Environmental Sensitivity of Lake Wollumboola:

Input to Considerations of Development Applications for Long Bow Point, Culburra

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Executive Summary

Land within the catchment of Lake Wollumboola on the NSW south coast is currently subject to development proposals, including a golf course proposed for Long Bow Point on the north western corner of the lake. The proponent (Realty Realizations) has commissioned an environmental assessment of the lake and hydrological modelling of the golf course proposal. The Realty Realizations documents claim that:

1) The ecology and biogeochemistry of the lake is no different to other NSW systems (e.g. the neighbouring Crookhaven River) and these other systems therefore provide valid references.

2) The existing water quality of the lake is currently degraded and therefore the lake is not as "fragile" as assumed by authorities.

3) That the "Comprehensive Protection" management classification given to Lake Wollumboola as part of the 2001 Classification of Coastal Lakes by the Healthy Rivers Commission was unjustified and non-transparent.

4) That all proposals within the lake catchment (both urban development and the golf course) would actually improve water quality in the lake over natural conditions.

5) That pollution of the lake caused by existing development within the catchment could be offset by allowing the proposed development.

The Estuaries and Catchment Science unit of NSW OEH has reviewed the Long Bow Point proposals and the supporting material, as well as the available scientific literature relevant to the biogeochemistry and ecology of the lake. This report is intended to provide background and scientific justifications for OEH's (separate) detailed assessment of the proposals. Here, we aim to provide a comprehensive picture of the lake's typology, key processes, ecological significance and sensitivity. We argue that potential impacts can only be realistically assessed if the key processes underpinning lake ecology are first determined and then examined in any impact assessment.

OEH analysis of the ecological and biogeochemical functioning of Lake Wollumboola

OEH made use of a wide range of sources of data, including the many studies of Lake Wollumboola, OEH estuarine research and OEH sampling of over 130 other NSW estuaries. We also utilised the detailed knowledge from published work and from within OEH about the fundamental processes that maintain estuary function. It is critical to realise that whilst basic biogeochemical and ecological processes are common to most estuaries, the way in which they are expressed and interact can produce vastly different outcomes in different types of estuaries. It is also important to understand that the basic function of intermittently opening and closing estuaries in NSW does not conform to many of the paradigms developed for northern hemisphere estuaries (Scanes et al. 2007, Scanes et al. 2011, Scanes et al. in press) and simplistic application of concepts such as standard eutrophication definitions (e.g. as reported in Simmons and Beveridge 2008) are quite inappropriate in many NSW estuaries.

The main points from the OEH analysis are:

- Analysis of a wide range of system attributes for over 130 NSW estuaries, including detailed statistical analysis of 34 estuaries with low catchment disturbance, indicates that Lake Wollumboola is clearly different from the majority of estuaries and is grouped within a very small subset of estuaries now referred to as a 'back-dune lagoons' biotype. This group comprises less than 5% of NSW estuaries.

- Variation within the back-dune lagoons group means that system function needs to be assessed on a case by case basis.

- Relatively large concentrations of forms of dissolved nitrogen in the water and a large biomass of submerged vegetation (charophytes and macrophytes) in Lake Wollumboola are not indicative of eutrophication, but are characteristic of undisturbed back-dune lagoons.

- Lake Wollumboola is a unique system of high ecological value, characterised by high primary productivity and overall biological diversity, particularly for birds. This translates to high social value, primarily centred on its birdlife.

- The high concentrations of coloured dissolved organic matter in the water, plus a range of other factors, are indicative that groundwater is most probably a major component of freshwater inputs to the lake. Pollution of groundwater therefore represents a major risk to the lake.

- Extreme temporal and spatial variation in water quality gradients present significant challenges for monitoring and interpretation of data. Until a comprehensive understanding is gained about the processes that sustain lake ecology it is clear that interpretation of monitoring data cannot be reliably based on existing conceptual models developed for much better studied systems (e.g. coastal lakes and riverine estuaries).

- The dominant vegetation of charophytes and macrophytes provides three dimensional structure to the lake environment in a way that forms strong feedback controls over the biogeochemical cycling of nutrients. These feedbacks convey a competitive edge over other primary producers (e.g. phytoplankton and filamentous macroalgae) which could otherwise outcompete the existing vegetation if conditions change. The current state of the lake system is dependent on the continued existence of the existing charophytes and macrophytes.

- Charophytes have been studied extensively in Australia and internationally and are reported to be very sensitive to water quality. Given the strong control that charophytes exert on lake ecology and water quality, we consider that the lake is vulnerable to a catastrophic state change if key processes are disrupted by nutrient enrichment and there is significant loss of charophytes and macrophytes.

- If a change of state occurrs it is not possible to reverse it. The lake would never recover from loss of the charophytes and macrophytes and the ecosystem services they provide, instead it will move to an alternate state which is turbid and phytoplankton or macroalgae dominated.

- Higher levels of the food chain are dependant on the charophytes and macrophytes and loss of them will result in the loss of swans and other fauna.

OEH assessment of claims made by Realty Realizations

We find that none of the above claims by the proponent of the Long Bow Point golf course proposal are supported, and furthermore, that the environmental assessment by Simmons and Beveridge (2008) contains numerous serious scientific flaws and is not an adequate basis for assessing the proposal. It is not our intention to make a detailed critique of Realty Realizations' environmental assessment and modelling reports as part of this document, however we summarise our main issues with the proposal and claims made by the proponent below.

- Only a very select amount of the existing literature was reviewed as part of the assessment by Simmons and Beveridge (2008), and naive or invalid methods (e.g. loading calculations) and interpretation were used to assess the relative impacts of the proposal.

- Lake Wollumboola can not be considered to be "…. no different to other NSW systems ". We have demonstrated that the lake is a unique back-dune lagoon, and cannot be compared with other systems outside of this group.

- There was no explicit conceptual understanding of lake processes developed as part of the Simmons and Beveridge (2008) assessment and as a consequence, much of the analysis was based on inappropriate models or comparisons and most conclusions were simplistic and/or fundamentally flawed. For example, the relatively large concentrations of some forms of nitrogen, large biomass of vegetation and extreme physicochemical gradients in Lake Wollumboola are not indicative of eutrophication, but are characteristic of undisturbed back-dune lagoons in NSW.

- There was a fundamental lack of understanding by by Simmons and Beveridge (2008) of the differences between loads and standing stocks of nutrients resulting in flawed conclusions regarding impacts of nutrient loads

- All evidence shows that the lake is highly productive and ecologically diverse.

- The unique ecology of the lake appears to be underpinned by a complex set of interactions and feedbacks making it very sensitive to catastrophic state change. It is definitely "fragile".

- The proponent appears to be confused about the management classification given by the Healthy Rivers Commission. "Comprehensive Protection" is given in recognition of the lake's intact ecological values and the minimal need for rehabilitation. We believe that the evidence available supports this classification.

- The modelling undertaken to support the Long Bow Point golf course proposal was simplistic, not validated and inadequate to provide confidence that the proposals would actually improve runoff quality. Assertions from the modelling that the development would result in a net improvement in water quality (and would be better than undisturbed forest) are not supported by any evidence from similar treatment systems in other places.

General implications of this analysis for development around Lake Wollumboola

- The demonstrated ecological significance of the lake, the relative rarity of its biotype and its sensitivity to catastrophic state change justify the current limitations to development within the lake catchment.

- It is recommended that a precautionary approach to assessing development near the lake be adopted as a high priority, as impacts on the lake are likely to be irreversible.

- Any future development in the vicinity of Lake Wollumboola should be placed as far from the lake as possible to minimise risk of contamination of groundwater aquifers which may be directly linked to the lake.

- It is essential that any future assessment of potential impacts is based on a sound conceptual and empirical understanding of lake ecology and processes. Because of the uniqueness of many of the processes within Lake Wollumboola, it is clear that interpretation of monitoring data cannot be reliably based on existing conceptual models developed for much better studied systems (e.g. coastal lake or riverine estuaries). The conceptualisation of ecological processes for back-dune lagoons that has begun here needs to be further refined and tested.

- Pollution of groundwater by nutrients is a major risk that needs to be properly assessed. Any models used must be calibrated and verified.

Introduction

Land within the catchment of Lake Wollumboola on the NSW south coast is currently subject to development proposals, including a golf course proposed for Long Bow Point on the north western corner of the lake. The proponent (Realty Realizations) has commissioned an environmental assessment of the lake and hydrological modelling of the golf course proposal. These reports claim that:

- The ecology and biogeochemistry of the lake is no different to other NSW systems (e.g. the neighbouring Crookhaven River) and these other systems therefore provide valid references.
- The existing water quality of the lake is currently degraded and therefore the lake is not as "fragile" as assumed by authorities.
- That the "Comprehensive Protection" management classification given to Lake Wollumboola as part of the 2001 Classification of Coastal Lakes by the Healthy Rivers Commission was unjustified and non-transparent.
- That all proposals within the lake catchment (both urban development and the golf course) would actually improve water quality in the lake over natural conditions.
- That pollution of the lake caused by existing development within the catchment could be offset by allowing the proposed development.

The Estuaries and Catchment Science unit of NSW OEH has reviewed the Long Bow Point proposals and the supporting material, as well as the available scientific literature relevant to the biogeochemistry and ecology of the lake. This report is intended to provide background and scientific justifications for OEH's assessment of the proposals. We aim to provide a comprehensive picture of the lake's typology, key processes, ecological significance and sensitivity. We argue that potential impacts can only be realistically assessed if the key processes underpinning lake ecology are first determined.

OEH made use of a wide range of sources of data, from the many studies of Lake Wollumboola and over 100 other NSW estuaries. We also utilised the detailed knowledge from published work and within OEH about the fundamental processes that maintain estuary function. It is critical to realise that whilst basic biogeochemical and ecological processes are common to most estuaries, the way in which they are expressed and interact can produce vastly different outcomes in different types of estuaries. It is also important to understand that the basic function of intermittently opening and closing estuaries in NSW does not conform to many of the paradigms developed for northern hemisphere estuaries (Scanes et al. 2007, Scanes et al. 2011, Scanes et al. in press) and simplistic application of concepts such as standard eutrophication definitions (e.g. as reported in Simmons and Beveridge 2008) are inappropriate in NSW estuaries.

Is Lake Wollumboola Like All other Estuaries?

NSW OEH has, through the state Monitoring Evaluation and Reporting (MER) Program, been involved in a broad scale sampling of estuarine water quality and ecology in NSW for over 8 years. NSW has 184 recognised estuaries and OEH have data from 132 estuaries collected during the MER Program. These estuaries have been divided into types based on morphology and hydrologic characteristics (Roper et al. 2011). The morphological estuary types present in NSW are Drowned River Valleys, Barrier Rivers, Lakes and Lagoons - which are subdivided into Lagoon type A (medium sized lagoons) and Lagoon type B (small creek estuaries).

Based on analyses of these data OEH have identified that estuary types have intrinsically different water quality. OEH have commenced a process of identifying ANZECC style water quality objectives for each type of NSW estuary. In this process, we have identified that the current morphological classification may not be sufficient because there are estuaries which differ significantly from other estuaries in their Type in aspects of ecology, water quality and biogeochemistry. Lake Wollumboola was one of these estuaries (Figure 1).

In order to demonstrate definitively that Lake Wollumboola and similar estuaries can not be considered as the “same” as all other NSW estuaries and thus avoid any special consideration, OEH undertook statistical analysis of water chemistry and biology data from 34 low impact estuaries, across all morphological types. Only estuaries that were classified as having low levels of catchment disturbance (Roper et al. 2011) were analysed. This avoids bias due to human induced changes. Lake Wollumboola was included in this analysis.

The objective of the statistical analysis was to determine if there is an estuary type, based on chemical and biological characteristics, that is not captured by the current hydrologic or morphometric typologies.

Data for estuaries with low or very low catchment disturbance were taken from the MER database. Two systems with extensive data that we believe were erroneously classified as moderate disturbance (Brou and Termeil) were also included. Many estuaries had incomplete data and only those estuaries where there was some data for all variables under consideration (temperature, salinity, turbidity, chlorophyll, nutrients: see Appendix 1) were retained. This left 34 low disturbance estuaries. A mean value for each variable was calculated for each estuary. Analyses were done with bloom and non-bloom data for Nadgee Lake (Scanes et al. 2011). Only the non-bloom analyses are presented here because they allow more detail to be seen for other estuaries, though the same general pattern was evident in both analyses.

Non-metric MDS (Primer 6) was used to examine multivariate patterns in data. Data were normalised and similarity among estuaries calculated using Euclidian Distance. After MDS plots were generated, estuary type was superimposed. Two plots were generated, one using the CERAT estuary types only and another using CERAT types plus an additional “Atypical” type (Appendix 2). Estuaries were initially assigned to the “Atypical” class based on field observations.

Principle Co-ordinate Analysis was used to indicate the main factors influencing separation between estuaries in multi-dimensional space. Analysis of Similarity (ANOSIM) was used to examine whether there were significant differences in MDS space among estuary types based on the water and biological variables used.

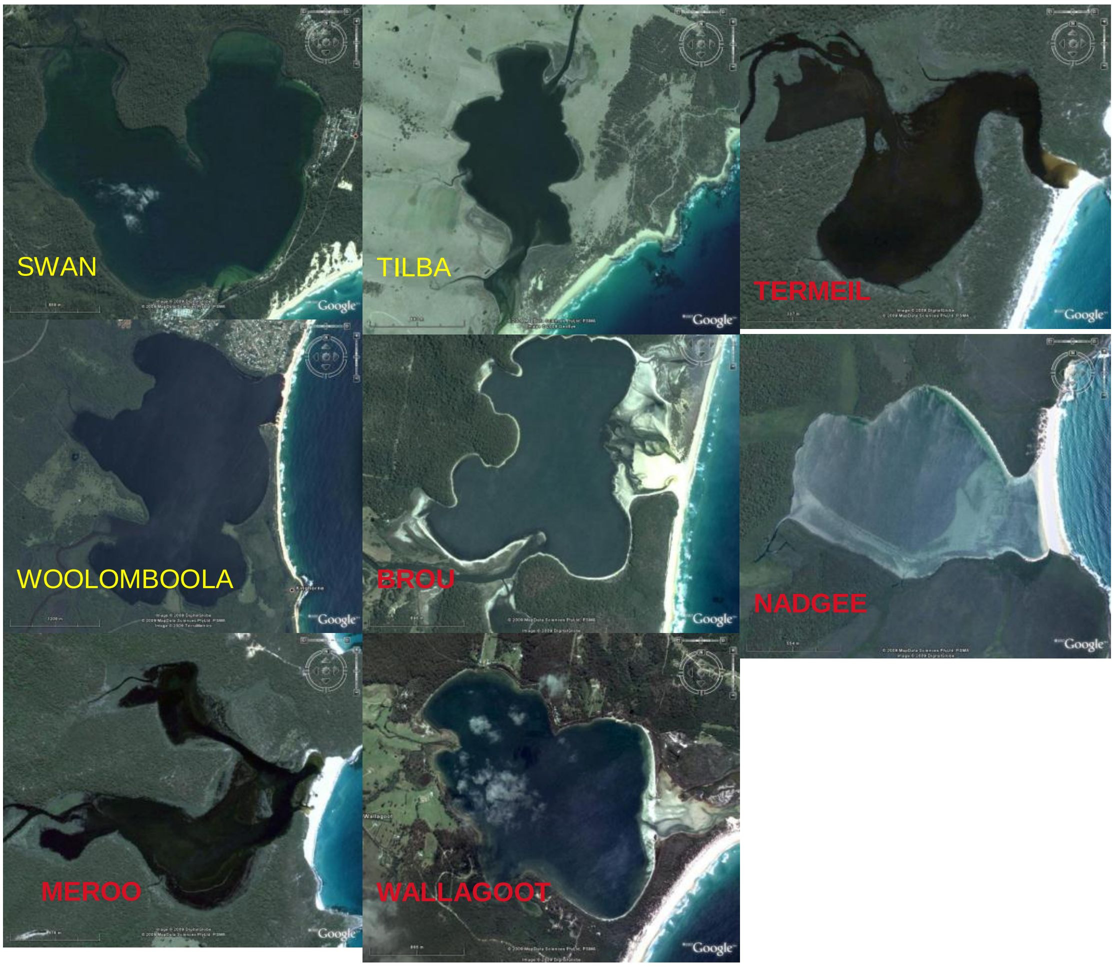


Figure 1 – Examples of the Back-dune Lagoon biotype.

Most estuaries tended to clump together in the MDS, but there were several that were separate (Figure 2; see Appendix 2 for abbreviations). Separation was not according to estuary type (symbols in Figure 3). When the additional class was added (AT in Figure 3) it can be seen clearly that there is a clear separation between AT estuaries and all others. It is also evident that AT estuaries are spread across Estuary Types “Lake” and “Lagoon”. PCA showed that high concentrations of dissolved organic nitrogen (DON), moderate chlorophyll, high ammonia (NH_4^+) and very low phosphate and turbidity were the factors that differentiated AT estuaries (Figure 4). ANOSIM analyses indicated that AT estuaries were significantly different from all other estuary types, but that there were no other significant differences among types (Table 3).

Lake Wollomboola was classified among the “AT” estuaries. Other detailed analyses of nutrient concentrations shows clearly that Lake Wollumboola is a representative of this bio-type (Appendix 3).

OEH has assigned the name Back-dune Lagoon to the biotype represented by “AT” estuaries. Back-dune lagoons are typically simple rounded estuaries, relatively shallow (<6m) with intermittent entrances and are found in back dune depressions. They typically have relatively small catchments and as a consequence, groundwater is most probably a large component of the freshwater inputs. Examples of back-dune lagoons include Nadgee Lake, Wallagoot Lake, Brou Lake, Meroo Lake, Termeil Lake, Tilba Tilba Lake, Tabourie Lake, Lake Willinga, Swan Lake, Lake Woolumboola (Figure 1).

In NSW, back-dune lagoons seem to be found only on the south or central coast and are typified by clear (but often coloured) waters, high concentrations of dissolved organic nitrogen (DON) (Figure 3), intermittently high concentrations of ammonium (NH_4^+), but low concentrations of NO_x and very low concentrations of phosphate (Appendix 1). They are also characterised by dense beds of macrophytes, primarily *Ruppia*, *Zostera* and charophytes such as *Lamprothamnion*. Most of the time, chlorophyll concentrations are low, but occasionally algal blooms occur – even in pristine examples (Scanes et al. 2011). The relatively high concentrations of organic nitrogen, low concentrations of phosphate and large abundances of charophytes are not in any way indicative of eutrophication but are a natural state for back-dune estuaries.

Whilst back-dune lagoons are clearly differentiated from other estuary types, there is significant variation among examples of back -dune lagoons. This is attributed to the isolation of each, meaning that they each develop in slightly different directions. Each back-dune lagoon is truly unique in many characteristics.

Currently, not all back-dune lagoons have extensive charophyte beds, but OEH believes it is likely that prior to European catchment disturbance all would have had these macrophytes. In OEH’s survey of 132 NSW estuaries, extensive charophyte beds were observed in only 8 estuaries (4% of NSW estuaries), Lake Wollumboola, Myall Lake, Swan Lake, Termeil Lake, Lake Tabourie, Wallagoot Lake, Barragoot Lake and Willinga Lake. All these are ranked in Roper et al. (2011) as having low catchment disturbance and conform to the description of back-dune lagoons.

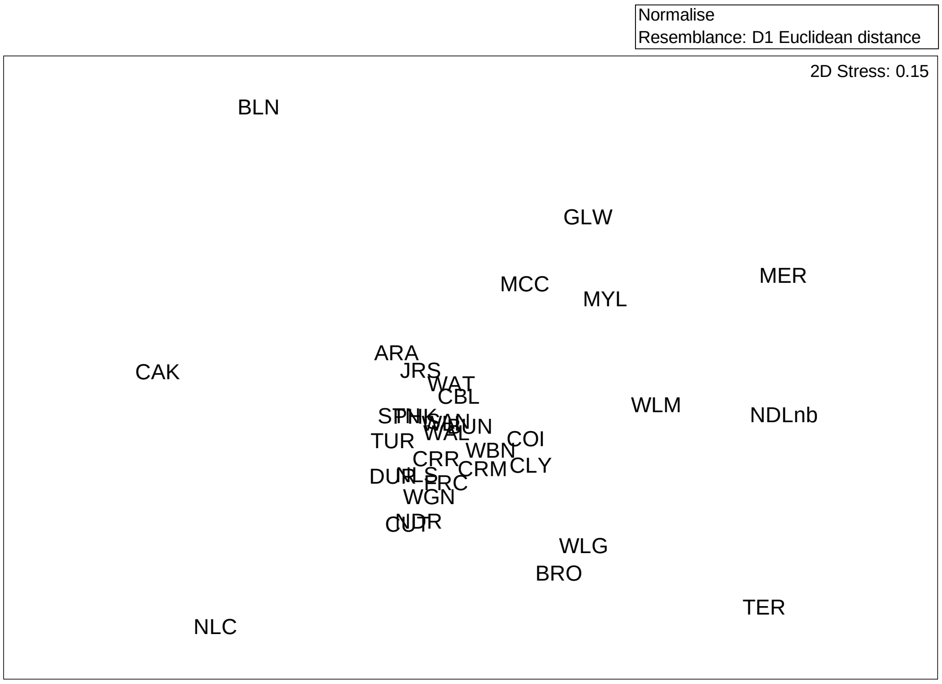


Figure 2 2D representation of MDS for estuaries based on physical, chemical and biological data. WLM represents Lake Wollumboola. Key to other Estuary Site Codes is in Appendix 2.

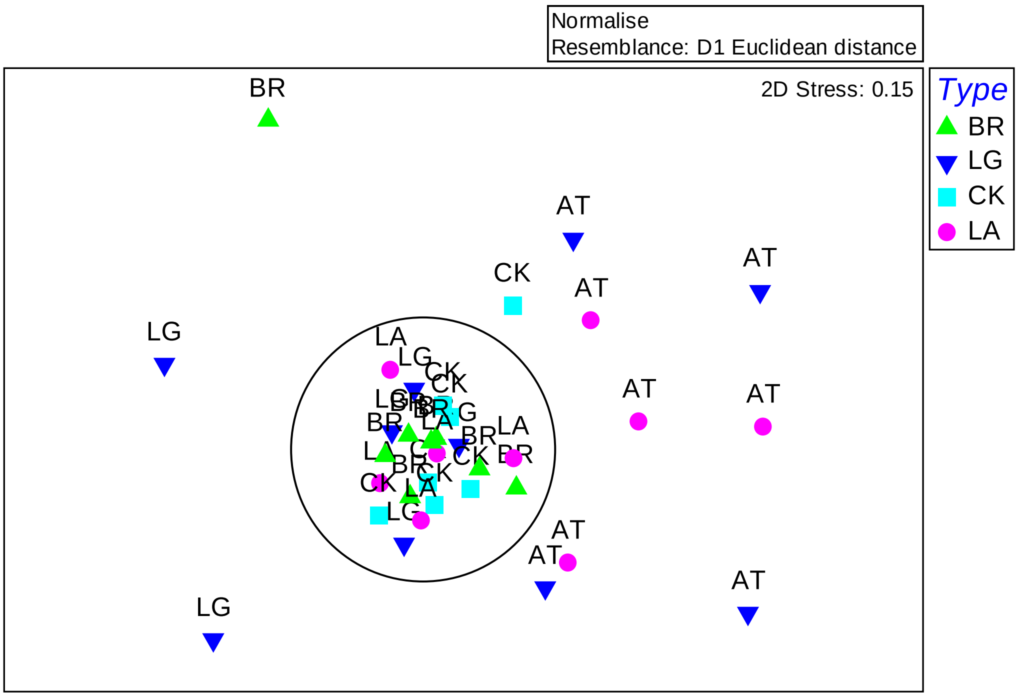


Figure 3 2D MDS plot showing distribution of CERAT estuary types (coloured symbols; BR – Barrier Rivers, LG – Lagoon A, CK – Lagoon B, LA - Lake) and modified typology (which now includes “AT” type; lettering on plot). AT type is clearly distinguished from other types (circled). There are no “AT“ within the circle.

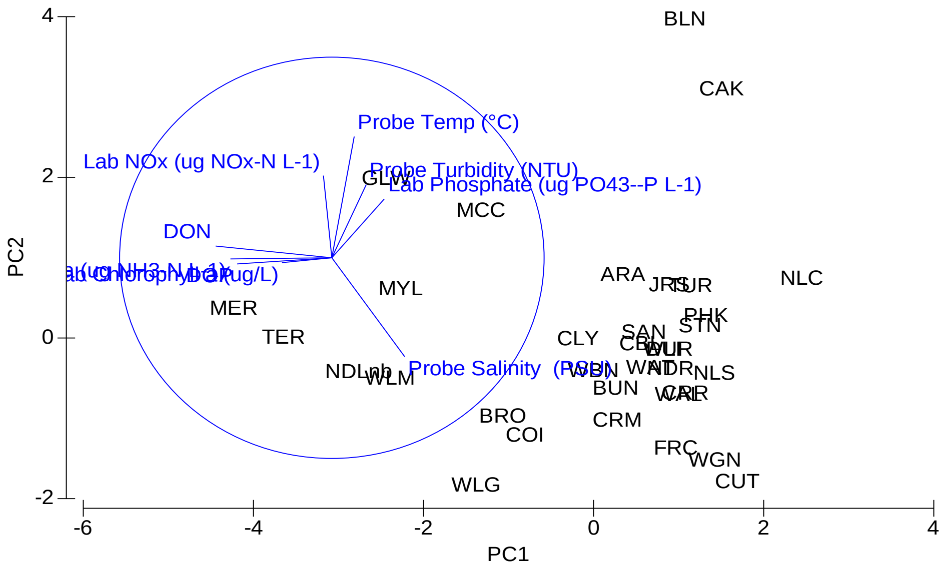


Figure 4 PCA showing main factors determining spread in 2D space.

Table 3 Results of pairwise comparisons between groups based on estuary type. A significance level less than 5% is deemed to indicate significant difference between groups (highlighted).

Pairwise Tests

Groups	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >= Observed
BR, LG	0.043	24.6	3003	999	245
BR, CK	0.007	41.1	6435	999	410
BR, LA	0.091	21.2	1287	999	211
BR, AT	0.424	0.1	6435	999	0
LG, CK	0.032	30.6	1716	999	305
LG, LA	-0.08	78.6	462	462	363
LG, AT	0.494	0.1	3003	999	0
CK, LA	0.01	41	792	792	325
CK, AT	0.423	0.2	6435	999	1
LA, AT	0.317	3.2	1287	999	31

How does Lake Wollumboola Function?

In order to make a rational and realistic assessment of how different catchment activities may impact on lake ecology, it is first necessary to develop a sound understanding and conceptualisation of how the ecology functions and the processes that underpin it. It is clear from the analysis in the first section of this report that Lake Wollumboola is a unique ecosystem, however there is currently no comprehensive description of the linkages between catchment inputs, lake biogeochemistry, and lake ecology. This section attempts to fill this knowledge gap by drawing together existing information on the lake.

Conceptual model of lake function

Lake Wollumboola is a shallow estuary with a wave dominated entrance (Roy et al. 2001). Wave dominated estuaries often have intermittent entrances because the rate at which waves push sand into the entrance is greater than the rate at which freshwater and tidal flows can clear the sand. Lake Wollumboola is infilling at a rate of approximately 0.4 – 0.7 mm per year (Baumber 2001). The lake consists of three primary geomorphic units: 1) the fluvial delta; 2) the central mud basin; and 3) the marine delta. These units have distinct sedimentology, and support distinct biogeochemical and ecological processes. The Lake entrance can close for periods of up to 3 – 5 years, however, the duration of lake closure is variable, determined by rainfall and ocean wave climate.. Functionally, the lake shifts between two very distinctly different states which are illustrated in Figure 5.

Under open entrance conditions, the lake becomes much shallower and more marine dominated, with large areas of the marine and fluvial delta shoals becoming exposed. Areas of charophytes and macrophytes contract as shallower shoals are exposed, however this creates opportunities for other organisms such as microalgae, invertebrates, and birds. Once the entrance closes, lake levels rise in response to freshwater inputs and the relative area of charophytes and macrophytes expands, thereby increasing opportunities for different organisms (e.g. swans). When the lake is perched (i.e. lake level is greater than sea level) there is usually some leakage of water through the beach to the ocean.

The large standing stocks of charophytes and macrophytes, and the very high numbers of water birds that utilise the lake (Hedge and Dickinson 2010), both indicate an extremely productive and diverse ecosystem. The diversity of plant, invertebrate and bird life may not be as evident in the fish fauna – intermittent lagoons often have fewer species of fish than open estuaries.

This is despite a relatively small and nutrient-poor catchment, suggesting that the lake's ecology is supported by unique combination of internal biogeochemical processes and feedbacks. The nature of these feedbacks remains undescribed, however various lines of evidence exist in the form of separate studies undertaken in the lake. The remainder of this section summarises pertinent aspects of these studies to provide a more detailed picture of lake function.

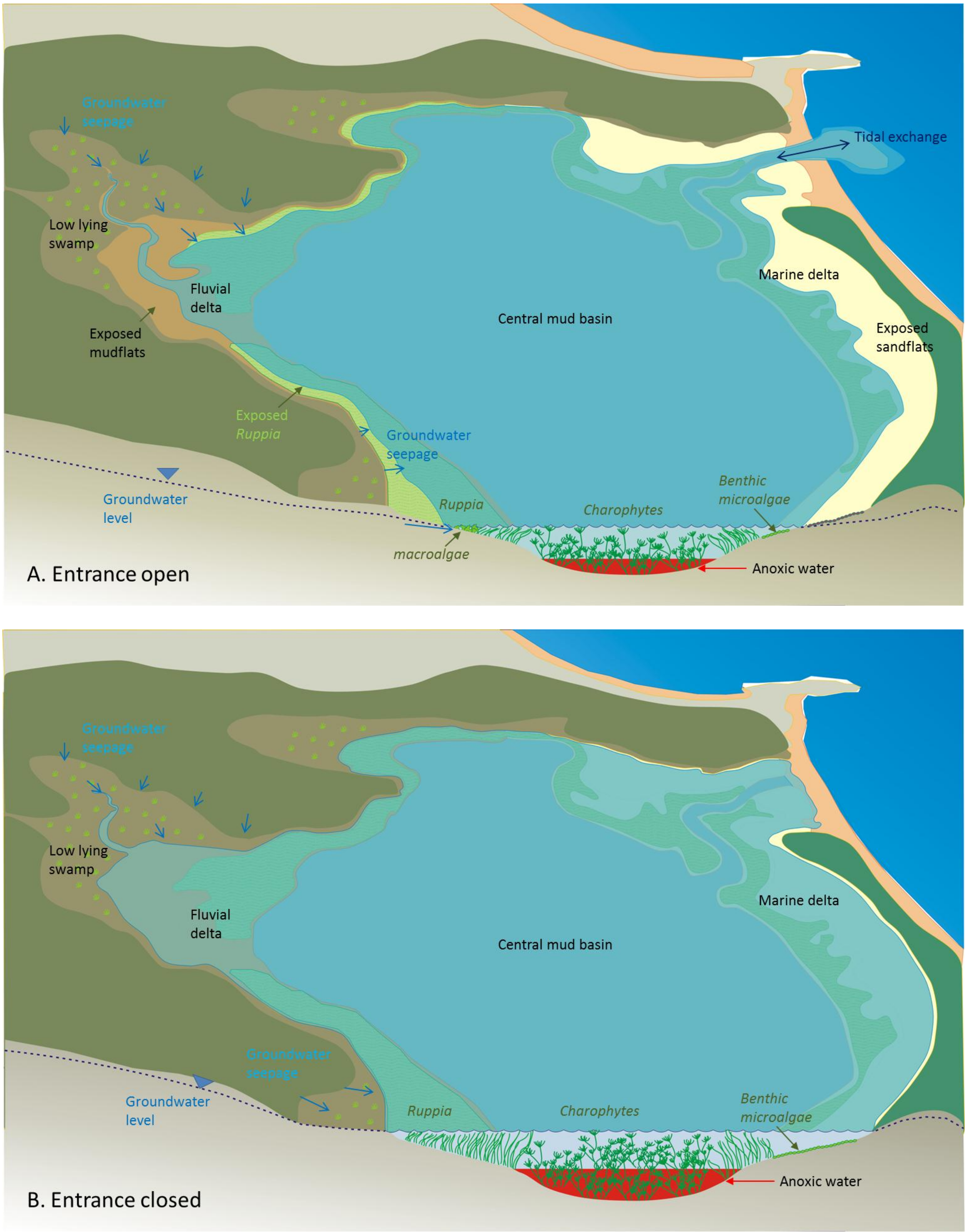


Figure 5 Conceptual model of Lake Wollumboola under A) entrance open; B) entrance closed conditions

Entrance opening and salinity regime

While Lake Wollumboola is clearly grouped within the Back-dune Lagoon biotype (meaning it is groundwater-dependent and intermittent), unique features of its climate, catchment size and geology, combined with its geographic situation on the coast (e.g. wave climate and littoral sand supply) mean that its entrance opening and salinity regimes are distinctly unique. These features combine to shape the unique nature of the lake's biogeochemistry, productivity and ecological diversity.

The entrance berm at Lake Wollumboola intermittently opens on a long-term average frequency of about 3 – 5 years. The duration of opening depends on the amount of scour at the entrance berm upon opening, and the littoral sand supply during the period following opening. Natural opening occurs once lake levels reach approximately 2 – 3 m AHD, depending on the height of the entrance berm at the time of major rainfall events. NSW NPWS maintain a policy of artificially opening the lake to protect low lying property in the lake catchment once levels reach 2.75m AHD, and ad hoc opening of the lake also commonly occurs due to the actions of local residents. Some local residents associate lake opening with favourable outcomes (e.g. surfers and fishermen), while others associate it with negative outcomes (e.g. fish kills and sulfidic odours).

Once open, the lake level drops quickly to approximately 0m AHD exposing extensive sandflats of the marine delta and mud flats of the fluvial delta (Figure 6). Salinity increases rapidly to approximately seawater and the lake becomes tidal (tidal attenuation depending on the depth of the entrance channel). The exposure of aquatic vegetation (e.g. *Ruppia*) and sediments potentially causes wide scale shifts in the relative area of different habitats and biogeochemical processes within the lake.

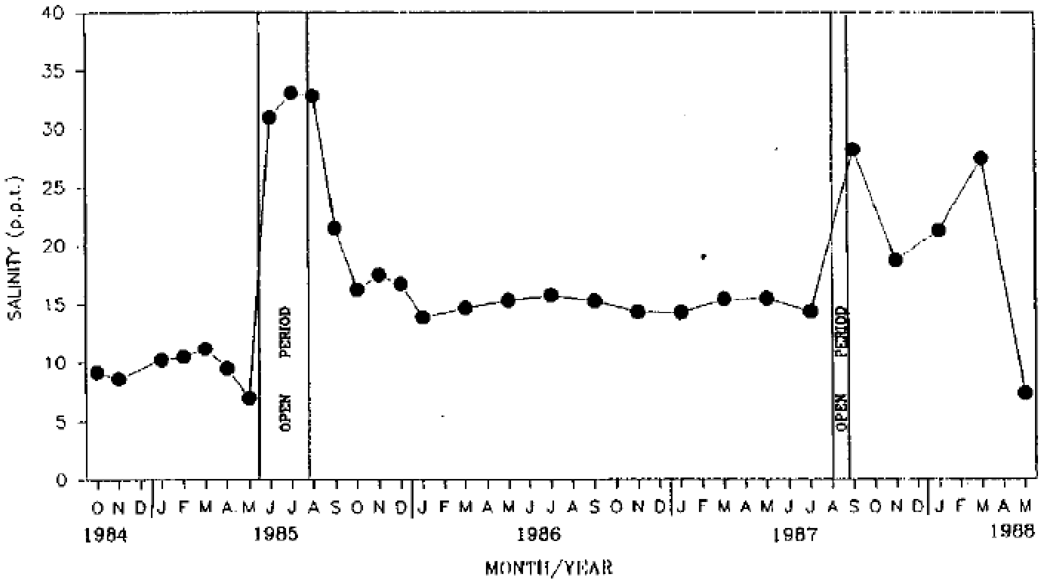
Figure 6 Lake Wollumboola with an open entrance.

Once the beach berm closes, the lake environment can progress along different trajectories depending on rainfall conditions at the time:

1) Low rainfall: lake levels remain low and evaporation exceeds freshwater inputs from groundwater and overland flow resulting in the development of hyper-saline conditions. There are conflicting data on how high salinities can go, but most reliable sources suggest that ~45 psu (PSU - practical salinity units, are now the international standard unit for salinity. PSU are directly comparable to parts per thousand) seems plausible. The very high salinities (90-100 psu) reported from 1990-91 by McCotter & Associates (1991) and discussed in Simmons & Beveridge (2008) are not consistent with any other data measured in the last 3 decades and are considered by OEH to be unreliable or rare.

2) Median rainfall: lake levels increase and salinity decreases in response to rainfall events but are relatively stable in between events (Figure 7). It is likely that outside rainfall events (when overland flow reaches streams), that groundwater (both baseflow to streams and direct seepage to the lake) constitutes the main pathway of freshwater input.

3) High rainfall: lake levels increase and salinity decreases progressively when freshwater inputs exceed evaporation.



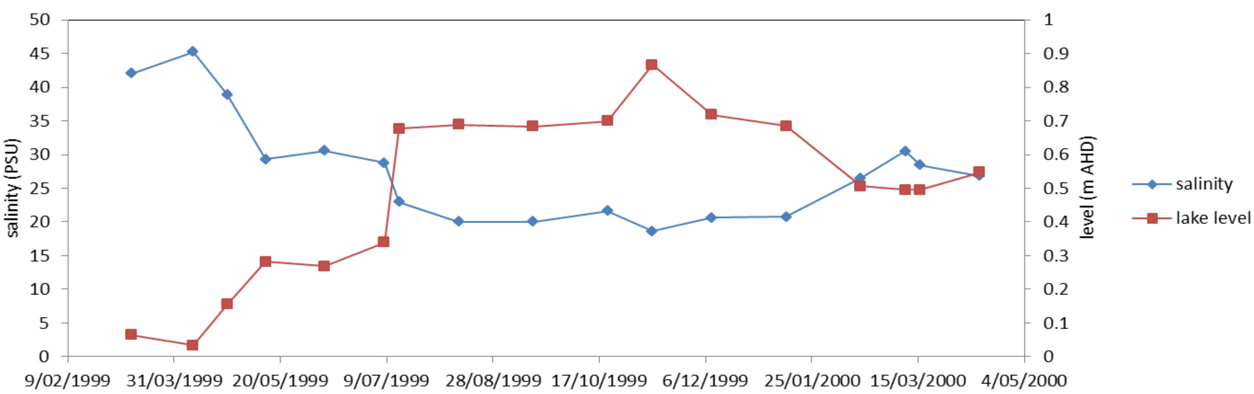


Figure 7 Salinity and lake levels in Lake Wollumboola

Stratification

Data from water quality loggers deployed between 1999 and 2001 (MHL 2001) show that the lake undergoes extended periods of stratification, whereby surface waters become slightly warmer and supersaturated in dissolved oxygen, while bottom waters within the charophyte matrix remain hypoxic to anoxic (Figure 8). The oxygen stratification is the most prominent feature, and most likely arises from high rates of photosynthetic production by macrophytes in surface waters, and a combination of bacterial mineralisation of organic matter and oxidation of hydrogen sulphide in bottom waters. The presence of thick *Ruppia* and *Lamprothamnion* stands most likely dampens mixing between surface and bottom layers, however extended strong wind events cause seiching and can eventually lead to the breakdown of stratification.

The occurrence of such dramatic stratification combined with the effects of wind-driven seiching creates extreme biogeochemical gradients at various vertical and horizontal scales within the lake. These gradients create a strong control over the lake ecology and are most likely directly linked to its high productivity in a relatively oligotrophic setting, and with the diversity of microbial, floral and faunal communities. As noted above, the presence of thick stands of *Lamprothamnion* create feedbacks which help create or reinforce strong biogeochemical gradients. The nature and implications of these gradients remain completely unknown and warrant further research.

It should be noted that extreme temporal and spatial variation in water quality gradients present significant challenges for monitoring and interpretation of data. Further, until a comprehensive understanding is gained about the processes that sustain lake ecology it is clear that interpretation of monitoring data cannot be reliably based on existing conceptual models developed for much better studied systems (e.g.coastal lakes or riverine estuaries).

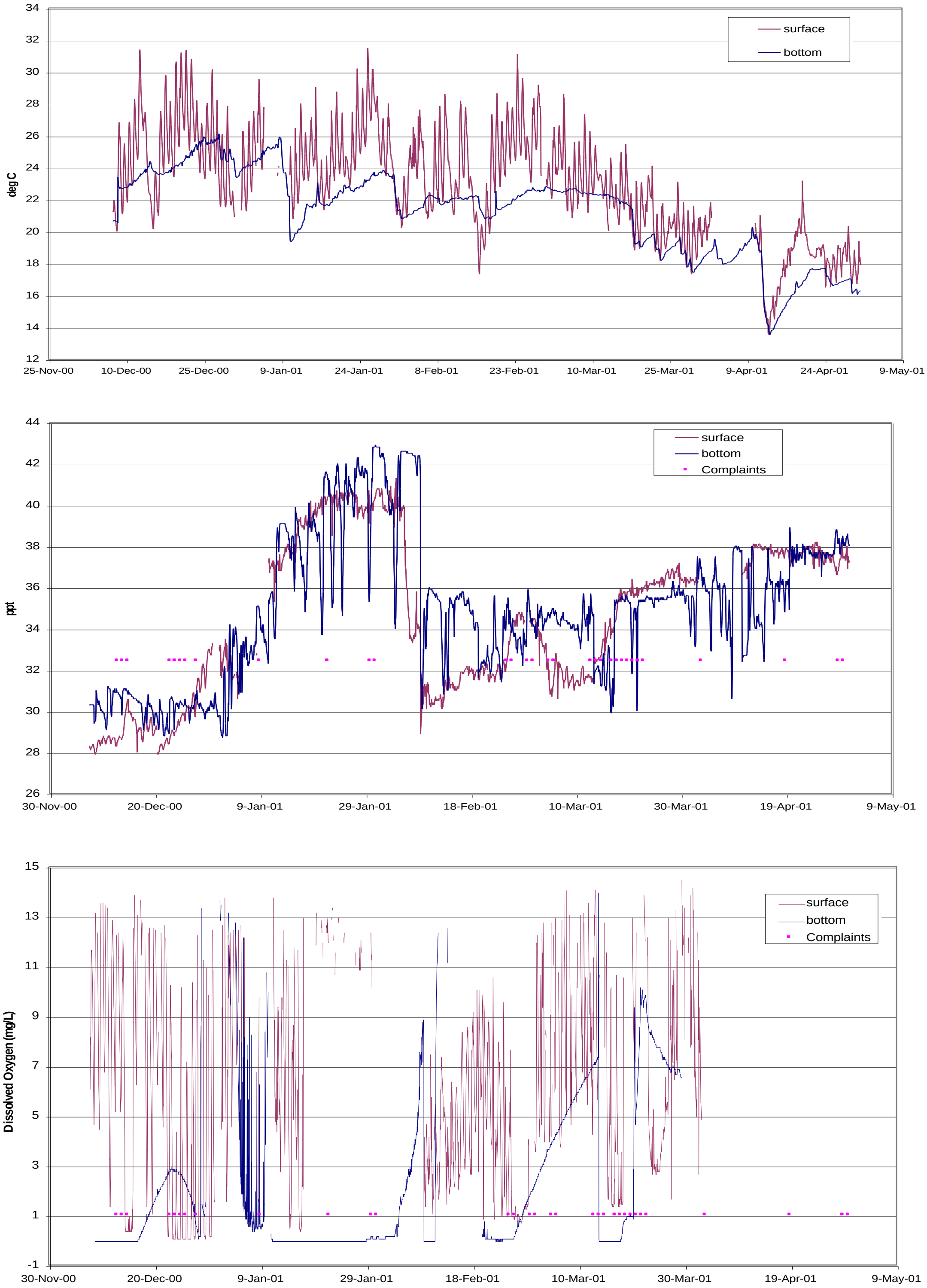


Figure 8 Variation in temperature, salinity and dissolved oxygen (DO) in surface and bottom waters of Lake Wollumboola. Periods where DO rises indicate the breakdown of stratification caused by wind driven mixing.

Water Column Nutrients

Concentrations of nutrients in the water column are one of the most commonly used variables when characterising water bodies. Water column nutrients and other measures of water chemistry were used in the first section of this report to classify different estuaries and define the back-dune lagoon biotype.

Interpretation of the ecological meaning of concentrations of nutrients must, however, be done with great care. The two major macro-nutrients that are generally considered are nitrogen (N) and phosphorus (P). They are present in three forms -

- inorganic nutrients are dissolved ions (e.g. ammonium NH_4^+, nitrate NO_3^-, phosphate PO_4^{3-}). Inorganic forms are readily available to plants and are the primary stimulants of plant growth.
- organic nutrients are found in a dissolved form that is bound with carbon as an organic molecule e.g. amino acids, humic acids. The brown tannin colouration of many coastal waterways is due to high concentrations of organic nitrogen. Organic nutrients are generally considered to be unavailable (directly) for plant growth, but there is evidence that bacterial action may break them down into inorganic forms
- particulate nutrients are bound to, or incorporated into, a particle such as sediment grains, cells, plant fragments

Chemical analyses can distinguish between the three forms and the sum of the concentrations of all 3 forms (for each nutrient) is known as the "total" concentration of the nutrient. Knowing the relative amounts of the three forms is critically important to understanding how they influence (or are influenced by) biological reactions. For example, if the total concentration is dominated by organic forms then most of the nutrient is not in a form available to stimulate algal growth. If that same concentration was, however, in an inorganic form it could quickly stimulate algal blooms. It is for this reason that comparisons of "total" nutrient concentrations are of very limited value. The current ANZECC guidelines for estuaries are based on data from waterways that do not have much organic nitrogen and the total nitrogen (TN) guidelines are quite inappropriate for most of NSW's estuarine lakes, lagoons and creeks. OEH has recognised this and has recommended revised nutrient triggers to ANZECC that account for this shortcoming.

Back-dune lagoons are strongly characterised by high dissolved organic nitrogen (DON) and so it is no surprise that DON, and hence TN, is very high in Lake Wollumboola. To equate this high TN concentration with poor water quality (or eutrophication), as Simmons and Beveridge (2008) did, is naive and incorrect. This is the natural state for back-dune lagoons and the nitrogen is mostly in a form that is not able to directly stimulate algal growth. The second characteristic of back-dune lagoons is naturally occasionally high concentrations of ammonium and continuously very low concentrations of phosphate. The absence of phosphate means that algae are not able to utilise the ammonium (see Nutrient Limitation section below), but the presence of the ammonium means that any addition of phosphate could be a great concern for the ecology of Lake Wollumboola.

The interpretation of estuary condition using water column concentrations is thus very complex and requires detailed analysis of the forms that the nutrient is in and of the relative concentrations of both N and P, not and should not be limited to a simple comparison to guidelines or general statements about eutrophication.

As discussed below for sediment nutrients and nutrient loads, nutrients in the water column are passing through one of the three primary pools (or standing stocks) in an estuary – water, sediments and biota. The nutrient cycle is the constant steady-state flux of inorganic nutrients from the sediment to water, water to biota via almost immediate assimilation by plants and then secondary consumers, and back to sediment when the biota die and fall to the lake floor, where the process starts all over again. If there is no outside influence, this is a relatively conservative cycle that maintains a constant biomass of plants in the system (this is not quite true, because under some circumstances microbial action forms N_2 gas which effectively removes nitrogen from the cycle). The inorganic nutrients in the water column are simply those that have not yet been incorporated in plant biomass ("the bits left over"). It is well demonstrated that plant biomass will rapidly expand to assimilate any additional nutrients introduced into the cycle.

Sediment Nutrients

The sediments of Lake Wollumboola are broadly characterised by the distribution of geomorphic features: the marine delta, fluvial delta and the central mud basin (Figure 8). Sediment analyses indicate that organic matter contents of the marine delta are generally low (<1%), higher in the fluvial delta (3 – 4%), and highest in the central mud basin (6.5%). This is within the expected range for NSW systems.

Sediments typically have very high concentrations of nutrients (in comparison to concentrations in water) but those nutrients are strongly chemically bound to the sediment and require microbial action or severe changes in water chemistry to make the nutrients bioavailable. In Lake Wollumbolla (and all other estuaries) sediment nutrient concentrations correlate with the amount of organic matter in the sediments (Figure 9). Due to constraints from sediment chemistry, phosphorus limitation increases with organic content (Figure 9).

Simmons and Beveridge (2008) suggested that, because there is a large pool of nutrient in the sediment, Lake Wollumboola already has a high nutrient environment. Implicit in this suggestion is the assumption that the nutrients in sediments are readily biologically available (see also Nutrient Loads Section below). OEH did not have any access to data to test this assumption, but in general sediment nutrient concentrations are poor predictors of nutrient supply rates to the broader ecosystem because both biotic and abiotic processes tend to retain the nutrients in the benthic layers. In fact, effective nutrient flux from sediments is often so low that many primary producers in the water column (i.e. phytoplankton and floating macroalgae) are almost totally reliant on inputs of nutrients from external sources (runoff, groundwater or oceanic inputs) to sustain productivity. This is particularly the case for phosphorus. Figure 10 shows that P fluxes from the sediment to the water column are low to negligible especially when sediment respiration rates are greater than -1000 umol O_2 m^{-2} hr^{-1}. The reason for this is that most of the P released from the sediment by microbial action is intercepted and assimilated by benthic plants (i.e. benthic microalgae, macroalgae and charophytes) when light is available or adsorbed to various mineral complexes in the sediment when oxic conditions occur at and below the sediment-water boundary. The mechanism is that the P that is separated from organic detritus by microbial action within the sediment remains chemically bound to sediment particles unless anoxic conditions occurs. In the absence of oxygen, P desorbs from particles and can efflux to the water column at high rates. In Lake Wollumboola bottom waters can be anoxic but surface water phosphate concentrations are very low. Our explanation for this is that the charophytes are utilising all the available phosphate before it reaches the surface waters, which would explain their large biomass in what appears to be a nutrient poor environment. It also explains the relatively low biomass of micro and macroalgae in the surface waters – which could be expected to bloom if a phosphorus source was available to them (see also Primary Productivity Section below).

Claims by Simmons and Beveridge (2008) that comparisons of sediment nutrient concentrations can be used to determine the relative ecological status or similarity of estuaries are misleading. The statement by Simmons and Beveridge (2008) "Sediment nitrogen and phosphorus levels of Lake Wollumboola were comparable and consistent with those of other waterways along the NSW coastline" [page 2, Executive Summary] – whilst possibly true, is of very limited value from an estuary ecology perspective. What is required for it to be even partially useful is some measure of the rates at which those nutrients are being involved in ecological processes.

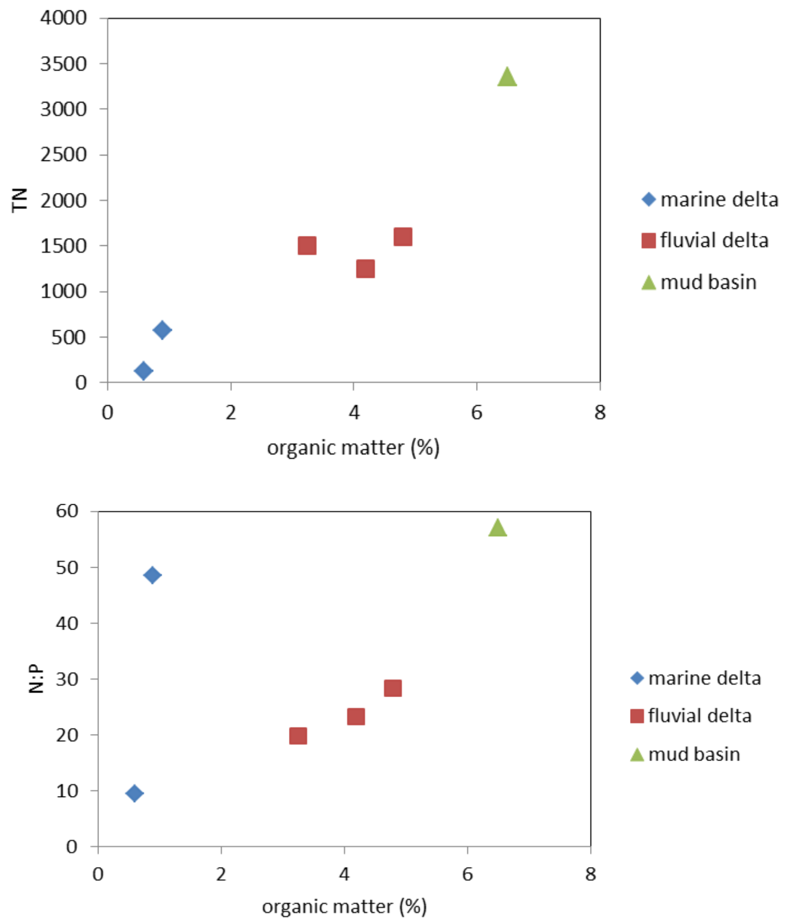


Figure 9 Relationship between sediment organic matter and nutrient composition.

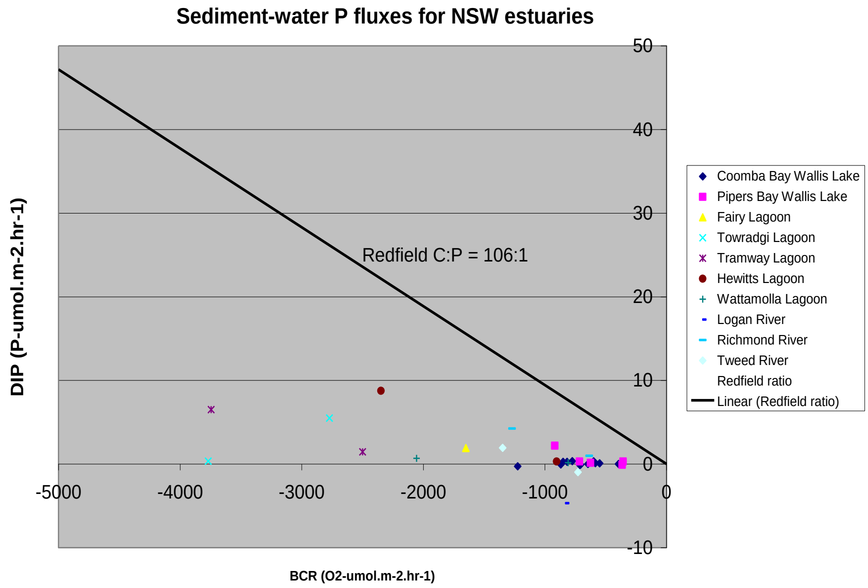


Figure 10 Sediment-water P fluxes versus O_2 flux (measured as benthic community respiration - BCR) for NSW estuaries. P fluxes are always lower than expected. The line is the predicted fluxes using C:P ratios for phytoplankton (Redfield 1958). Redfield predicts that efflux rates of carbon (C, = -O_2 flux) to phosphorus (P) for phytoplankton organic matter should be 106 carbon molecules for each P molecule. If the actual rate of P efflux for a given O_2 flux is below the line, then P is being retained in the sediment. Lake Wollumboola can not be plotted on this graph because the relevant data are not available.

Hydrogen sulfide

Extremely high concentrations of hydrogen sulfide in sediments and anoxic bottom waters have been observed in Lake Wollumboola (Murray & Heggie 2002), and are associated with ongoing complaints by local residents about "rotten egg gas" odours. The H_2S is most likely a natural phenomenon, arising as the product of sulfate reduction in sediments (the breakdown of organic matter by bacteria using sulfate instead of oxygen as an electron acceptor produces sulphide [S^{2-}] which quickly reacts with H^+ ions to form H_2S). The observed H_2S concentrations in sediments are considerably higher than in comparable systems with similar sediment OM contents (1 – 6.5%), however the reasons for this anomaly are unclear.

The accumulation of H_2S in bottom waters most likely occurs as a consequence of oxygen stratification, whereby there is insufficient oxygen available to oxidise H_2S diffusing from sediments. Intense oxygen production by macrophytes in the surface waters effectively caps the H_2S-rich bottom waters, until stratification breaks down and H_2S-rich bottom water mixes with and exerts a large oxygen demand on surface waters (Figure 11). If oxygen demand exceeds existing concentrations plus supply (photosynthesis and atmospheric exchange), H_2S escapes to the atmosphere creating odour problems. A predominance of sulfate reduction, and the formation of H_2S ($S^{2-} + 2H^+ = H_2S$) both in the sediment and water column tend to raise pH.

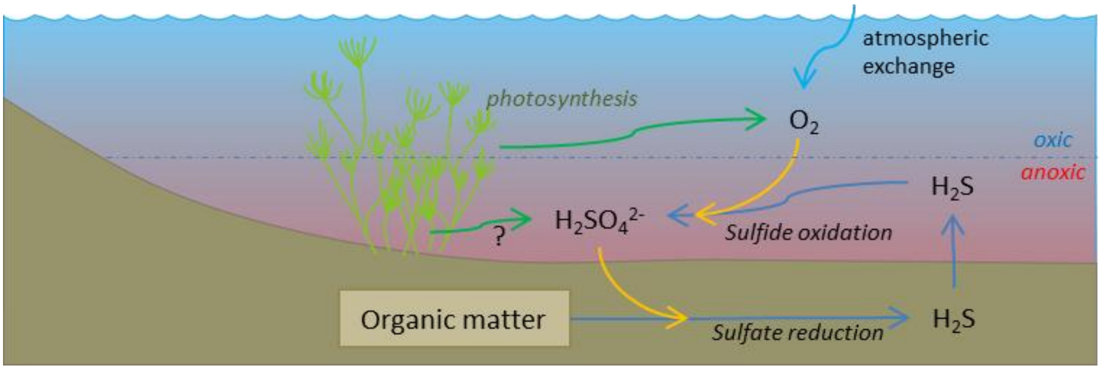


Figure 11 Conceptual diagram of the dominant sulfur cycling processes in Lake Wollumboola.

High concentrations of H_2S in Lake Wollumboola exceed observed values in other systems with similar sediment organic contents. While this phenomenon is almost certainly natural, it is unclear why such high concentrations are maintained (aside from the physical trapping mechanisms outlined above). It is possible that lake sediments are iron-poor and the normal mechanism of iron sulfide formation (which maintains generally low H_2S concentrations in most NSW systems) is largely absent. There are no data on solid phase sulfur or iron concentrations for Lake Wollumboola, therefore no assessment can be made of this. Another plausible (yet undescribed) mechanism for the concentration of sulfur in the lake is the exudation of sulfur-rich compounds by charophytes.

The occurrence of such high H_2S concentrations in Lake Wollumboola have significant flow on implications for microbial ecology. Hotspots of high H_2S concentrations promote the development of natural purple sulphide oxidising bacteria communities on sediments (Figure 12). These bacteria are mixotrophic, meaning they can switch between photoautrophic and chemoautotrophic modes depending on conditions. As such, they represent a potential large input of autochthonous (internally fixed) carbon to the system and most likely support significant foodwebs. There are very few, if any, other examples along the NSW coast where significant development of these bacterial communities occur.

Figure 12 Aerial photo of Lake Wollumboola showing prominent purple colour. It is unclear whether this colour is due to the presence of dinflagellates or purple sulfur oxidising bacteria.

N vs P limitation

Two macro-nutrients, nitrogen (N) and phosphorus (P), are essential for plant growth and plants utilise them in a very specific ratio, which differs among plant types. The ratio of constituents for phytoplankton was originally defined by Redfield (1958) and are known as the Redfield ratios. The ratio for nitrogen and phosphorus is 16:1 N to P by mass. If nutrients are available at a ratio different to this, then the nutrient that is in excess is generally unable to be assimilated and is found in the water column. If one nutrient is in excess, then the other is, by definition, “limiting” for plant growth. The determination of which nutrient limits production is fundamental to an assessment of potential impacts on the lake that might arise from nutrient pollution due to development within the catchment. Conventional thinking holds that nitrogen is limiting in estuarine and marine systems. There is, however, increasing evidence that phosphorus is limiting in many NSW coastal lakes. Two lines of evidence support this view for coastal lakes: 1) high ambient concentrations of bio-available nitrogen (in particular ammonium) coupled with trace concentrations of phosphorus (i.e. high N:P ratios) in surface waters; and 2) experimental stimulation of productivity associated with the addition of P.

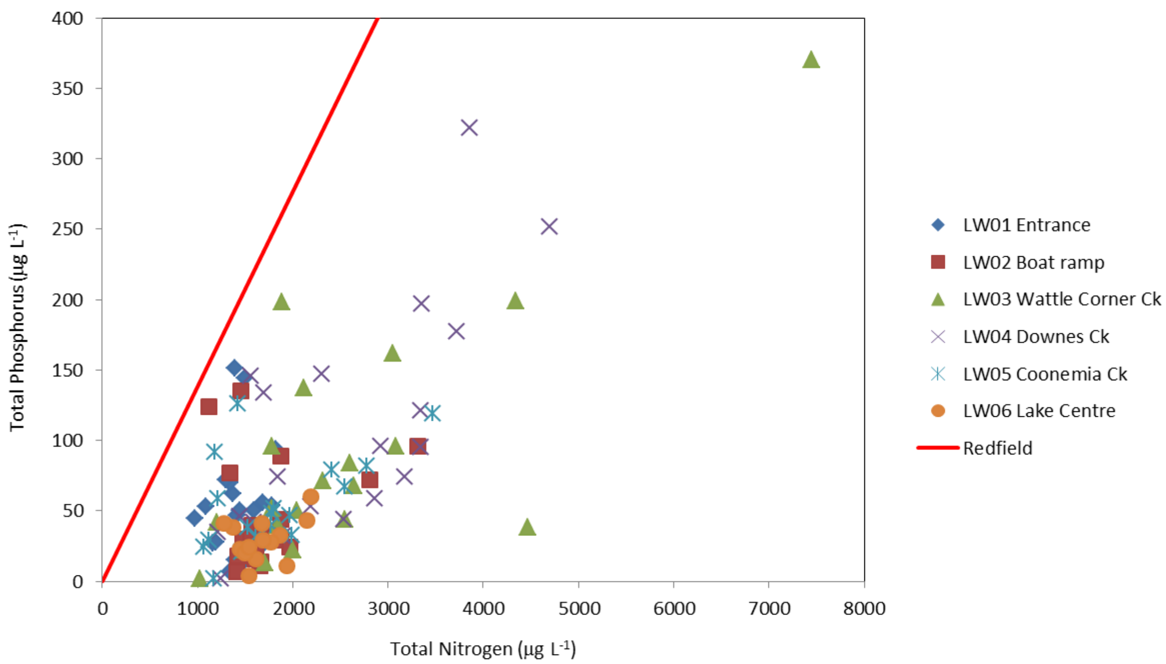


Figure 13 Comparison of total nitrogen and phosphorus in Lake Wollumboola with the Redfield N:P ratio (see text for explanation). Points falling below the Redfield line indicate potential phosphorus limitation.

Water column N:P ratios

Water quality data from Lake Wollumboola indicate that N:P ratios are consistently below the Redfield ratio (Figure 13), indicating that the availability of phosphorus is likely to be limiting production especially for phytoplankton. Due to the presence of extreme water quality gradients in the lake, it is likely that water quality measurements of surface waters only reveal part of the complex biogeochemical cycle that controls productivity in the lake. However, the data are a strong indication of P limitation at a system level. It is possible that both *Ruppia* and *Lamprothamnion* are able to capitalise on this environment by having alternative mechanisms to access P. Feedbacks associated with these plants most likely exert strong controls over biogeochemical cycles, thereby influencing the maintenance of its current ecological state of P limitation.

Experimental addition of nutrients

Experiments to investigate the consequences of phosphorus additions have been done on waters from 4 of NSW back-dune lagoons (OEH unpubl. data). Lagoons tested were Nadgee Lake, Brou Lake, Meroo Lake and Lake Tabourie. In each experiment, ambient water was collected and ecologically realistic concentrations of dissolved inorganic nitrogen (as ammonium) and dissolved inorganic phosphorus (as phosphate) were added, separately and in combination. The additions raised existing concentrations by 250 and 25 ug/L for ammonium and phosphate respectively. The experiments measured the change in algal growth (as chlorophyll). The experiment has been repeated 4 times and the result has always been the same, additions of phosphorus stimulated algal growth by up to 5 times that in control samples. In Brou, both nutrients were required to stimulate growth. This indicates that back-dune lagoons (such as Wollumboola), where phosphorus concentrations are low in comparison to nitrogen, are extremely susceptible to eutrophication and excessive algal growth occurs if external nutrient inputs (particularly phosphorus) increase (Figure 14).

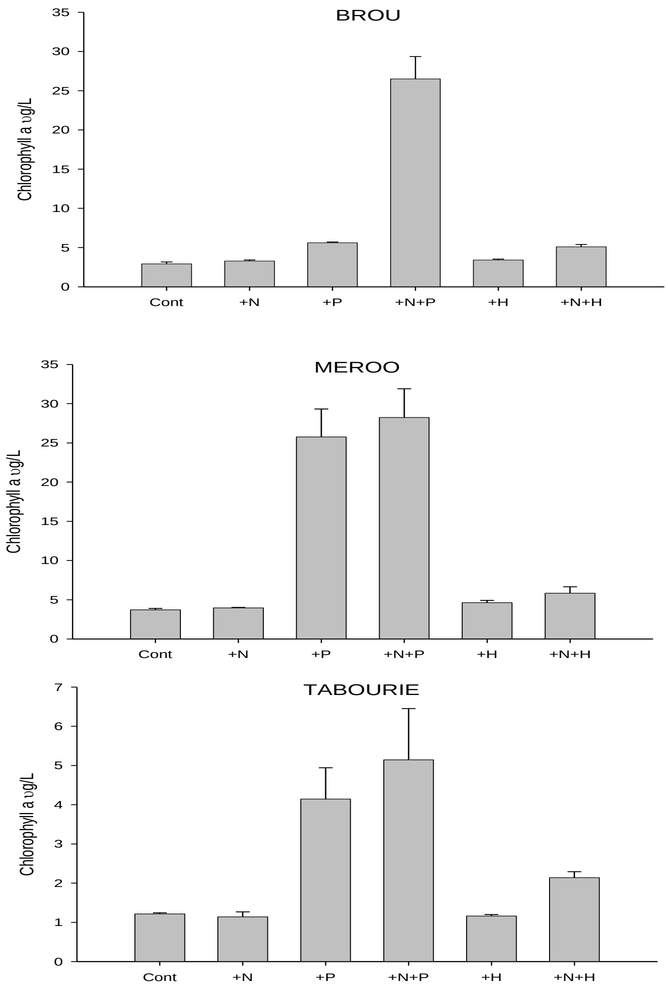


Figure 14 Results of experimental nutrient additions in three back dune lagoons. Phytoplankton productivity was consistently stimulated by P addition.

Primary productivity

No detailed assessment has been made of the relative contributions of different primary producers to autochthonous (locally fixed) organic carbon production in Lake Wollumboola. Visual assessment suggests that productivity is dominated by charophytes and *Ruppia,* with lesser contributions from various macroalgal species (e.g. *Cladophora* sp., *Chaetomorpha* sp. and *Enteromorpha intestinalis*.). It is also likely that benthic microalgae and sulfur oxidising bacteria constitute major inputs to lake foodchains on sediments not colonised by macrophytes. Phytoplankton biomass is generally low (<3 ug L^{-1}), however some data and anecdotal evidence indicate large blooms can occur (> 45 ug L^{-1} chlorophyll-*a*) (MHL 2001). This is common in undisturbed back-dune estuaries (e.g. Scanes et al. 2011) and is generally associated with inputs of phosphorus (OEH unpubl. data).

The patterns of primary production in the lake are most likely controlled by its shallow morphology (leading to a predominance of benthic plants), the opening closing regime (which limits production of certain species on regularly exposed shoals), the nature of freshwater inputs (a predominance of groundwater seepage may favour *Ruppia* around the lake margins), and the extreme biogeochemical gradients (anoxic bottom waters favouring *Lamprothamnion*).

The nutrient status (P limitation) of the lake is also likely to have a primary control over vegetation communities, favouring species that have strategies to adapt to local conditions, or alternatively can engineer local conditions to provide a steady nutrient supply from the sediments. For example, *Lamprothamnion* appears to maintain anoxic conditions within the lower part of the water column which would favour the release of phosphate from the sediments. Vigorous production by the *Lamprothamnion* ensures that no remineralised nutrients ever reach the upper part of the water column thereby controlling competition by other primary producers (e.g. phytoplankton).

The high primary production in the lake occurs despite no obvious major nutrient inputs from either diffuse or point sources. This suggests that internal biogeochemical processes are likely to be important in sustaining both the level and diversity of productivity in the system. Due to the unique and poorly understood nature of these processes, we can not be certain what impacts nutrient enrichment would have on the lake, though all the literature suggests it would be negative. Investigations in the heavily impacted Tuggerah Lakes system suggest that groundwater pollution constitutes a major threat due to the rapid and profuse blooms of macroalgae.

Importance of Groundwater

Santos et al. (2013) have used concentrations of radon gas in northern NSW estuaries to demonstrate definitively that a large proportion of the freshwater input in some estuaries is derived from groundwater. They also showed that estuaries with large groundwater inputs also had other characteristic indicators, primarily high concentrations of coloured dissolved organic matter (CDOM – often referred to as tannins), high concentrations of dissolved organic nutrients and relatively low concentrations of P in comparison to N in the water column. These characteristics overlap with those which we independently found to define back-dune lagoons. From this we conclude that back dune lagoons along the NSW coast are most likely to be groundwater-dependent, though this conclusion needs to be tested using radon surveys. Recent surveys of Currambene Ck which drains to Jervis Bay showed a close correlation between coloured dissolved organic matter (CDOM) and radon (the indicator of groundwater); Figure 15), supporting the evidence from northern NSW of a link between CDOM and groundwater dominance. This strengthens the case that high concentrations of CDOM (or tannins) in back dune lagoons is a strong indication of groundwater intrusion into in these systems. Despite a lack of direct evidence, a number of lines of evidence suggest significant groundwater influence in Lake Wollumboola. These are briefly outlined below.

High CDOM (tannin) and dissolved organic nitrogen

OEH CDOM data for Lake Wollumboola in summer 2011-12 indicated a range of 576 – 2050 and mean of 1562 RFU (RFU - relative fluorescence unit). To put this in perspective, data for the state ranged from 20 to 2100 RFU and Currambene Ck recently had maximum of 1500 (Figure 15). It is clear that the waters of Lake Wollumboola have very high CDOM concentrations. Average dissolved organic nitrogen (DON) concentrations in Lake Wollumboola in this period were 923 ug/L (Appendix 1), making them one of the highest concentrations in the state (Appendix 1). I

In addition, inspection of Google Earth images of Long Bow Point area reveal what appear to be tannin water inputs adjacent to the low lying swamps at the mouth of Downs Creek and the northern drainage depression. Further, images of the lake after major rainfall show the entire lake dominated by tannin waters, suggesting that even during major events the primary flow paths are dominated by groundwater.

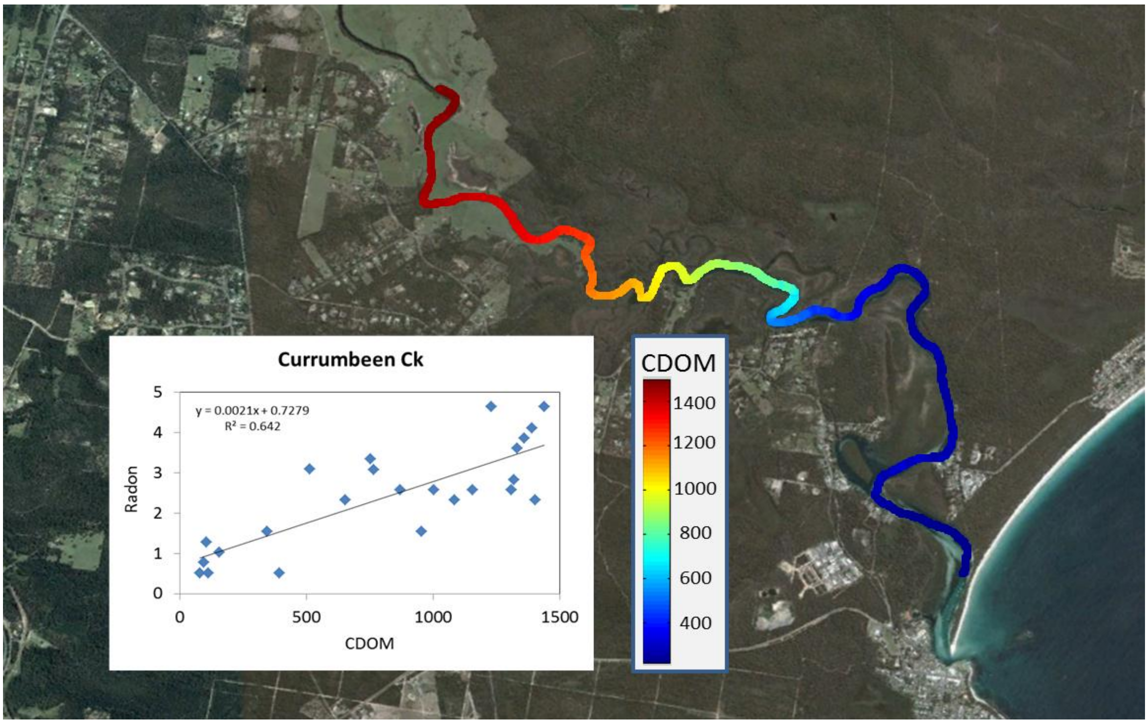


Figure 15 Results of a groundwater survey along Currambene Ck (Jervis Bay), showing the correlation between radon (groundwater tracer) and CDOM.

Indistinct freshwater drainage lines

The lack of permanent, flowing freshwater streams coupled with slowly changing salinity levels during periods of entrance closure (see Figure 7), suggest that outside of major rainfall events the lake is subject to constant groundwater seepage. Keating and Pegler (2003) noted that surficial freshwater soaks around Lake Wollumboola originated from diffuse and point sources and while they also indicate that groundwater seepage occurs (predominately in the SEPP 14 wetland at the Lakes periphery), there is little data on groundwater hydrology of Lake Wollumboola.

High N:P ratios in waters and sediments

There is growing evidence from other NSW systems that high N:P ratios are common in groundwater dependent systems (Santos et al. 2013). The reasons for this are unclear to date.

Aquatic vegetation distributions in the lake

The prevalence of macroalgae and *Ruppia* around the lake margins provides indicator of likely groundwater influence. *Ruppia* tolerates a wide range of salinity conditions but tends to be more common in areas influenced by freshwater inputs or lower salinity (Ferguson et al. 2013). Macroalgae blooms opportunistically in response to nutrient-rich freshwater inputs. The disaggregated distribution of macroalgae along the lake margins suggest groundwater seepage, especially adjacent to the low lying swamps either side of Long Bow Point (Figure 16,17). Growth of macroalgae around margins can also be seen in pristine back-dune lagoons such as Nadgee Lake (OEH unpubl. data). Similar patterns of aquatic vegetation distribution have been observed in Tuggerah Lakes, where groundwater pollution greatly exacerbates the excessive production of macroalgae along the shoreline leading to the development of sulfidic sediments (Ferguson et al. 2013, Brennan 2013).

Risks associated with groundwater pollution

Due to the likely primary influence of groundwater inflows and seepage over nutrient loads, groundwater pollution represents a major risk to the lake ecology. The exacerbation of macroalgae blooms is a likely direct consequence, however it is uncertain what secondary or flow-on effects this might have. The proponent of the golf course at Long Bow Point has discounted any possibility of groundwater pollution, despite admissions that the development would increase the ratio of groundwater to overland flows. The model used predicts complete binding of all phosphorus added via fertilisation – a highly unrealistic scenario and not supported by any data or other studies. Further, the simplistic modelling of groundwater seepage assumed uniform phosphorus adsorption capacity (based on limited sampling), despite clear evidence of complex stratigraphy across the Low Bow Point area.

Figure 16 Filamentous algae blooms adjacent to likely groundwater inputs along the shoreline, giving way to *Ruppia* just offshore (photo from Simmons & Beveridge 2008).

Figure 17 Two images of Low Bow Point area showing indicators of groundwater seepage from low lying swamps.

Nutrient loads

The water quality assessment (Simmons and Beveridge 2008) uses a simplistic and fundamentally flawed approach to assessing the impact of pollutant loads from proposed developments. The definition of 'loads' as used in the water quality assessment is incorrect: sediment and water column nutrients are standing stocks within the system, not loads. Standing stocks are already within the system and transform from one state to another (i.e. from sediment to water to plants to sediment) during the normal nutrient cycle. Only inputs (overland flow and groundwater) to the system are considered loads, and their ecological relevance cannot be assessed by simply comparing them to some arbitrary depth (10cm) of sediment nutrients. In reality, most of this standing stock is not actively involved in the biological function of the system, with a very small fraction of the surface 0.5 – 1mm sediment nutrient stock being returned to the water column in a bio-available form.

The nutrient load assessment also assumes complete mixing of catchment loads within the lake, ignoring the localised impacts of groundwater seepage along the shoreline adjacent to proposed developments (see section above). This is a fundamental flaw in the assessment since the most likely impact of the proposed golf course on Long Bow Point is the enrichment of groundwater with phosphorus and the subsequent development of macroalgal blooms along the adjacent shorelines.

Charophyte Beds

Charophytes are algae of the Family Characeae, of which *Chara* is the type genus. Charophytes are primarily freshwater algae but there are salt tolerant genera such as *Lamprothamnion* which can grow in brackish to hypersaline water bodies, where the salinity can decrease through rainfall and freshwater inputs, or increase with evaporation and sea spray (Casanova 1993). Charophytes are notable because they have some of the largest cells known, cells may be up to 10 mm long and 1-2 mm in diameter. These large cells often incorporate calcium structures in the cell wall for support.

Occurrence of charophytes in coastal NSW:

Only a few coastal lakes in NSW have extensive beds of charophytes. OEH have surveyed 134 out of 184 NSW estuaries and have only observed extensive charophyte beds in 8 estuaries, Myall Lake, Swan Lake, Termeil Lake, Lake Tabourie, Wallagoot Lake, Barragoot Lake, Willinga Lake, and Wollumboola Lake, though there may a small number more. Small, sparse patches have been reported to exist in several other lakes including Tuggerah Lakes and Lake Illawarra. Wallis Lake has extensive beds of charophytes in it's southern bays. The large beds in Myall Lakes are dominated by freshwater charophytes.

One of the distinguishing features of back-dune lagoons in general, and Lake Wollumboola specifically, are the beds of charophyte algae, primarily in the genus *Lamprothamnion*. These dense algal beds can be up to 1m thick and have pronounced effects on the water chemistry (see above) and the ecology of back-dune lagoons. The most extensive beds of *Lamprothamnium succintum* (also reported as *Lamprothamnium papulosum*) in NSW are found in Swan Lake and Lake Wollumboola (Adriana Garcia. pers. comm.). *L. succintum* was reported to occupying up to 90% of the lake bed of Wollumboola (Murray & Heggie 2002).

Ecological role (adapted from Casanova 1993)

Characeae enhance biodiversity by providing substrate, food and shelter for a wide range of organisms including algal epiphytes, invertebrates, fish and birds (Kairesalo et al. 1987). Charophytes can support a greater density and diversity of invertebrates than other macrophytes (Kingsford & Porter 1994, Kuczynska-Kippen 2007) including rare and endangered invertebrate species (Davies 2001). Glasby & van den Broek (2010) found that the greatest abundance and diversity of sponges occurred in *Lamprothamnium* beds in Wallis lake. Many of these sponges are unique to Wallis Lake. In general, dense Characeae beds are thought to be indicators of healthy, clear-water ecosystems.

Charophytes provide food for invertebrates (Proctor 1999) and vertebrates (Noordhuis et al. 2002, Hindle et al. 2010), and contribute to carbon and nutrient cycling as organic matter (Pereyra-Ramos 1981). During production they remove nutrients from the water column. The presence of dense beds protects sediments from resuspension (Scheffer et al. 1994, Kufel & Kufel 2002) thus reducing turbidity and nutrient release from the sediment. Systems where charopytes occur tend to have high species diversity in phytoplankton communities (Casanova & Brock 1999) and when charopytes have been experimentally removed, there has been an increase in phytoplankton abundance (particularly blue green algae) (Villena & Romo 2007).

Charophytes such as *Lamprothamnium papulosum* cannot tolerate high levels of phosphates and nitrates (Bingham 1997) probably because most species are unable to successfully compete with dense growths of filamentous algae such as *Cladophora* spp. Nutrient enrichment has been implicated in the decline of brackish charophyte species in Europe (Martin 1999). *Lamprothamnium papulosum* was absent where soluble reactive phosphate (SRP) levels exceed 30 $\mu g\ L^{-1}$ in the water column and total phosphates (TP) are about 100 $\mu g\ L^{-1}$ (Martin 1999). The central basin of brackish coastal lakes in NSW with extensive *Lamprothamnion* beds have low SRP and TP concentrations (Figure 4, Appendix 1). Calcium carbonate production in charophytes binds phosphate and leads to extremely low phosphate concentrations in waters with charophytes (Adriana Garcia. pers. comm.).

Charophyte beds are the preferred food for black swans and access to food is a prime determinant of the presence of swans on lagoons (Hindle et al. 2010). Natural loss of charophyte beds in Nadgee Lake in 2007 has resulted in a complete absence of swans, despite documented evidence of continuous populations for the previous 40 years (Figure 18).

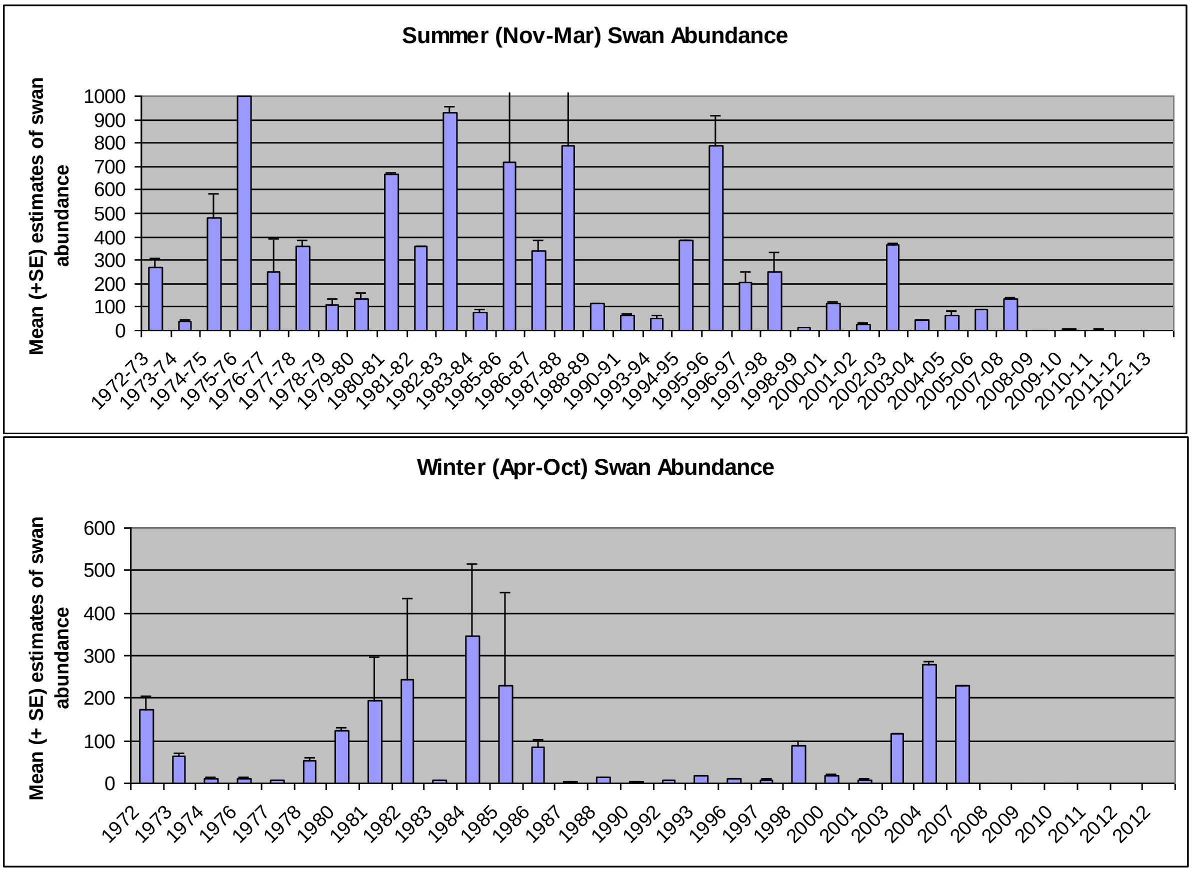


Figure 18 Swans ceased to utilise Nadgee Lake following the loss of charophyte beds after storms in June 2007

Charophytes Summary

Charophytes are clearly an "ecological engineer" species in that their presence defines and fundamentally influences the ecological and chemical processes and thus the entire ecology of Lake Wollumboola.

- The large biomass results in complex water chemistry due to stratification of water within the beds,
- the plants absorb any phosphate released from sediments, thus limiting the growth of nuisance algae
- The physical structure of beds protects the shallow lake floor from being re-suspended by wind, thus promoting clarity
- A wide range of biological diversity, from large abundances of food chain basics such as invertebrates to a wide variety of top consumers such as water and shore birds is dependent on the dense charophyte beds

Charopytes are, however, threatened by catchment development, with documented cases of extensive loss (Martin 1999) due to excessive external nutrient inputs or absence in similar lagoons with high catchment pressure (unpubl. OEH data).

Sensitivity to change in Lake Wollumboola

It is clear that Lake Wollumboola is a unique coastal lagoon that supports extremely high productivity and overall ecological diversity in a relatively nutrient-poor environment. The dominant macrophytes and charophytes provide the primary food source for waterbirds that utilise the lake. They also provide structure to the lake environment in a way that forms strong feedback controls over the biogeochemical cycling of nutrients and ensures their continued survival. These feedbacks also convey a competitive edge over other primary producers (e.g. phytoplankton and filamentous macroalgae) which could otherwise easily outcompete with the existing vegetation if conditions change. As such, the current state of the lake system is dependent on the continued existence of the existing vegetation.

Evidence from other NSW and European systems shows that charophytes are susceptible to nutrient pollution, in particular phosphorus (see Charophytes Section). Losses of charophytes have been observed to be catastrophic, usually involving local extinction. Given their role as “ecological engineers”, their loss from Lake Wollumboola would most likely cause a cascade of impacts and lead to a state change, whereby the system becomes dominated by other primary producers such as filamentous macroalgae or phytoplankton. The loss of ecosystem services provided by the presence of charophytes means that the physico-chemical environment would change dramatically (e.g. turbidity due to wind-driven resuspension of sediments would increase), and biogeochemical processes would also change further feeding back on the physico-chemical environment.

Once charophytes and macrophytes are lost from the system, the loss of beneficial feedbacks and changes in biogeochemical processes would mean that it is unlikely that they would re-establish. Essentially, the system would shift to an alternate state (e.g. macroalgae and phytoplankton dominated), and would no longer support the same productivity and diversity. All the animals that depend on the current ecosystems, including invertebrates, fish, shore birds and particularly swans will no longer be supported. Similar state changes have been observed in other shallow coastal lakes (e.g. Tuggerah Lakes).

Conclusion – Implications for development

Lake Wollumboola should be regarded as a unique and highly valuable example of an intact back-dune lagoon, and accordingly be given high conservation status. Given the high ecological values of the lake, coupled with its potential sensitivity to permanent state change (and loss of these ecological values), we recommend that a precautionary approach be adopted as a high priority when assessing development proposals in the Lake Wollumboola catchment. We do not believe that the current proposals have demonstrated a sound understanding of the system, nor have they provided any confidence that the impacts would be negligible.

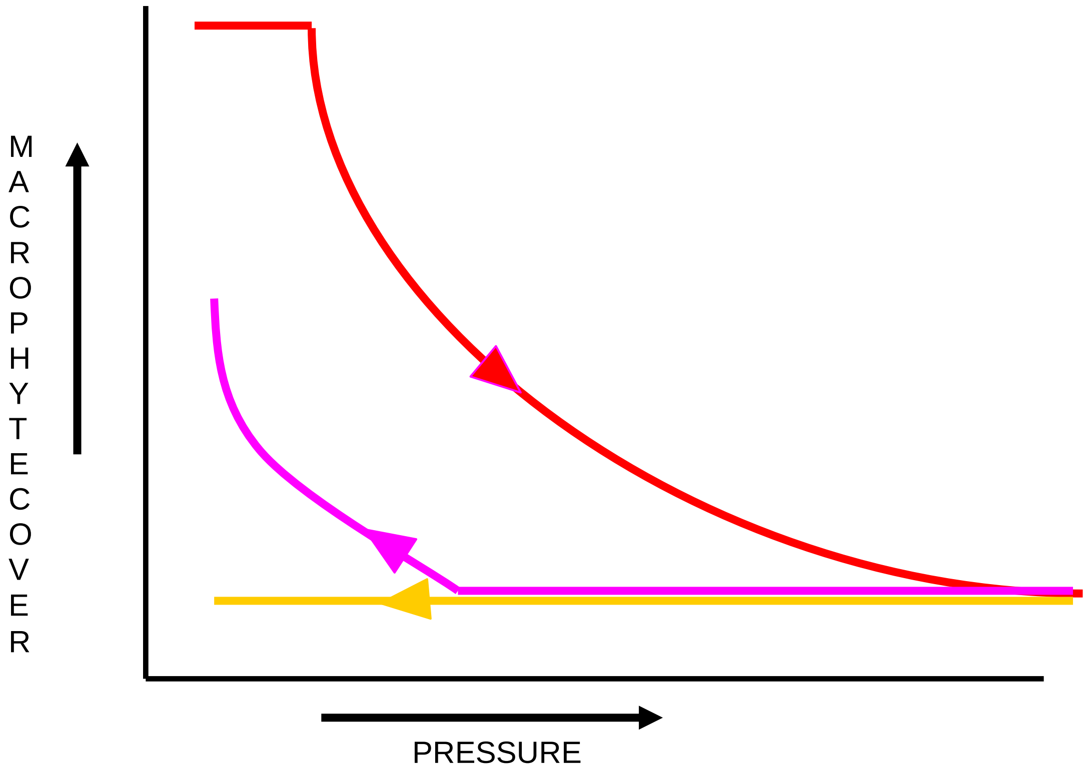


Figure 19 A conceptual diagram of system response ('macrophyte cover') to an increase in some pressure (red line), and recovery trajectories as the pressure is reduced. In most cases, perturbed systems never recover to the same state (pink line), while others never recover at all (yellow line). This is because of the loss of fundamental ecosystem services provided by the macrophytes which maintained tolerable or competitive conditions to ensure their survival.

Acknowledgements

In accordance with the OEH Scientific Rigour Statement, this report has been reviewed by Dr Jocelyn dela-Cruz and Ms Kerryn Stephens.

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Appendix 1 Mean values for physical, chemical and biological variables from 33 estuaries with low catchment disturbance.

Estuary Number	MER Estuary Name	Site Code	Estuary Type	Disturbance	Probe Temp (°C)	Salinity (PSU)	Turbidity (NTU)	Chlorophyll a ($\mu g.L^{-1}$)	NH3 ($\mu g.L^{-1}$)	PO4 ($\mu g.L^{-1}$)	NOx ($\mu g.L^{-1}$)	DOP ($\mu g.L^{-1}$)	DON ($\mu g.L^{-1}$)
32	Bellinger River	BLN	BARRIER RIVER	L	25.63	9.08	4.13	4.02	20.63	3.86	111.83	2.65	33.54
161	Bunga Lagoon	BUN	LAGOON	L	22.34	24.33	2.59	1.96	17.76	0.62	3.57	3.95	425.34
15	Cakora Lagoon	CAK	LAGOON	VL	26.75	19.20	13.08	6.50	5.22	4.26	1.85	3.14	395.93
110	Captains Beach Lagoon	CBL	CREEK	VL	23.63	17.54	0.62	2.57	14.85	0.91	5.19	2.43	256.97
104	Carama Creek	CRM	CREEK	VL	22.89	32.87	1.30	2.75	6.74	1.30	1.84	7.46	352.75
132	Clyde River	CLY	BARRIER RIVER	L	22.77	22.81	1.52	2.38	12.44	2.01	26.45	11.01	152.83
142	Coila Lake	COI	LAKE	L	21.19	25.22	1.91	3.08	10.42	0.45	1.33	7.47	668.38
103	Currarong Creek	CRR	CREEK	L	22.20	25.31	0.23	0.97	14.43	3.03	2.46	2.90	235.07
159	Cuttagee Lake	CUT	LAGOON	L	20.00	35.62	1.71	2.06	6.67	2.41	5.98	1.84	112.18
128	Durras Lake	DUR	LAKE	L	22.73	32.84	7.13	6.31	13.33	1.80	4.52	5.09	297.56
109	Flat Rock Creek	FRC	CREEK	VL	20.94	29.21	0.43	2.33	24.93	2.13	5.26	1.83	261.47
42	Goolawah Lagoon	GLW	LAGOON	VL	24.67	0.21	0.92	3.49	37.82	2.97	27.94	11.73	856.75
12	Jerusalem Creek	JRS	LAGOON	VL	25.67	20.77	2.22	1.80	15.60	0.78	4.79	2.00	288.86

14	Lake Arragan	ARA	LAKE	VL	24.47	28.29	7.55	3.20	26.59	1.11	7.74	3.23	693.87
146	Lake Brou	BRO	LAGOON	L	21.24	30.37	3.73	14.10	21.86	1.48	11.44	10.00	462.05
0	Meroo lake	MER	LAGOON	L	22.36	3.53	0.66	0.10	266.16	1.15	8.95	10.14	970.35
59	Middle Camp Creek	MCC	CREEK	L	25.40	5.35	2.39	2.92	8.71	2.22	3.39	8.85	756.57
52.2	Myall Lakes	MYL	LAKE	L	23.12	1.78	1.06	6	91.7	1	2.15	2.83	993.44
184	Nadgee Lake	NDL	LAKE	VL	18.38	20.55	3.86	4.91	535.03	0.90	71.46	7.95	791.68
183	Nadgee River	NDR	CREEK	VL	20.10	23.12	7.59	2.83	13.98	1.80	9.15	4.04	219.03
164	Nelson Lagoon	NLS	BARRIER RIVER	VL	22.01	32.39	2.74	1.61	24.97	3.83	12.97	3.53	197.40
173	Nullica River	NLC	LAGOON	VL	21.60	32.03	4.38	1.75	18.43	9.73	18.50	3.60	137.40
81	Port Hacking	PHK	DRWN VALLEY	L	24.81	28.67	1.82	3.19	5.64	2.01	15.48	3.26	147.88
16	Sandon River	SAN	BARRIER RIVER	VL	21.96	19.29	4.58	1.65	30.99	1.58	11.19	2.60	329.73
18	Station Creek	STN	LAGOON	VL	24.39	30.97	4.82	1.73	38.01	0.91	8.90	2.84	179.92
124	Termeil Lake	TER	LAGOON	L	21.94	13.14	2.59	21.46	131.09	1.67	9.06	8.89	948.93
143	Tuross River	TUR	BARRIER RIVER	L	22.78	18.18	2.65	4.46	13.55	4.31	16.48	2.56	176.30
149	Wagonga Inlet	WGN	LAKE	L	21.06	33.69	0.80	2.19	0.69	2.82	0.30	3.68	131.02
197	Wallagoot Lake	WLG	LAKE	L	20.84	34.61	0.97	11.92	40.81	1.00	6.16	9.52	602.99

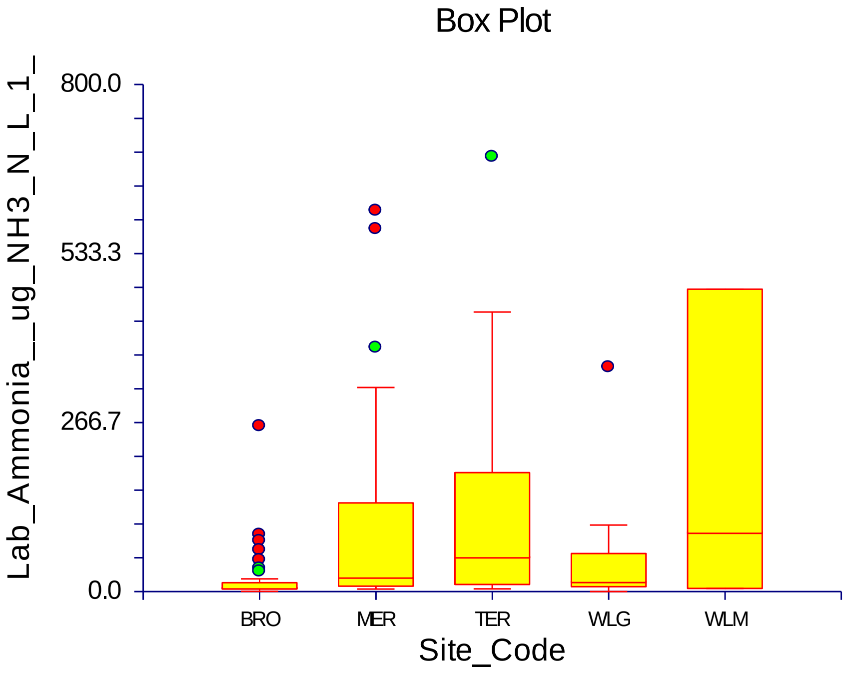
50	Wallis Lake	WAL	LAKE	L	23.64	30.70	1.84	1.7	4.29	0.47	1.55	3.78	230.17
82	Wattamolla Creek	WAT	CREEK	VL	21.81	11.90	0.98	1.1	14.7	0.9	4.2	1.58	152.23
102	Wollumboola Lake	WLM	LAKE	L	21.83	24.53	4.25	1.5	192.0	1.0	2.4	7.73	923.57
180	Wonboyn River	WBN	BARRIER RIVER	VL	22.36	22.84	1.15	9.1	34.84	1.07	21.08	3.73	245.74
17	Wooli Wooli River	WLI	BARRIER RIVER	VL	23.48	27.45	3.75	2.6	25.975	0.86	8.6335	3.47	263.39

Appendix 2 Estuary Site Codes and Types for ANOSIM analyses. Types - BR – Barrier Rivers, LG – Lagoon A, CK – Lagoon B, LA – Lake, AT – alternative type (under investigation)

Estuary	Site Code	CERAT Type	Alternative Type
Bellinger River	BLN	BR	BR
Bunga Lagoon	BUN	LG	LG
Cakora Lagoon	CAK	LG	LG
Captains Beach Lagoon	CBL	CK	CK
Carama Creek	CRM	CK	CK
Clyde River	CLY	BR	BR
Coila Lake	COI	LA	LA
Currarong Creek	CRR	CK	CK
Cuttagee Lake	CUT	LG	LG
Durras Lake	DUR	LA	LA
Flat Rock Creek	FRC	CK	CK
Goolawah Lagoon	GLW	LG	AT
Jerusalem Creek	JRS	LG	LG
Lake Arragan	ARA	LA	LA
Lake Brou	BRO	LG	AT
Meroo Lake	MER	LG	AT
Middle Camp Creek	MCC	CK	CK
Myall Lakes	MYL	LA	AT
Nadgee Lake	NDL	LA	AT
Nadgee River	NDR	CK	CK
Nelson Lagoon	NLS	BR	BR
Nullica River	NLC	LG	LG
Port Hacking	PHK	BR	BR

Sandon River	SAN	BR	BR
Station Creek	STN	LG	LG
Termeil Lake	TER	LG	AT
Tuross River	TUR	BR	BR
Wagonga Inlet	WGN	LA	LA
Wallagoot Lake	WLG	LA	AT
Wallis Lake	WAL	LA	LA
Wattamolla Creek	WAT	CK	CK
Wollumboola Lake	WLM	LA	AT
Wonboyn River	WBN	BR	BR
Wooli Wooli River	WLI	BR	BR

Appendix 3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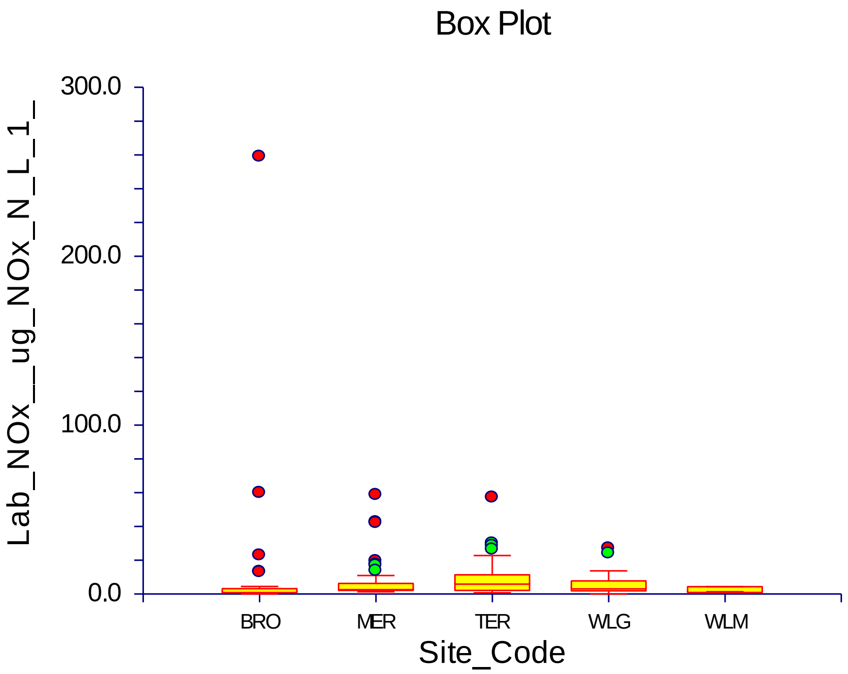
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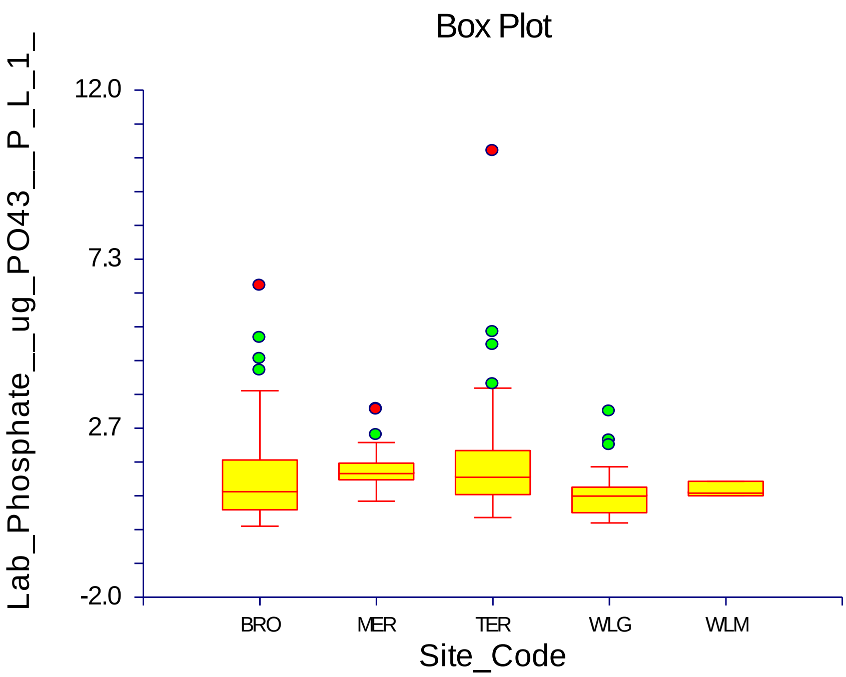
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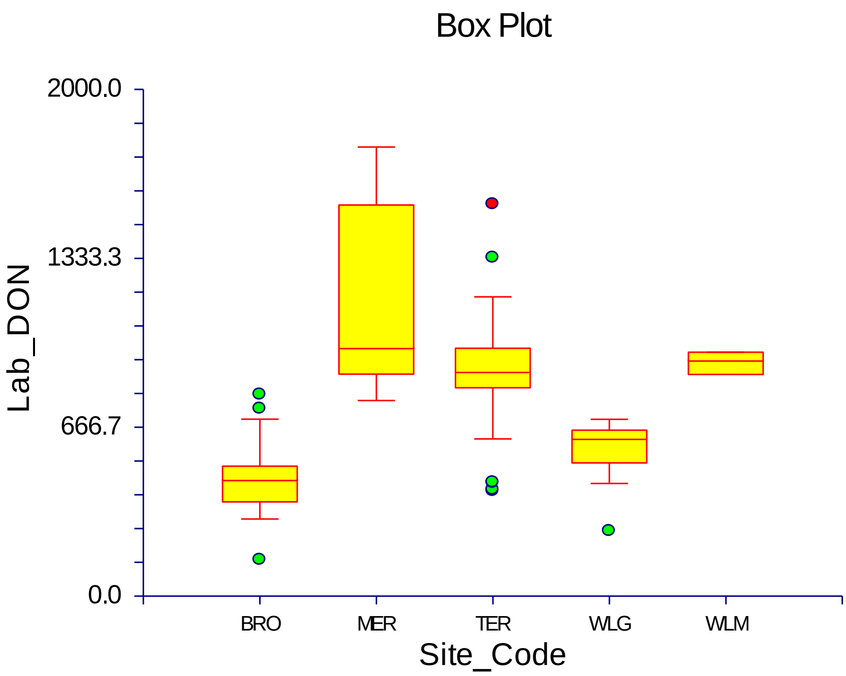
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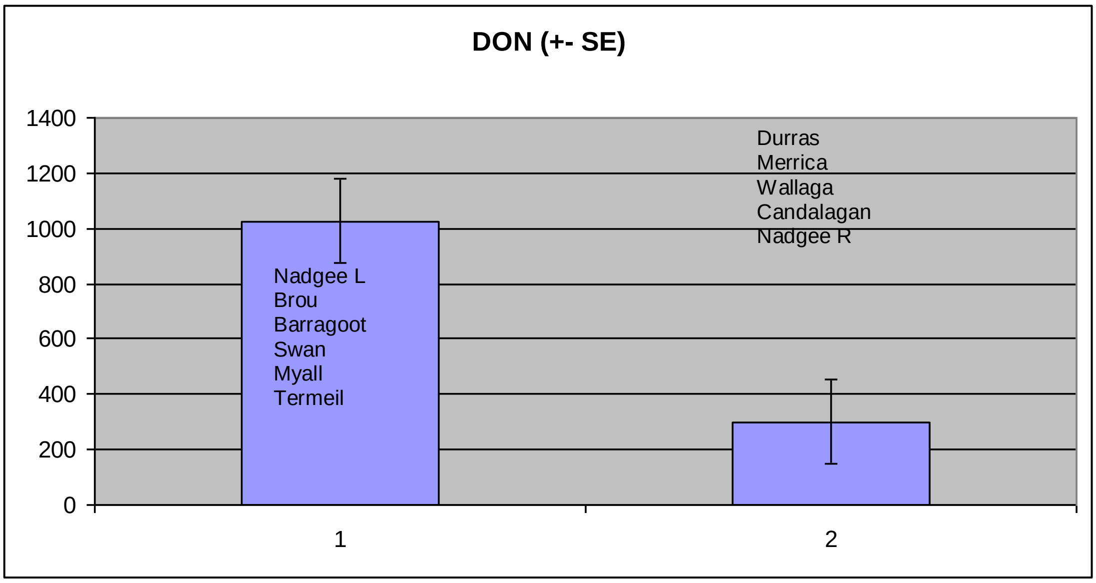

Appendix 4 Dissolved Organic Nitrogen (DON) concentrations (ug/L) in Back dune Lagoons are 3 times greater than other estuaries.