EUTROPHICATION OF COASTAL LAGOONS: A LITERATURE REVIEW

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Cover photo: Modified catchment and shore of Waituna Lagoon (M. Schallenberg)

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SUMMARY

- This literature review was undertaken to help inform the management of Waituna Lagoon and, specifically, to obtain guidance from previously published work on nutrient and sediment loading rates that are compatible with *Ruppia* or other seagrass communities.

- In this report we summarise published studies, the available 'grey' literature and some unpublished data that are relevant to the seagrass, macroalgae and phytoplankton dynamics in Waituna Lagoon.

- Our survey of the published literature revealed that the majority of information relevant to the aims of this report comes from studies of the multitude of ICOLLs and lagoons in southern Australia.

- In particular, the ICOLLs, Lake Illawara, Wilsons Inlet and Smiths Lake in Australia and East Kleinemonde Estuary in South Africa show strong similarities to Waituna Lagoon and a deeper study of their dynamics could improve understanding of the functioning of Waituna Lagoon.

- A number of models have been developed for ICOLLs and lagoons. Some are specific to a particular ICOLL (e.g. the model of Everett et al. (2007) of Smiths Lake) whereas others are more easily scalable to Waituna Lagoon (e.g. the model of the model of Sanderson & Coade, (2010)). The model of Webster & Harris (2004) also appears applicable to Waituna Lagoon and has been developed to simulate regime shifts and changes in denitrification efficiency, which indicates that it may be appropriate for scenario forecasting for Waituna Lagoon.

- A number of studies have demonstrated useful relationships across a wide range of ICOLLs and lagoons. These often showed consistent nutrient thresholds for seagrass collapse which generally lie between 20 and 100 kg N/ha/y, with the threshold for many ICOLLs in the lower end of this range. The nutrient thresholds for seagrasses are

compared and summarised in this report and thresholds for macroalgae and dentirification are also presented. In addition, estimates of N loading for Waituna Lagoon and Lake Ellesmere/Te Waihora are compared to the empirical thresholds, indicating that N loading in these ICOLLs exceeds the published thresholds for seagrass health.

- This literature review has identified detailed studies on individual ICOLLs, ICOLL models of different types, and empirical relationships among ICOLLs, lagoons and embayments which help place Waituna Lagoon in to a broader context and could potentially provide guidance as to the management and restoration of Waituna Lagoon.

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BACKGROUND

Waituna Lagoon is an intermittently closed and open lagoon/lake (ICOLL) on the south coast of the South Island, which is internationally recognised under the RAMSAR convention as a wetland area of high ecological value. It is eutrophic but still retains a seagrass community dominated by *Ruppia* sp., which has been identified as a keystone species furnishing important ecosystem values and services and providing a degree of ecological resistance to further eutrophication (Schallenberg & Tyrrell 2006; Robertson et al. 2011). However, in recent years, the abundances of seagrass and of potentially competing nuisance macroalgae have fluctuated dramatically (Robertson et al. 2011), suggesting that the ecological resilience of the lagoon may be faltering (van Nes & Scheffer 2004) and that a regime shift to algal dominance may be imminent.

Environment Southland in conjunction with various other agencies and stakeholders have responded to the ecological warning signs by commissioning studies to help understand the lagoon, predict its assimilation capacity and to help develop guidelines for managing the lagoon to safeguard its ecological values. To assist with these tasks, Environment Southland has commissioned this survey of the scientific literature focussing on the ecology of ICOLLs and coastal lagoons and on the environmental factors and thresholds which have caused many ICOLLs around the world to lose their aquatic plant communities and become degraded water bodies. The information will contribute to the effective management of Waituna Lagoon.

SCOPE OF STUDY

The aim of this study is to collate all available information on temperate ICOLLs worldwide which could be relevant to the management and protection of New Zealand ICOLLs against eutrophication. Information illustrating nutrient and sediment assimilation capacities of ICOLLs was sought and, specifically, the relationships between land use, nutrient loading, nutrient concentrations, opening regimes and salinity vs eutrophication responses such as phytoplankton, macroalgae and aquatic plant biomass and productivity were sought. As information on ICOLLs was limited, we also collected information on estuarine embayments such as tidal lagoons.

Along with empirical relationships between abiotic drivers and biological responses, we also collected relevant raw data to enable new analyses to be conducted. In addition we collected papers which developed deterministic eutrophication models for ICOLLs and estuarine embayments.

DATA SOURCES

We interrogated a number of sources in our data collection survey. When interrogating databases we searched for the following terms (individually and in combinations): ICOLL, intermittently closed and open lakes and lagoons, TOCE, temporarily open and closed estuaries, lagoon, estuary, coastal lake, macrophyte, seagrass, eutrophication, nitrogen loading, phosphorus loading, and nutrients.

We obtained data and information from the following sources:

1. PEER REVIEWED JOURNAL ARTICLES

We searched for articles from peer reviewed journals using Google Search and the Web of Science. We also searched the reference sections of relevant papers and reports.

2. REPORTS

We searched for reports using Google Search and the Web of Science. We also searched the reference sections of relevant papers and reports. Unfortunately, many useful reports cited in papers such as Qu et al. (2003), Harris (2008), and Scanes (2012), were not available because they are internal reports and were not published.

3. BOOKS AVAILABLE WITHIN THE AVAILABLE TIME FRAME

We searched the University of Otago library. Due to time constraints we didn’t interloan books from other libraries.

4. UNPUBLISHED DATA

We used unpublished data from the DoC/NIWA/University of Otago CDRP project which surveyed the ecological integrity of 46 shallow coastal lakes around New Zealand (Drake et al. 2010).

5. EXPERT CONSULTATION

To complete our search, we consulted three experts in estuarine research to ensure that we hadn't missed any key papers, reports or any relevant unpublished data of which they were aware. These experts were Barry Robertson (Wriggle), Graham Harris (University of Tasmania) and Di Walker (University of Western Australia).

We collected data and information on the lagoon characteristics shown in Table 1.

Table 1. Information sought in literature review.

1. Historical or reference condition (if available)	
Condition of water quality	Concentrations or qualitative information
Condition of macrophytes	Species present, cover, biomass
Opening regime	Frequency, mean salinity
2. Present condition	
Water quality	Concentrations or qualitative information
Macrophytes	Species present, cover, biomass
Opening regime (natural or modified) parameters)	Frequency, duration, mean salinity
N loading	kg/ha/y or kg/y
P loading	kg/ha/y or kg/y
Sediment loading	kg/ha/y or kg/y
State of catchment – pollution point sources	e.g. sewage outfall, septic tanks, industrial outfall
State of catchment – diffuse pollution	e.g. farming, stocking rates

sources	
Internal nutrient loading	Vertical stratification, anoxia, nutrient release, kg/y
Nutrient limitation status	N or P limitation, co-limitation or none limitation
3. Documented changes/trends	
Documented regime shift	Date, inferred cause
Key species changes	Date, inferred cause
Key water quality changes	Date, inferred cause
Thresholds?	Linear or non-linear dynamics of autotrophic organisms and quantitative thresholds
Other stories of change	Narrative, anecdotes
Mitigations	Attempts to restore, were they successful?
4. Background information	
Location	Latitude and longitude
Morphology	Surface area, maximum depth, volume
Water residence time	During closed period, based on freshwater inflows and lagoon volume
Tidal prism	Tidal range when open to the sea
Flushing/mixing	Any data or comments on effectiveness of marine flushing when lagoon is open

We had hoped that there would be enough ICOLL data to analyse it in a meta-analysis but this was not the case. Thus, in this report, we have summarised the most relevant studies on individual ICOLLs, collected any information on seagrass, macroalgae and phytoplankton threshold responses to nutrient and sediment loading to ICOLLs, and we also collected information on nutrient loading thresholds for seagrasses in coastal embayments and estuaries.

SUMMARY OF FINDINGS

STUDIES ON SPECIFIC ICOLLS

Below we provide a brief summary of studies carried out on ICOLLs which are potentially relevant to Waituna Lagoon. Key data and information on these ICOLLs is summarised in Appendix I.

1. EAST KLEINEMONDE ESTUARY, SOUTH AFRICA

Background: This is a small ICOLL, with a surface area of 35 ha and a maximum depth of 6 m. Its water level varies between 0.18 and 2.3 m and salinity ranges between 15 and 32 ppt.

Condition: The ICOLL contains *Ruppia cirrhosa* and *Potamogeton pectinatus* and chlorophyll *a* ranges from around 2 – >20 μg/L. In many ways, this ICOLL is similar to Waituna.

Key findings: Was studied in detail over two different 1-year periods. Whitfield et al. (2008) conducted a multidisciplinary study looking at the effects of the state of opening on nutrients, chlorophyll *a*, macrophytes, invertebrates, fish and birds. Riddin & Adams (2008) examined macrophyte dynamics.

- *Ruppia* does better after a deep opening resulting in high salinity. As the ICOLL freshens (or after overtopping or a shallow opening), *Potamogeton* begins to become more abundant, gradually replacing *Ruppia*.
- During the closed phase, the ICOLL sometimes stratified with DO concentrations at times declining to < 2.0 mg/L.
- Macrophytes are affected by mouth opening, freshwater inflows, tidal exchange sedimentation, salinity and water level fluctuation.
- Submerged macrophyte cover was most strongly related to water

temperature (-ve) and water level in the two months preceding the time of sampling (+ve).

- Macroalgal cover (*Ulva* and *Cladophora*) began to increase once the saltmarsh vegetation became inundated and was positively related to water level at the time of sampling.
- During prolonged closed periods, dissolved nutrient concentrations decline, probably because there is no nutrient regeneration within the ICOLL.
- Outwash and seepage promotes phytoplankton growth in the marine environment.
- Phytoplankton tended to peak around 5 weeks after a short opening, because inflowing sea water replenished nutrients.
- Phytoplankton was dominated by diatoms, cryptophytes and dinoflagellates

References: Riddin & Adams (2008) and Whitfield et al. (2008).

2. MECOX BAY, USA

Background: A shallow ICOLL, artificially opened multiple times a year to reduce water levels and allow exchange with ocean water. Maximum water level variation is around 1 m. This ICOLL contains and important oyster and clam fishery and its openings are managed to benefit the fishery.

Condition: Salinity varied from 6 – 27 ppt and chlorophyll *a* varied from 2 to 20 μg/L. No mention was made of macrophytes or macroalgae. There is a high biomass of shellfish and potentially high grazing rates of shellfish larvae (not measured).

Key findings: Was sampled fortnightly for one year. Tributaries and groundwater were also sampled for nutrients.

- Nitrate dynamics most affected by seasonality (uptake in summer).
- While salinity dynamics showed strong influence of marine flushing, nutrients were mostly compensated for by groundwater influx during openings
- Groundwater contains high concentrations of DIN and DIP.
- 64% of chlorophyll *a* was due to cells < 5 μm (pico- and nano-plankton), but dinoflagellate blooms did occur at times
- Chlorophyll *a* increased in response to ICOLL openings, despite the fact that seawater was low in nutrients.
- Phytoplankton was sometimes P-limited (winter/spring) and sometimes N-limited (summer/autumn), with occasional episodes of no-nutrient-limitation

Reference: Frano (2004) and Gobler et al. (2005).

3. MHLANGA ESTUARY, SOUTH AFRICA

Background: This is an 80 ha, supertrophic ICOLL receiving wastewater discharges.

Condition: Subject to intense episodic algal blooms (e.g. chlorophyll *a* reached 375 μg/L). Salinity varied between 1 and 30 ppt.

Key Findings:

An intensive study was carried out over 2 months in winter, through 3 breaching events. A water balance was carried out and a number of physico-chemical measurements were taken.

- Algal blooms developed c. 14 days after lagoon closure. Mouth closure allows nutrient accumulation and algal blooms to develop.
- This study developed a simple model for algal bloom scenario-testing, but it is not directly applicable to Waituna Lagoon because it is focused on

wastewater inputs as drivers of the blooms. The simple model concept could be useful if it were decided to divert water into Waituna Lagoon for flushing purposes.

Reference: Lawrie et al. (2010)

4. WILSON INLET, AUSTRALIA

Background: Large eutrophic ICOLL that undergoes seasonal opening (winter-spring) and closing. Much of the ICOLL's catchment is in agriculture with sandy soils. During wet season, high nutrient load to ICOLL.

Condition: Chlorophyll *a* varies from around 1 – 50 μg/L. Salinity varies from 9 – 35 ppt from spring to autumn respectively. The ICOLL undergoes salinity stratification in spring in 5m deep basin, anoxia in bottom waters with release of nutrients (mainly ammonium and phosphorus) from sediments. *Ruppia megacarpa* biomass has increased to nuisance proportions as a result of high nutrient loads. At the time of the Twomey & Thompson study (2001), increasing spring phytoplankton blooms suggested the increased potential for destabilisation/regime shift.

Key Findings: The Carruthers et al. (1999) study on *R. megacarpa* was carried out over 15 months. Samples were collected fortnightly to examine hydrological and water quality factors that related to *R. megacarpa* biomass in the ICOLL. The Twomey & Thompson (2001) study was conducted over 2-years and determined the nutrient limitation status of phytoplankton using nutrient enhancement bioassays.

- In terms of both spatial and temporal variation, *R. megacarpa* biomass was correlated to turbidity (-ve), ICOLL water level (+ve), and salinity (-ve), however the relationships occurred at different time scales. The *Ruppia* response to salinity lagged by 6 months, whereas the response to water level lagged 2 months (turbidity relationships had no significant lags).

- Chlorophyll *a* blooms in spring during open period and seems to respond to internal nutrient loading.
- Winter/spring openings caused density stratification, anoxia and internal nutrient loading in spring, which fuelled phytoplankton blooms.
- Harvesting of seagrass biomass at end of growing season was suggested to reduce internal nutrient cycling.
- Phytoplankton was least nutrient-limited in spring (although N-limited at that time) and strongly limited by N and P in summer and autumn. Occasional Si and Fe limitation was observed.
- Redfield ratios didn't work well at predicting nutrient limitation status especially during spring when phytoplankton were N-limited. Nutrient ratios did not indicate P surplus at that time. Authors suggested that either high rates of night-time nutrient recycling or phytoplankton utilisation of sources of P other than phosphate could have been the causes of the discrepancy. Authors did not mention the possibility of luxury P-uptake and storage by phytoplankton.

Reference: Carruthers et al. (1999) and Twomey & Thompson (2001).

5. WAMBERAL LAGOON AND SMITHS LAKE, AUSTRALIA

Background: Wamberal (surface area = 0.6 km^2) is artificially opened 2-3 times a year but only stays open for 1-2 weeks, whereas Smiths (surface area = 11 km^2) is artificially opened once every 18 months and stays open for 1-4 months.

Condition: Little information is given about the condition of the ICOLLs.

Key Findings: The 2006 paper examined vertical stratification and bottom water oxygen depletion over a c. 1-month period. The 2007 examined mixing and flushing in the ICOLLs.

- Flushing and mixing dynamics were very different in the two ICOLLs and were scaled to ICOLL area
- Mixing in the smaller ICOLL was dominated by tide (diurnal) and wind effects, whereas mixing in the larger ICOLL was dominated by sub-tidal (fortnightly tidal variation), diurnal tides and wind played a lesser role.
- Oxygen depletion was tied to vertical stratification.
- Gale et al. (2006) did not discuss some key issues such as the effect of salt wedges on stratification and the effect of ICOLL morphometry on oxygen depletion.

References: Gale et al. (2006; 2007).

6. CORUNNA LAKE, AUSTRALIA

Background: Corunna Lake is a small (surface area = 2km^2; maximum depth = 3.5 m) ICOLL. It has three sub-catchments dominated by scrub and grasslands. One sub-catchment has 30% of area in dairy farms. No information was given on eutrophication or algal blooms. It opens seasonally.

Condition: Little information is given about condition. It was not clear from the study whether seagrasses were present in the lagoon or not and the only water quality measurements taken were salinity, temperature and Secchi disk depth.

Key Findings: Benthic chambers were deployed at 4 sites to measure sediment-water fluxes and to relate these to sediment characteristics at the sites. Key attributes measured were sediment nutrient concentrations, denitrification efficiency and fluxes of nutrients to overlying waters.

- Benthic chambers were only deployed for 6h periods and so anoxia wasn't achieved.
- Sediment phosphorus was related to (bound to) Fe, not Ca
- Ammonium sediment-water fluxes were highest in the bay affected by dairy farming, whereas phosphorus fluxes were higher in another bay. No nitrate fluxes were measurable.
- Nitrate was almost always low in the water column suggesting little nitrification and the importance of denitrification, which could be fuelled by high sediment organic matter content.
- Denitrification was highest in winter.
- Floods caused a barrier breach and vertical stratification, anoxia and a strong rise in bottom water DRP. This likely reduced the rate of nitrification-denitrification although no data were available.

Reference: Spooner & Maher (2009)

7. LAKE ELLESMERE/WAIHORA AND WAITUNA LAGOON, NEW ZEALAND

Background: Lakes Ellesmere/Te Waihora is around 15 – 20 times the size of Waituna Lagoon, whereas both ICOLLS have a similar maximum depth (c. 3 m). Both ICOLLs are opened artificially in response to rising water levels. Historically, Lake Ellesmere/Te Waihora underwent regime shifts between a turbid water phase without macrophytes and a relatively clear water phase with extensive macrophyte beds in the shallows. Since the Wahine storm in 1968, which scoured the lake's macrophytes from the lake bed, Lake Ellesmere/Te Waihora has been in a turbid state with virtually no macrophytes present. High nutrient loading from the catchment is thought to fuel algal blooms which reduce light penetration, preventing macrophytes from re-establishing. In contrast, Waituna Lagoon has a seagrass-dominated macrophyte community that has persisted until now despite increasing nutrient and sediment loading from the catchment. In recent years, the biomass of seagrasses in Waituna Lagoon has varied and macroalgae have been implicated in recent seagrass declines.

Condition: Lake Ellesmere/Te Waihora is hypertrophic and Waituna Lagoon is meso-eutrophic. Lake Ellesmere/Te Waihora generally has low water clarity due to resuspended sediment and high algal biomass, whereas Waituna Lagoon generally has clearer water with less phytoplankton biomass and suspended sediment but it has some staining due to humic acids derived from wetland plants and soils in its catchment.

Key Findings: Data on water quality and opening/closing was collected over numerous years.

- ICOLL opening was more effective at flushing nutrients and chlorophyll *a* in Waituna Lagoon than in Lake Ellesmere/Te Waihora. Waituna responds more strongly and faster to openings/closings than Lake Ellesmere/Te Waihora, mainly due to the size difference and its effect on mixing flushing when open (see Gale et al. 2007)

- Upon filling, nitrate levels increased temporarily in Waituna Lagoon, possibly reflecting the mineralised biomass of macrophytes and macroalgae stranded after the lagoon was opened.

- Waituna shows clear signs of leakage through the barrier bar.

- Chlorophyll *a* in Waituna tends to increase with increased duration of closure, whereas Lake Ellesmere/Te Waihora chlorophyll a levels appear more variable with increased duration of closure.

- Phytoplankton community in Lake Ellesmere/Te Waihora is often light-limited, whereas it is rarely light-limited in Waituna.

- Average nutrient stoichiometries of lake water indicate the phytoplankton are generally more N-limited in Lake Ellesmere/Te Waihora (only when it's not light-limited), and P-limited in Waituna, although no experiments were undertaken to confirm this.

- The nutrient stoichiometries of inflows compared to the ICOLLs suggest that denitrification and internal P-loading (by sediment resuspension) are important in both ICOLLs.

- Alteration of water level (opening) regime alone is not likely to aid with management and restoration of Lake Ellesmere/Te Waihora. Reductions in nutrient and sediment loading are also necessary.

- Alteration of water level (opening) regime has the potential to be a useful management and restoration tool for Waituna Lagoon, although suggests reduced catchment nutrient and sediment loads are also important.

Reference: Schallenberg et al. (2010).

8. LAKE ILLAWARA, AUSTRALIA

Background: A large (surface area = 35 km2) ICOLL with a maximum depth of 3.7 m. It has a small catchment in relation to its size and flushing from both freshwater and tidal flows has been estimated to be very slow (c. 60 days). Its salinity varies between 6 and 38 ppt and chlorophyll *a* can reach 20 μg/L. The ICOLL is subject to algal blooms, sediment resuspension and oxygen depletion in the bottom waters. It retains seagrass beds (*Ruppia megacarpa*) but has been increasingly subject to macroalgal blooms (*Chaetomorpha*, *Enteromorpha*, *Ulva*) as a result of increasing nutrient loading due to catchment development.

Condition: The ICOLL is considered to be degraded due to the increasing frequency of phytoplankton and macroalgae blooms and due to oxygen depletion. Water quality only meets national water quality guidelines for ecosystems < 25% of the time, but meets primary contact and fish consumption guidelines > 75% of the time (http://www.lia.nsw.gov.au/the_lake/lake_facts/water_quality).

Key Findings: Incubated sediment cores from a seagrass bed were used to examine the oxygen and nutrient dynamics across the sediment water interface and to examine macroalgal productivity during the winter and spring.

- In the spring, the presence of macroalgae can double the areal metabolism (productivity and respiration) of the system and affect fluxes of nitrate and ammonium between the sediment and water.

References: Ellis et al. (1977) and Qu et al. (2003)

COMPARATIVE ICOLL STUDIES

1. SCANES (2012)

This report examined 57 ICOLLs in New South Wales, Australia and assessed their condition as described by chlorophyll a, TN and TP as well as the nutrient and sediment loads derived from their catchments. The report classified the ICOLLs with regard to condition (reference, moderately disturbed, and highly disturbed) and with regard to their catchment loads (low, medium, high). The loads for Waituna Lagoon were compared to this dataset to derive loads that would reflect a “moderate environmental quality (some eutrophic symptoms but still supporting healthy seagrass and fish communities)”, based on the New South Wales data. Current loads to Waituna are in excess of those considered to reflect highly disturbed catchments in New South Wales. Limits for “moderate environmental quality” are 9 and 0.57 t/km^2/y for N and P respectively, indicating that the nutrient loads to Waituna Lagoon would have to be reduced by 52% for N and 23% for P (compared to the 2010 measured loadings), for Waituna to achieve such a state.

2. HAINES ET AL. (2006)

This paper examined the morphological variation of ICOLLs in New South Wales, Australia in order to assess how morphology and hydrology affect the ecological condition, resilience and sensitivity/vulnerability of the ICOLLs to nutrient loading. Three key indices were developed:

> *The first factor (called the Evacuation Factor) is a measure of how efficiently a coastal lagoon can remove pollutants and other inputs through tidal flushing (i.e. the tidal flushing efficiency). The second factor (called the Dilution Factor) is a measure of the relative difference between the input loads from the catchment and the resident volume of the coastal lagoon. The third factor (called the Assimilation Factor) is a measure of the water level variability in a coastal lagoon, which can subsequently influence the extent and diversity of biological processes and their capacity to assimilate or accommodate external inputs. Haines et al. (2006)*

A classification system based on these three indices is presented which can be used to determine the sensitivity/vulnerability of ICOLLs to catchment pressures. The assimilation factor was found to relate to seagrass cover in a large number of New South Wales ICOLLs whereby ICOLLs with an assimilation factor > 10 had virtually no seagrass cover. However, ICOLLs with assimilation factor < 10 had a wide range of seagrass cover, indicating that other factors must also be related to seagrass cover in ICOLLs with low assimilation factors.

3. HARRIS (2001)

This paper examines nutrient loadings to coastal ecosystems and briefly touches on impacts of catchment nutrient losses on lagoons. With regard to coastal lagoons it is very much a discussion piece drawing on other studies. Below are some key ideas from this study.

- Strong evidence that denitrification is important in coastal lagoons, some lagoons with long residence times and oxic bottom waters capable of denitrifying 80% of the N load. Oversupply or organic carbon can lead to bottom water oxygen depletion which greatly diminished denitrification.

- Curious low incidence of cyanobacterial blooms in lagoons compared to reservoirs, despite the low N:P ratios in lagoons. Micronutrient limitation or difference in internal nutrient cycling?

LAGOON MODELS

1. WEBSTER & HARRIS (2004)

These authors developed a deterministic model for lagoon ecology aimed at predicting the biological responses of nitrogen loading. The model was developed for Lake Macquarie, Australia, and simulates three states: macrophyte dominated, algae dominated, and a severely degraded state in which denitrification is inhibited. It takes into account hysteresis effects with regard to forward and backward changes in nitrogen loading. The model was not statistically validated in the paper. Thresholds from the model are 16 mg $N/m^2/d$, above which benthic primary producers collapse and 45 mg $N/m^2/d$ above which denitrification collapses. Predicted seagrass critical loads are plotted below against event return times and flushing time of the lagoon (from Webster & Harris 2004).

2. SANDERSON & COADE (2010)

These authors take a semi-empirical approach to lagoon modelling, relying on empirical relationships which drive “an analytical model of intermediate complexity”. Empirical relationship of catchment N-load vs chlorophyll *a* is used to predict % macrophyte cover.

The macrophyte cover model is based on both light penetration and water level variation and was tested on a dataset of 31 Australian lagoons. The model apparently worked well for 22 of 31 lagoons tested.

The model can easily be scaled to particular lagoons based on two input conditions: i) the macrophyte critical depth and ii) the equilibrium total nitrogen concentration.

The data on 31 lagoons and ICOLLs collected by Sanderson & Coade (2010) are presented in their paper allowing the examination of simple relationships between nitrogen loading and % seagrass cover in the lagoons. We have plotted the data in Fig. 1, below.

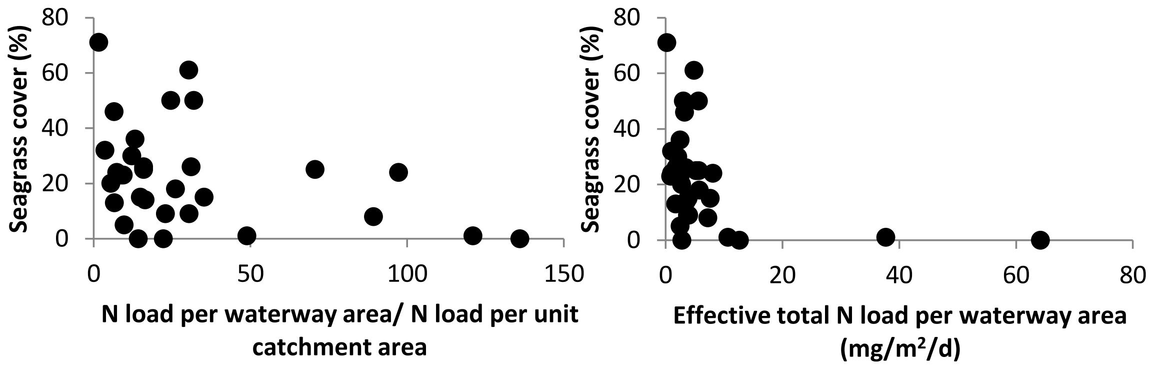

Fig. 1. Relationships of seagrass cover and nitrogen loading for 31 Australian lagoons. Data are from Sanderson & Coade (2010).

These relationships reveal strong effects of nitrogen loading on seagrass cover, with a strong, negative threshold on seagrasses apparent at an effective areal N load of c. 10 mg N/m^2/d (right panel). In comparison to this threshold, nitrogen loading estimates for Waituna Lagoon from Schallenberg et al. (2010; data collected from 2001-2007) give a nitrogen load of approximately 42 mg N/m2/d. Similarly, tributaries to Lake Ellesmere are responsible for a nitrogen load of approximately 44 mg N/m2/d to that ICOLL (Schallenberg et al. 2010; data collected from 1996-2006).

3. EVERETT ET AL. (2007)

This paper develops a spatially resolved (11 polygons) ecological model for Smiths Lake, New South Wales. It accounts for hydrology, opening regime, light, and lake ecology as reflected by 17 ecological variables. The model has four autotrophic components: large phytoplankton, small phytoplankton, epiphytic algae, and seagrass. Ecological parameter values are presented in the paper. The model is especially sensitive to zooplankton feeding efficiency. Unfortunately, the model is not statistically validated and no simulations of seagrass dynamics are presented.

4. SCHALLENBERG ET AL. (UNPUBLISHED), CDRP DATA ON NEW ZEALAND BRACKISH LAKES AND ICOLLS

Here I present some unpublished data on nitrogen loadings and concentrations vs % macrophyte cover and water column chlorophyll *a* from 10 brackish lakes and lagoons sampled as part of the CDRP project (Drake et al. 2010). The systems included lagoons, brackish lakes and ICOLLs from the North and South Islands. They were sampled only once in late summer and, at the time of sampling, ranged in specific conductivity from 3 to 30 mS/cm and in chlorophyll *a* from 1 to 80 μg/L.

Fig. 2 shows the relationships between % macrophyte cover vs nitrogen loading and chlorophyll a vs nitrogen loading.

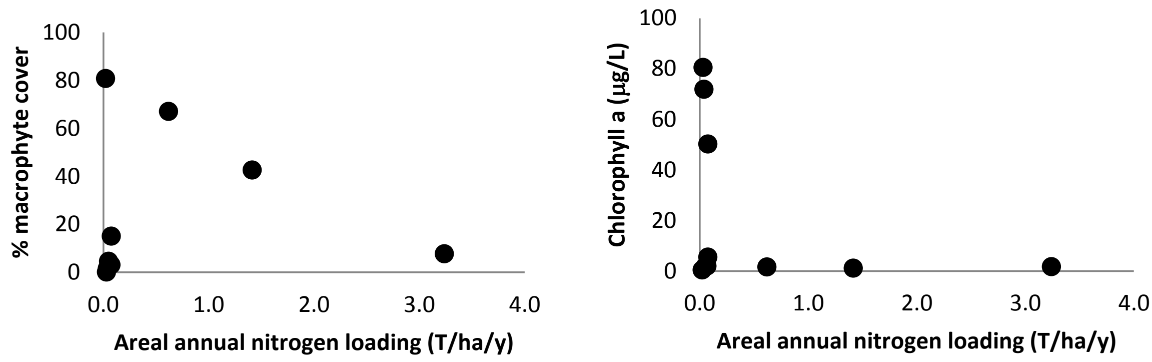

Fig. 2. Relationships between areal annual nitrogen load and % macrophyte cover (left panel) and areal annual nitrogen load and chlorophyll *a* (right panel) for 10 New Zealand brackish lakes and ICOLLs.

Unexpectedly, nitrogen loading seems to place an upper limit on % macrophyte cover and this limit declines with increasing loading while chlorophyll *a* shows a negative exponential relationship with nitrogen loading. This is due to the large range in residence times in these systems, which confounds the effect of N on plant growth in these systems. For example, Lake Onoke, an ICOLL in the Wairarapa, has a surface area of 6.2 km^2 but a catchment area of 3400 km^2, indicating a very short water residence time (estimated at 2 days) such that most of its nitrogen load would be exported from the lake.

Fig. 3 shows those relationships again, except with total nitrogen content of the lake water as the independent variable.

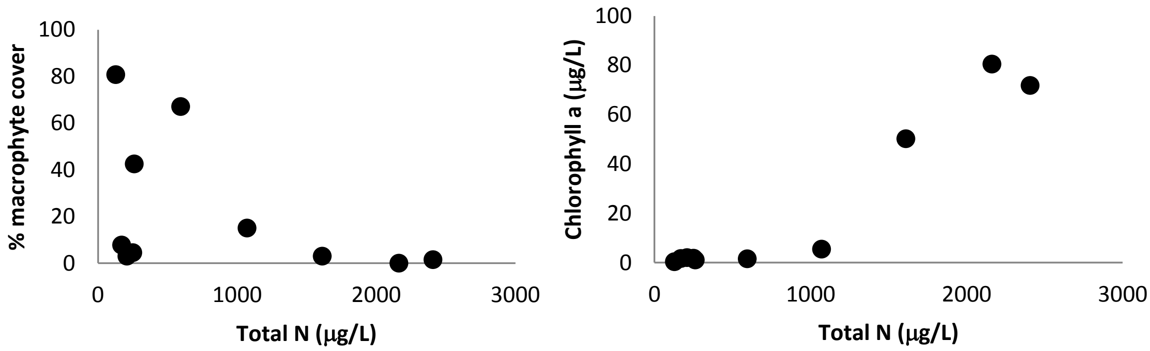

Fig. 3. Relationships between water column total nitrogen concentration and % macrophyte cover (left panel) and total nitrogen concentration and chlorophyll *a* (right panel) for 10 New Zealand brackish lakes and ICOLLs.

These relationships are more instructive, showing clear positive and negative trends with total nitrogen, such that a threshold of c. 1000 µg/L nitrogen seems to delineate states of macrophyte-dominance and phytoplankton-dominance in these systems. Note that in these systems exotic macrophytes are quite rare and, therefore, the data and relationships for % native macrophyte cover (not shown) are very similar to the data for % macrophyte cover (shown in Figs 2 and 3).

NUTRIENT LOADING VS SEAGRASS CONDITION FROM ESTUARIES AND ESTUARINE EMBAYMENTS

1. HARRIS (2008), AUSTRALIAN COASTAL SYSTEMS

In this technical report, Harris discussed critical nutrient loading thresholds for maintaining seagrasses in coastal systems. He discusses results of mesocosm experiments where seagrasses were enriched with nutrients, *in situ* experiments where slow-release nitrogen fertilisers were placed in existing seagrass beds, models of seagrass dynamics, and he summarises data in numerous reports discussing seagrass vulnerability to eutrophication. He states that in coastal systems where flushing is important, water residence times should be accounted for when assessing "effective" N loading. He indicates that a narrow range of effective nitrogen loading rates from 1–3 t N/km^2/y can be considered as the threshold above which seagrasses are no longer able to compete against macroalgae and phytoplankton in coastal systems.

2. BOYNTON ET AL. (1996), A COSTAL LAGOON IN MARYLAND, USA

This study examined the eutrophication of a large coastal lagoon, Chincoteague Bay, by developing empirical relationships between eutrophication indicators and nutrient loadings from 15 sub-regions of the lagoon and their 15 sub-catchments. The authors used Vollenweider-type equations to estimate nitrogen loadings to the sub-regions of the lagoon and compared the loadings to TN concentrations and chlorophyll *a* in those sub-regions.

The seagrasses *Zostera marina* and *Ruppia maritima* occur in the lower areas of the bay, generally in waters shallower than 1 m depth. While the distributional area of the plants had increased slightly, the density of the plants had decreased markedly and this was attributed to declines in water quality. Investigations of the seagrass dynamics in nearby Chesapeake Bay determined that seagrass beds are in good condition when light attenuation < 1.5/m, when chlorophyll *a* concentrations are < 15 μg/L, and when total nitrogen concentrations are less than 140 μg/L. Using the above regressions, the authors estimated that N loading would have to decrease to between 2 and 5 g N/m^2/y to restore seagrass communities in the upper Chincoteague Bay. These estimates did not consider nutrient dispersion processes (e.g. flushing) or denitrification and the authors called for more work to be done on these to help refine the simple guidelines above.

3. VIAROLI ET AL. (2008), MEDITERRANEAN LAGOONS

These authors summarise information on regime shifts from pristine macrophyte-dominated lagoons to macroalgae-dominated lagoons, ultimately to phytoplankton-dominated lagoons. They discuss many mechanisms which induce regime shifts, such as sediment geochemical interactions between Fe and S, and $CaCO_3$ and P. They provide a table describing the shifts that have occurred in 12 lagoons and a table showing N loading thresholds between the three different regimes. They also compare denitrification rates that occur in the different stable states.

4. FOX ET AL. (2008), WAQUOIT BAY, MARYLAND, USA

These authors examined macrophyte and macroalgal biomass and community structure in three sub-basins of Waquoit Bay with widely differing nitrogen loadings. They found that the site with low nitrogen loading (12 kg N/ha/y) maintained a population of seagrasses while the sites with intermediate (403 kg N/ha/y) and high (602 kg N/ha/y) nitrogen loadings had macroalgal blooms and no seagrasses.

5. BURKHOLDER ET AL. (2007), REVIEW ARTICLE OF SEAGRASSES AND EUTROPHICATION

This paper is a global review of the impact of nutrients on seagrasses. It contains an interesting table listing documented responses of seagrasses to experimental nutrient enrichments and eutrophication events. It also contains a table listing a number of parameters related to seagrasses that have been used to indicate nutrient enrichment in seagrass communities. It provides a critical assessment of these eutrophication indicators. The review also presents some relationships between nitrogen loading and seagrass cover, macroalgal cover and phytoplankton biomass.

CONCLUSIONS

The responses of seagrasses, macroalgae and phytoplankton to nutrient loading have been studied in many estuarine systems, but in relatively few ICOLLs.

Eutrophication instigates a generalised pattern of regime shifts in ICOLLS, lagoons and coastal embayments, with pristine seagrass communities eventually succumbing to macroalgae, which eventually succumb to phytoplankton such as cyanobacteria as nutrient loads and concentrations increase (Viaroli et al. 2008). These autotrophic components all increase in biomass in response to increasing nutrient loading and can co-exist in a relatively balanced state; however, specific nutrient loading rates tend to favour one of these groups. In some instances, the relationships, tend to be linear (e.g. Boynton et al. 1996; Fox et al. 2008), but in others they appear to be non-linear, with clear thresholds (e.g. Burkholder et al. 2007; Sanderson & Coade 2010), suggesting rapid shifts in communities as loading rates increase through the threshold values. The shapes of these relationships undoubtedly have to do with the lengths of the trophic gradients examined and with the strengths of the negative and positive ecological feedbacks specific to each system (van Nes & Scheffer 2004). Loading rates which delineate transitions from one group to another along a nutrient enrichment gradient have been referred to as nutrient loading thresholds (e.g. Harris 2008).

The nutrient loading thresholds defined in the studies examined in this review are listed in Table 2. Based on these thresholds, the loading conditions favourable to seagrasses, macroalgae, phytoplankton and denitrifiers are shown in Fig. 4.

Table 2. Thresholds summarised from the studies in this report. All loading rates have been converted to the same units.

Type of system	Ecological state	Threshold	Reference
Nutrient loading thresholds			
Australian lagoons and ICOLLs	Modest environmental quality	< 90 kg N/ha/y < 5.7 kg P/ha/y	Scanes (2012)
Model of an ICOLL	Loss of seagrasses Collapse of denitrification	> 58 kg N/ha/y > 164 kg N/ha/y	Webster & Harris (2004)
Australian lagoons	Loss of seagrass cover	> 37 kg N/ha/y	Sanderson & Coade (2010)
Australian Coastal zones	Loss of seagrasses	10 – 30 kg N/ha/y**	Harris (2008)
Chincoteague Bay, USA	Loss of seagrasses	> 20 – 50 kg N/ha/y	Boynton et al. (1996)
Mediterranean lagoons	Maintenance of seagrasses Macroalgae dominate Phytoplankton dominate	< 100 kg DIN/ha/y 100–500 kg DIN/ha/y >500 kg DIN/ha/y	Viaroli et al. (2008)
Waquoit Bay, USA	Seagrass threshold	Between 12 and 403 kg N/ha/y	Fox et al. (2008)
Global review of seagrasses	Loss of seagrasses	> 100 kg N/ha/y	Burkholder et al. (2007)

Other thresholds			
Australian lagoons and ICOLLs	Loss of seagrass cover	> 10 Assimilation Factor*	Haines et al. (2006)
New Zealand brackish lakes and ICOLLs	Loss of macrophytes and proliferation of phytoplankton	> 1000 μg TN/L	Schallenberg (unpublished)
Chesapeake Bay, USA	Seagrasses maintain good condition	Light attenuation < 1.5/m AND chlorophyll a < 15 μg/L AND total nitrogen < 140 μg/L	Boynton et al. (1996)

* $AF = R/SA*C$, where AF is the assimilation factor, R is the annual catchment runoff, SA is the surface area of the ICOLL, and C is the proportion of the time the ICOLL is closed (from Haines et al. 2006).

** corrected for residence time

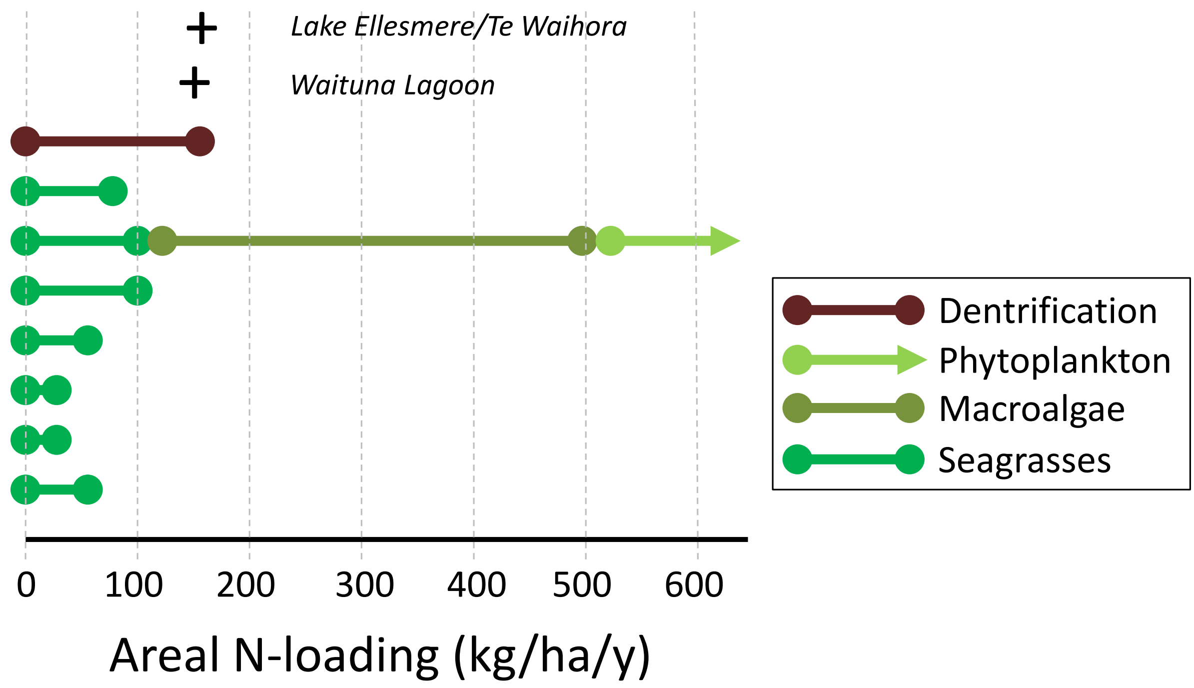

Fig. 4. Summary of nitrogen loading thresholds discussed in this report. Also indicated are the catchment nutrient loadings of Waituna Lagoon and Lake Ellesmere/Te Waihora reported in Schallenberg et al. (2010). Data were collected from the tributaries of Waituna Lagoon between 2001 and 2007, and from the tributaries of Lake Ellesmere/Te Waihora between 1996 and 2006.

It should be noted that these loading rates span a range of ICOLLs, lagoons and coastal embayments and, therefore, variable factors such as water residence time, opening regime, fetch, sediment characteristics, etc. will also affect the thresholds in specific systems. Nevertheless, there is some convergence with regard to nitrogen loading rates that negatively affect seagrass communities and the values summarised here give guidance to allowable nitrogen loads in ICOLLs in order to safeguard seagrass communities.

While the relative importance of nitrogen vs phosphorus in the eutrophication of estuaries is still debated by some in the scientific literature (e.g. Schindler et al. 2008; Conley et al. 2009), the role of phosphorus as a growth-limiting nutrient and driver of eutrophication and regime shifts in ICOLLs, lagoons, and coastal embayments generally appears to be of lesser importance than the role of nitrogen. For example, the comprehensive examinations of eutrophication and seagrass health by Webster & Harris (2004) and Viaroli et al. (2008) hardly mention phosphorus, but dwell at length on the importance of nitrogen in such systems. One reason for this could be that the seagrasses and epibenthic macroalgae of estuarine systems are well able to utilise phosphate recycled in the sediments and diffused from the sediments (Leston et al. 2008). In contrast, nitrogen loading to estuarine systems may be largely lost through high rates of microbial denitrification, sometimes exceeding 80% of the N load (Webster & Harris 2004). This substantial loss of nitrogen lowers the ratio of available N:P in comparison to the relative loading rates of these nutrients (e.g. Schallenberg et al. 2010).

The debates concerning the general importance of N and/or P in eutrophication are somewhat vexatious in a management context because the relative importance of either nutrient in a particular system depends on many specific factors such as the relative loading rates of the nutrients, the importance of nitrogen fixation and denitrification in the system, and the specific biogeochemistries of N and P at given salinities and oxygen concentrations. Examination of nutrient ratios can provide some insights, but these are inferential and a deeper understanding of the relative importance of N and P to the potential loss of seagrasses and the potential for algal or macroalgal blooms in Waituna Lagoon requires detailed biological investigation.

Our examination of the available literature revealed that there are a number of well-studied ICOLLs which share similarities with Waituna Lagoon. These include Lake Illawara, Wilson Inlet, and Smiths Lake in Australia as well as East Kleinemonde Estuary in South Africa. Deeper study of the published information on these ICOLLs should help improve understanding of the functioning of Waituna Lagoon.

A number of numerical models exist to assist with ICOLL management and some of these appear to be of interest with regard to simulating and forecasting scenarios of Waituna Lagoon. In particular, the numerical model of Webster & Harris (2004) and the semi empirical model of Sanderson & Coade (2010) are of interest. For example, the Webster & Harris model incorporates feedbacks and regime shifts as well as a sophisticated function for denitrification efficiency in relation to nutrient loading. These features indicate that the model might be appropriate for scenario forecasting. The model of Sanderson & Coade is designed to be easily scaled to different ICOLLs and suggests that it wouldn't take much effort to use it for Waituna Lagoon scenarios.

This review identified a wide range of previously published studies on ICOLLs, lagoons and coastal embayments. These include detailed studies on individual ICOLLs, ICOLL models of different types, and empirical relationships among ICOLLs, lagoons and embayments. The studies summarised here help place Waituna Lagoon in to a broader context and could potentially provide guidance as to the management and restoration of Waituna Lagoon.

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APPENDIX I: BACKGROUND INFORMATION ON ICOLLS DISCUSSED IN THIS REPORT

ICOLL	Latitude	Maximum depth	Surface area	Volume	Entrance closure index	Water level variation	Chlorophyll *a* range	Salinity range	Opening	Macrophytes	Macroalgae	References
		m	ha	10^6 m^3	proportion	m	µg/L	ppt or psu	natural or artificial	Dominant species	Dominant species	
1. Waituna Lagoon	46° 33'S	1.6 (open), 3.29 (full)	1630 (full)	26 (full)	0.46	1.6	0.5–37	0.7–33.6	artificial	*Ruppia megacarpa, Ruppia polycarpa, Myriophyllum triphyllum*	*Bachlotia antillarum*	Schallenberg et al. (2010)
2. Lake Ellesmere	43° 47'S	1.9 (open), 3.0 (full)	21300 (full)	301 (full)	0.82	1.0	6–221	2.3–14.2	artificial	None	NA	Schallenberg et al. (2010)
3. East Kleinemonde	33° 32'	2.3 (full)	11.6–35.7	0.664 (full)	0.9	2.1	approx. 2–20	15–32	natural	*Ruppia cirrhosa, Potamogeton pectinatus*	*Ulva* sp., *Cladophora* sp.	Ridden & Adams (2008), Whitfield et al. (2010)

ICOLL	Latitude	Maximum depth	Surface area	Volume	Entrance closure index	Water level variation	Chlorophyll a range	Salinity range	Opening	Macrophytes	Macroalgae	References
		m	ha	10^6 m^3	proportion	m	µg/L	ppt or psu	natural or artificial	Dominant species	Dominant species	
4. Mecox Bay	41° 55'N	2.2 (full)	423	NA	0.21	1.0	2–20	6–27	artificial	NA	NA	Gobler et al. (2005), Freno (2004)
5. Mhlanga Estuary	29° 42'S	NA	80	0.8 (full)	0.9 (natural), 0.5 (artificial)	2.5	2–375	1–26	both	NA	NA	Lawrie et al. (2010)
6. Wilson Inlet	34° 56'S	approx.. 5m (full)	4800	85 (open)	approx.. 0.35	NA	1–50	9–35	natural	*Ruppia megacarpa*	NA	Carruthers et al. (1999), Twomey & Thompson (2001)
7. Lake Illawara	34° 56'S	3.7	3500	62.4	NA	NA	NA	12.8–31.3	natural	*Ruppia megacarpa, Zostera capricorni*	*Chaetomorpha linum, Enteromorpha intestinalis, Ulva lactua*	Ellis et al. (1977), Qu et al. (2003)

ICOLL	Latitude	Maximum depth	Surface area	Volume	Entrance closure index	Water level variation	Chlorophyll a range	Salinity range	Opening	Macrophytes	Macroalgae	References
		m	ha	10^6 m^3	proportion	m	μg/L	ppt or psu	natural or artificial	Dominant species	Dominant species	
8. Wamberal Lagoon	33° 25'S	2.0 (open) 3.0 (full)	60	approx.. 1.2	approx.. 0.08	NA	NA	NA	artificial	NA	NA	Gale et al. (2006; 2007)
9. Smiths Lake	32° 23'S	3.5 (open) approx.. 5 (full)	1100	approx.. 33	approx.. 0.14	NA	NA	NA	artificial	NA	NA	Gale et al. (2006; 2007)
10. Corunna Lake	36° 29'S	3.5 (mean)	200	0.7	NA	NA	NA	NA	artificial	NA	NA	Spooner & Maher (2007)