of *A. australis* collected during this study.

**Eel blood plasma ion analysis in western Victoria**

**Treatment of data**

It has been suggested that the osmoregulatory ability of eels increases with morphological change and sexual development, with changes in the type of chloride cell identified as the mechanism for this change. (Sasai 1998).

At each sampling event for Lake Bolac, Lake Colac, Lake Tooliorook and Belfast Lough, eels sampled showed variability in their maturity as determined by Van den Thillart’s (2005) silvering index (Figure 19). Van den Thillart (2005) found that, from the four variables used in this model, mean eye diameter was found to be the most important explanatory variable, followed by fin length and weight. Body length was the least significant variable. Therefore mean eye diameter was used as a representative measure of maturity in a regression of blood sodium concentration with eye diameter, to explore the possible relationship of maturity on the blood plasma and osmoregulatory ability of the eels sampled at each sampling event.

The regression results (R²) are shown in Table 5. Mean eye diameter was found to have no significant effect (p >0.05) on blood sodium concentration of eels in all but those eels sampled during the eel deaths in Lake Bolac in March 2007 (p=0.01, n =21).

Three maturity classes were identified in the sample at Lake Bolac in March 2007 (stage II females n= 5, stage III females n= 15, stage IV females n= 1), but the sample sizes for all but the stage III females were small.

Further support for the applicability of the silvering index to *A. australis* is seen in the gonad development of the different stages. Gonad development (calculated from the gonadosomatic index, GSI = [gonad weight/bodyweight] x 100), increased with each class identified by the silvering index (Table 4). Mean GSI of females increased from 0.67 per cent ±0.16 (±95% CI) in resident stage II eels, to 1.03 per cent ±0.24 in pre-migrant stage III eels, and to 1.62 per cent ±0.19 in the migrant stage IV eels. These values are similar to those obtained by Van den Thillart et al (2005), who recorded a mean GSI of 0.54 per cent for stage II females, 0.8 per cent for stage III females and 1.5 per cent for stage IV females.

These results suggest that the use of the silvering index (Van den Thillart et al 2005), although based upon another species of eel, was appropriate to determine the maturity of *A. australis* collected during this study.
Regression of mean eye diameter and blood sodium concentration of these stage III female eels showed no significant relationship \( (p=0.36) \).

Regression suggests that maturity has no effect on the concentration of blood sodium of eels sampled during 2006–07. Although a statistically significant relationship was apparent in eels sampled at Lake Bolac in March 2007, the sample sizes of the smallest and largest eels were too small to make further conclusions. Blood ion concentrations were therefore examined as averages by sampling event for further analyses. No distinction between maturity stages was made.

**Comparison of plasma ion concentrations between lakes**

Principal component analysis was performed on the blood concentrations of sodium, chloride, potassium, magnesium, calcium and sodium/potassium ratio of 110 eels from four waterways (Figure 20).

With the exception of the sodium/potassium ratio and potassium concentration, all blood ion variables are positively correlated with axis 1 of the ordination plot (Figure 20). Axis 1 represents a blood ion concentration gradient, with the position of the clusters along the axis due primarily to the concentration of blood sodium and chloride, which increase in later sampling events at Lake Bolac and Lake Tooliorook.

Eels sampled during the death event at Lake Bolac in March 2007 form a cluster clearly separated from other samples, signifying the extreme concentrations of ions in the blood of these eels.

The sodium/potassium ratio is positively correlated with axis 2, while potassium is negatively correlated to this axis. Samples collected at Lake Tooliorook during the death event in November/December 2006 are positively associated with axis 2, reflecting a higher sodium/potassium ratio (generally) in comparison with other samples and have a greater dispersion across axis 2. This plot shows that samples for each sampling event display clear groupings on the ordination plot, indicating the blood ion concentrations of eels for each sampling event are relatively similar.

**Figure 20: Ordination plot of blood ion concentrations of 110 eels sampled at Lake Bolac, Lake Colac, Lake Tooliorook and Belfast Lough 2006–07**
Comparison of eel blood plasma ion values in western Victoria with published literature

Plasma values from studies of eels in freshwater, those adapting to seawater (in ‘sea-shock’) and those adapted to seawater are compared with the results of this study in Figures 21 and 22.

They show that mean sodium values for all western Victorian locations in this study fall outside the range that would be expected by linear interpolation between upper literature values for freshwater and seawater-adapted eels (Figure 21). This is even apparent in the mean sodium plasma concentration for the lowest water salinity sample from Lake Colac.

This suggests that either A. australis has relatively higher plasma sodium concentrations or that there are unmeasured differences between samples collected in the field and laboratory conditions.

The fact that all non-death event samples fall on the line of best fit, as determined for eels sampled in the western lakes during this study, is suggestive of a systematic difference between A. australis and other eels. Analysis under laboratory conditions would be required to further elucidate this.

Comparing the average plasma sodium in the two eel death sampling events, only Lake Bolac samples during the March 2007 death event are elevated in comparison to the straight-line increase for A. australis. The average plasma sodium for the Lake Tooliorook deaths falls on the line of best fit for A. australis non-death event samples.

Mean chloride plasma values for the lower salinity sampling events (Lake Colac, December 2006 and Lake Bolac, November 2006) fall within the range of linear increase between upper literature values (Figure 22).

Analysis of inter-laboratory comparisons showed there is some uncertainty in the absolute chloride values, but the relative difference between samples in this study should be accurate. Based on the water salinity during the deaths at Lake Bolac and Lake Tooliorook, average plasma chloride values clearly exceed what would be expected based on the linear increase for A. australis non-death event values.

This suggests that eels during the death events were failing to regulate chloride (and sodium) at Lake Bolac. The chloride values recorded for A. australis during the death events show a similar degree of rise to the sea-shock values recorded for A. anguilla (Kirsch 1972a) and A. dieffenbachii (Shuttleworth and Freeman 1973) (Figure 22). Literature sea-shock values refer to animals that have been subjected to osmotic shock from being transferred directly from freshwater to seawater.

Metals analysis at Lake Bolac

Sampling in January 2006 for metals returned high results, particularly for aluminium and selenium. High levels of suspended sediment during sampling in January 2006 prevented filtration of the samples. Filtered samples are usually used to determine if the metal is bioavailable and hence a risk to organisms. In other lakes, filtered samples were below guidelines, even if unfiltered (total) results were over guidelines (Leahy et al 2007).

Metals sampling was repeated at Lake Bolac in March 2007 during eel deaths, on unfiltered and filtered samples. The results of this analysis and guidelines from ANZECC-ARMCANZ (2000) are presented in Table 6.

The hardness of water (calcium and magnesium) considerably reduces the toxicity of many metals, and the guidelines are elevated for higher hardness, following ANZECC-ARMCANZ (2000). A hardness of 840 mg/L was used, as this is the minimum hardness recorded in Lake Bolac since 2006. The hardness during the eel deaths was substantially higher (over 2000 mg/L) and so the use of the guidelines is conservative.

With the exception of aluminium and zinc, all metals were below guideline levels during the Lake Bolac eel deaths (Table 6). Aluminium results were all below guideline values for filtered samples. This shows that the aluminium is not likely to be bioavailable. The high total aluminium is likely to be due to the clay minerals present in the water column, of which aluminium forms a major component.

Total zinc concentrations were below guideline levels, but filtered zinc concentrations exceeded guidelines. The most likely explanation for this is contamination during the filtration procedure, as filtered samples should be lower than or similar to unfiltered values. In any case, the filtered concentrations recorded are not likely to cause acute fish deaths, particularly given that the water hardness during the deaths (over 2000 mg/L) was much higher than the value used for hardness correction (840 mg/L), which would further reduce the bioavailability of zinc (ANZECC-ARMCANZ 2000).

The results of the metals testing at Lake Bolac suggest that metals were not a factor in the eel deaths at Lake Bolac. This is consistent with the results of metals testing in the other lakes (Leahy et al 2007).

Algal analysis

The concentrations of algae recorded during the monthly algal monitoring are presented in Figure 23. The results of algal analysis during deaths at Lake Tooliorook and Lake Bolac are presented in Table 7 and Table 8.
Figure 21: Mean sodium concentration in blood plasma plotted against salinity in this study and in published literature. (Error bars are ± standard error of measure – SEM)

Figure 22: Mean chloride concentration in blood plasma plotted against salinity in this study and in published literature. (Error bars are ± standard error of measure – SEM)
Many of the species recorded in the four lakes are characteristic of marine waters. During the Lake Bolac eel deaths, algae were abundant but had low diversity, and were dominated by marine diatoms, particularly *Cylindrotheca closterium* (Table 7). In contrast, Lake Tooliorook samples had a diverse range of algae at low abundance (Table 8).
**Table 7: Algae results for Lake Tooliorook collected during eel deaths**

<table>
<thead>
<tr>
<th></th>
<th>Lake Tooliorook</th>
<th>Lake Tooliorook</th>
<th>Lake Tooliorook</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>South east</td>
<td>West</td>
<td>North</td>
</tr>
<tr>
<td></td>
<td>30-Nov-06</td>
<td>30-Nov-06</td>
<td>30-Nov-06</td>
</tr>
<tr>
<td>Estimated Cells/mL</td>
<td>Estimated Cells/mL</td>
<td>Estimated Cells/mL</td>
<td></td>
</tr>
<tr>
<td><strong>Total Phytoplankton</strong></td>
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<td>279</td>
<td>23,375</td>
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<tr>
<td><strong>Diatoms</strong></td>
<td>8</td>
<td>14</td>
<td>832</td>
</tr>
<tr>
<td><strong>Dinoflagellates</strong></td>
<td>2</td>
<td>15</td>
<td>62</td>
</tr>
<tr>
<td>Other flagellates</td>
<td>88</td>
<td>250</td>
<td>22,482</td>
</tr>
<tr>
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<tr>
<td>Aulacoseira sp.</td>
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<td></td>
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</tr>
<tr>
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</tr>
<tr>
<td>Cocconeis spp.</td>
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<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Cymbella sp.</td>
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</tr>
<tr>
<td>Cylindrotheca closterium</td>
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<td>770</td>
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<tr>
<td>Diploneis sp.</td>
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<tr>
<td>Naviculoid sp.</td>
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</tr>
<tr>
<td>Nitzschia spp.</td>
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<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Thalassiosira sp.</td>
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<tr>
<td><strong>Dinoflagellates</strong></td>
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<tr>
<td>Gymnodinioid spp.</td>
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<td>10</td>
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<td>Gyrodinium spp.</td>
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<td>3</td>
</tr>
<tr>
<td>Heterocapsa rotundata</td>
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<tr>
<td>Peridinium sp.</td>
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<td>3</td>
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<td>Prorocentrum sp.</td>
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<td>3</td>
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<td>Prorocentrum cordatum</td>
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<tr>
<td><strong>Chrysophytes</strong></td>
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<tr>
<td>Calycomonas sp.</td>
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<td>5</td>
</tr>
<tr>
<td>Ochromonas spp.</td>
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<td>3</td>
<td>85</td>
</tr>
<tr>
<td><strong>Cryptophytes</strong></td>
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<tr>
<td>Chroomonas spp.</td>
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<td>Leucocryptos marina</td>
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<tr>
<td>Plagioselmis prolonga</td>
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<td>Rhodomonas sp.</td>
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</tr>
<tr>
<td>Scenedesmus quadricaudus</td>
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<td>1</td>
</tr>
<tr>
<td>cf. Kirchneriella 3um crescent</td>
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<td></td>
<td>22,000</td>
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</tr>
<tr>
<td>Tetrakirchonema sp.</td>
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<td>1</td>
<td>18</td>
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<tr>
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<tr>
<td>Trachelomonas spp.</td>
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### Table 7 continued: Algae results for Lake Tooliorook collected during eel deaths

<table>
<thead>
<tr>
<th></th>
<th>Lake Tooliorook South east</th>
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<th>Lake Tooliorook North</th>
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<td></td>
<td>Estimated Cells/mL</td>
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<td></td>
<td>30-Nov-06</td>
<td>30-Nov-06</td>
<td>30-Nov-06</td>
</tr>
</tbody>
</table>

**Cyanoprokaryota**
- *Anabaena* sp. (filaments) 3
- *Anabaena* sp. (cells) 61
- *Aphanizomenon* sp. (filaments) 1
- *Aphanizomenon* sp. (cells) 19

**Ciliates**
- *Mesodinium rubrum* 1
- Unidentified ciliates 1

**Other**
- Unidentified amoeba 1
- Unidentified bodonids 1
- Unidentified heterotrophic flagellate 1

### Table 8: Algae results for Lake Bolac collected during eel deaths

<table>
<thead>
<tr>
<th></th>
<th>Lake Bolac South</th>
<th>Lake Bolac North</th>
<th>Lake Bolac East</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated Cells/mL</td>
<td>Estimated Cells/mL</td>
<td>Estimated Cells/mL</td>
</tr>
</tbody>
</table>

**Total Phytoplankton** 559,000
**Total Diatoms**
- *Chaetoceros* spp. 549,000
- *Cylindrotheca closterium* 482,000
- *Minidiscus trioculatus* 57,000
- *Nitzschia* spp. 3,000
- *Pleurosigma* sp. 7,000
**Chlorophytes**
- *Ankistrodesmus* sp. 10,000

**Total Diatoms**
- 5,000
- 288,000
- 54,000
- 1,000
- 5,000
- 264,000
- 16,000
4. DISCUSSION

Water quality conditions in the lakes

The four lakes fit into two categories:
1) algal-dominated
2) aquatic macrophyte-dominated.

Lake Modewarre and Lake Tooliorook are characterised by an abundance of seagrass (*Ruppia sp.*), low turbidity and high pH (typically greater than 9–10.5).

Lake Colac and Lake Bolac are characterised by high algal concentrations, high turbidity and lower pH (typically 8.5–9).

The presence of seagrass is likely to play an important role in this difference, reducing wind-suspended turbidity and increasing the pH of the two lakes to extreme values through high productivity. The high productivity is likely to deplete acidic hydrogen ions, although the exact mechanism requires further investigation.

The rise in pH at Lake Bolac in the late summer–autumn period suggests photosynthesis by algae in the two lakes may be the cause of increased pH, although this requires confirmation. Algal concentration was higher in both Lake Bolac and Colac during this period (Figure 23).

Salinity in all the monitored lakes was unprecedented in historical records. Salinity in Lake Tooliorook was over one-half that of seawater during the eel deaths and, at Lake Bolac, it was nearly one and a half times that of seawater. The salinity in Lake Colac is somewhat lower than the other lakes, but it doubled in the 2006–07 summer and a similar rise is expected to lead to fish deaths. The salinity in Lake Modewarre continued to rise throughout the 2006–07 summer, due to evaporation, with salinity rising fourfold between 2004 and 2007.

It is highly likely that similar changes occurred during past dry periods, but they went unrecorded, as did any fish deaths that occurred (EPA 2006).

Blood plasma in western Victorian eels

In order to have normal physiological functioning, eels need to maintain the salt content of their blood plasma within a narrow range.

In this study, *A. australis* was found to have higher plasma sodium than has been reported elsewhere in the literature, even in waterways where eel deaths did not occur. However, plasma sodium (Lake Bolac March 2007) and chloride (Lake Tooliorook November–December 2006 and Lake Bolac March 2007) were found to be elevated in the two waterways experiencing eel deaths, beyond even the background elevation of *A. australis* plasma.

Failure to regulate blood plasma within narrow bounds has been found to be characteristic of eels experiencing ‘hypermineralisation’, also known as sea-shock (Kirsch 1972a; Shuttleworth and Freeman 1973). This sea-shock is seen in eels transferred from low-salinity freshwater to higher-salinity seawater.

This period has been shown to be temporary, with plasma salinity stabilising, albeit at a moderately higher level, once the eels adjust to seawater. The blood plasma results for western Victorian eels in this study, particularly those from the lakes experiencing eel deaths, appear abnormal and look similar in magnitude to sea-shock eels from other studies (Kirsch 1972a; Shuttleworth and Freeman 1973).

The high plasma sodium and chloride results for dead eel samples from Lake Bolac (March 2007) and Lake Tooliorook (November/December 2006) are clear evidence of a failure to maintain plasma concentrations within normal bounds and are the likely cause of the eel deaths.

The water salinity in the two lakes at the time of the deaths was very different. The salinity of Lake Bolac was 60 ppt (approaching twice that of seawater), whereas Lake Tooliorook was 20 ppt (approaching two-thirds that of seawater), so clearly there is not a single threshold for all waterways. Individual factors in each lake are likely to accentuate or suppress the effect of salinity. The most likely of these is lake water pH, but dissolved oxygen and others may also play a role. As discussed in the background to fish osmoregulation, pH plays an important role in the functioning of fish gills. Wilkie and Wood (1996) have shown that fish that can tolerate the conditions seen in the western Victorian lakes are rare and can only survive due to specialised adaptations.

The role of pH in eel deaths in western Victorian lakes

Alkaline pH values that are toxic to fish are typically around 9 and above, but these are based on freshwater conditions (Alabaster and Lloyd 1982). In freshwater, ammonia toxicity increases with increasing pH, because the relative proportion of the toxic form (free unionised ammonia, NH₃) is pH-dependent. However, in more saline water, evidence for increasing ammonia toxicity with increasing pH is still the focus of research and there is still much to be discovered (Eddy 2005).

Some studies have found that ammonia toxicity may be greatest at mid-range salinities, similar to those levels in Lake Modewarre and Lake Tooliorook during the eel deaths (Harader and Allen 1983).

It is apparent from the data from the lakes studied that eels died at lower salinities when pH was greater than 9. The difference between the two lakes with higher pH (Lake Modewarre and Lake Tooliorook) and those with lower pH (Lake Colac and Lake Bolac) is the
presence of the submerged aquatic macrophyte *Ruppia*.

**Potential for fish deaths in Lake Colac**

Figure 24 shows a general model of the eel deaths in Western District lakes. From this it can be seen that, at Lake Modewarre and Lake Tooliorook, pH was high in the lakes and conditions became critical for eels when salinity rose by around 20 per cent per month.

At Lake Bolac, pH was lower but rose during summer, particularly once turbidity declined. With salinity rising by more than 20–40 per cent per month and pH reaching close to 9.5, a critical point was reached for eels.

Commercial fishermen estimate that there may be over 500 tonnes of fish in Lake Colac, including European carp, eels, redfin and a number of other species (pers. comm., Western District Eel Growers Group). A sharp rise in salinity and pH in Lake Colac in the 2006–07 summer took the lake close to the conditions that saw European carp die in Lake Modewarre in December 2004.

The salinity reached in Lake Colac in the summer of 2006–07 is unprecedented in 30 years of monitoring the lake (see Leahy et al. 2007). The potential for large fish deaths in Lake Colac in the 2007–08 summer is heavily dependent on good rainfall in the intervening period.

The salinity in Lake Colac at the beginning of summer 2006–07 was one-fifth that of seawater and had doubled by April 2007. As a result of the increased salinity, turbidity decreased, causing increased pH. It is assumed that this trend will continue in the summer of 2007–08 unless sufficient rainfall is received.

To keep the salinity under the tolerance thresholds for the fish species that exist in Lake Colac, the salinity needs to decrease to similar levels seen at the start of the 2006–07 summer. Because salinity is closely related to water volume, this effectively requires a doubling of the water volume in Lake Colac before the 2007–08 summer.

If rainfall remains low before the 2007–08 summer, it is predicted that Lake Colac will follow the pattern of Lake Bolac. Past patterns suggest European carp may die early in the summer, due to rising salinity, but it is likely that eels will die later in the second half of summer if pH has risen to around 9.5.

**Climate change implications for fish in shallow western Victorian lakes**

Climate change models for south-western Victoria predict lower rainfall, higher evaporation and greater variability (DSE 2004). The consequence of this for fish like eels with long lifespans will mean that their populations will become increasingly unviable in Victoria’s shallow western lakes and deaths will become more frequent. The shallow western lakes may become unsustainable in the long term as commercial eel fisheries, because the time between dry periods may be insufficient for commercially viable growth and harvest.

Fish with shorter life spans like galaxiids may be able to complete their reproductive cycle during wetter phases and survive in the lakes. Stocking of recreational species may also come under threat if they are not able to grow to a suitable size before conditions become too extreme.
a. Model of response in turbid algae dominated lakes (for example Lake Bolac and predicted trajectory for Lake Colac))
b. Model of response in clear macrophyte dominated lakes (for example, Lake Modewarre and Lake Tooliorook).

Figure 24: General model of eel deaths in western Victorian lakes
5. CONCLUSIONS

EPA’s investigations during the summer of 2006–07 set out to answer remaining questions regarding the cause of eel deaths. With the exception of Lake Colac, the conditions in all the lakes were extremely unfavourable for the survival of any fish. By worldwide comparison, few fish are known to survive the conditions recorded in the lakes where deaths occurred.

Clear evidence of the importance of environmental stress on eel deaths has emerged. In particular, the combined effect of high salinity and high pH has been found to lead to abnormal eel blood plasma ion concentrations. At Lake Modewarre, Lake Bolac and Lake Tooliorook, a pH of around 9–9.5 and a salinity increase of over 20 per cent a month is the common link in all deaths. Research over the 2006–07 summer has shown the abnormal internal response of eels to these conditions.

While there are some remaining unanswered questions regarding the exact role of seagrass in elevated pH and the cellular-level response of eels to high salinity and pH, the patterns in eel deaths have been well established and follow predictable paths.

The eel deaths since 2004 have caused large environmental, economic and social losses. The commercial value of the eels that died in the 2006–07 summer alone amounts to over $750,000.

Unless water quality conditions improve before the 2007–08 summer and greater inflows occur, it is unlikely eels will be present in lakes Modewarre, Bolac and Tooliorook in the coming summer.

Eels were still present in Lake Colac at the end of the 2006–07 summer, but they are likely to be one of the last large inland lake populations. There is potential for significant fish deaths in Lake Colac in the summer of 2008 if the current low rainfall level continues.

The future condition of the western lakes clearly depends on a period of sustained, higher rainfall. If sufficient rainfall occurs and some of the salt is flushed from the lakes, then there is no reason the lakes cannot support a healthy fishery once again. Periodic drying and high salinity is a natural part of many lake systems in Australia. The plants and animals that inhabit the lakes should quickly recover if higher rainfall occurs.

The greatest threat to the re-establishment of the Western District lakes fishery over the long term is likely to be climate change. These lakes tend to act like large rainfall gauges and sustained below-average rainfall and low run-off into lakes leads to low water levels and, eventually, drying out.

The investigation into eel deaths has underlined the susceptibility of even hardy fish like eels to low rainfall conditions.
7. REFERENCES


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Victorian Water Quality Monitoring Network www.vicwaterdata.net

