Atypical Estuaries in NSW: Implications for management of Lake Wollumboola

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Abstract

In order to define something as “atypical” we need to establish what is “typical”. Most commonly this is assumed to be characteristics of the majority of the population. Paradigms about the structure and function of estuaries have largely developed in the northern hemisphere, the most commonly used definition of an estuary (Pritchard 1967) describes the type of large riverine estuary common in Europe, but is not relevant to a large proportion of Australian east and west coast estuaries. In this paper we explore "atypical" at two scales, comparing NSW estuaries with those from other parts of the world, and comparisons among estuaries in NSW.

We show that most NSW estuaries differ from those in the northern hemisphere in both form and function and suggest a more inclusive and relevant definition of estuaries. Within NSW, we use data on the physical, chemical and biological attributes of over 130 estuaries to demonstrate that a subset of about 14 estuaries are ecologically different from all other NSW estuaries. We have named these estuaries "back dune lagoons". We then use Lake Wollumboola as a case study to demonstrate distinctive ecological characteristics and processes in these lagoons and how they could be irreversibly disrupted by inappropriate development. We make the point that because the ecological processes within these estuaries are fundamentally different, then it is not possible to use conventional understanding to make predictions about the impact of additional stress. This has profound implications for management of these estuaries.

Introduction

(A)typical depends on your point of reference

The most commonly used definition of an estuary is that of Pritchard (1967) – “an estuary is a semi-enclosed coastal body of water, which has a free connection with the open sea, and within which sea water is measurably diluted with freshwater derived from land drainage”.

Increasingly this definition is being viewed as inadequate to account for the wide variety of estuary types around the world. McLuskey and Elliot (2004) have proposed that “an estuary is an inlet of the sea reaching into a river valley as far as the tidal rise, usually being divisible into three sectors: a) a marine or lower estuary, in free connection with the open sea; b) a middle estuary subject to strong salt and freshwater mixing; and c) an upper or fluvial estuary, characterised by freshwater but subject to strong tidal action. The limits between these sectors are variable and subject to constant changes in the river discharges” . This definition, whilst an improvement, still does not allow for estuaries with entrance barriers. In NSW, the majority of estuaries have an entrance which is not part of a river valley with a free connection to the sea (Figure 1).

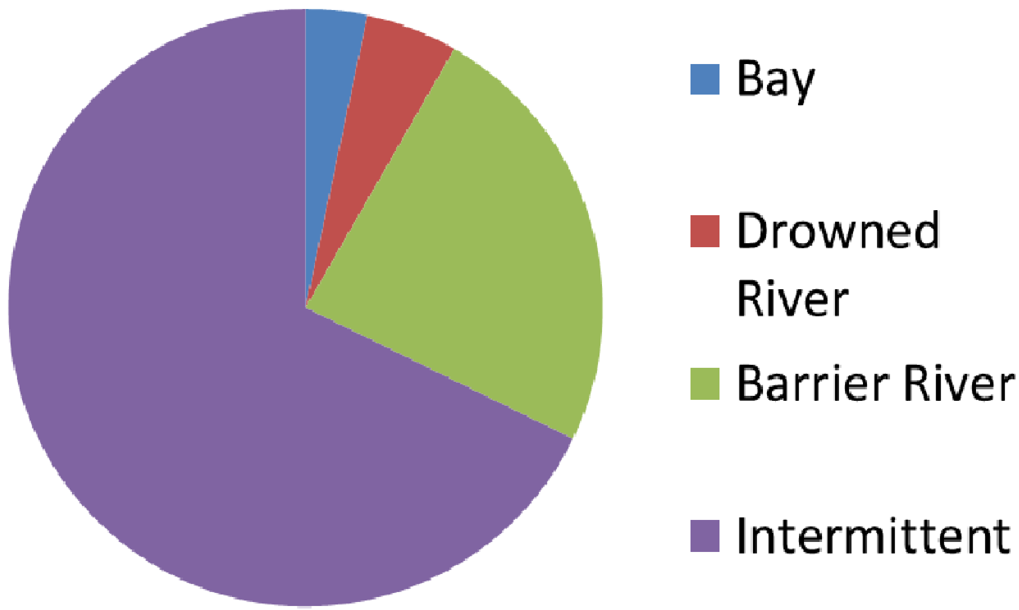


Figure 1 – Estuary types in NSW - River 24%, bay DRV 8%, lake/lagoon/creek ICOLL 68%

To account for these estuaries, a new definition is suggested “an estuary is a semi-enclosed coastal body of water which is connected to the sea either permanently or periodically, has a salinity that is different from the adjacent open ocean due to freshwater inputs or evaporation and includes a characteristic biota. The estuary extends upstream to the limit of influence by the sea (including tidal rise).”

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).

These data have led to a new understanding of the chemical and biological properties of NSW 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.

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 are inappropriate in NSW estuaries. If

Method

In order to demonstrate definitively that there is a group of estuaries that can not be considered as the "same" as all other NSW estuaries, 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.

HYPOTHESIS:

That some NSW estuaries have significantly different chemical and biological properties and their ecology/response to disturbance is not well explained by current conceptualisations

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) 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.

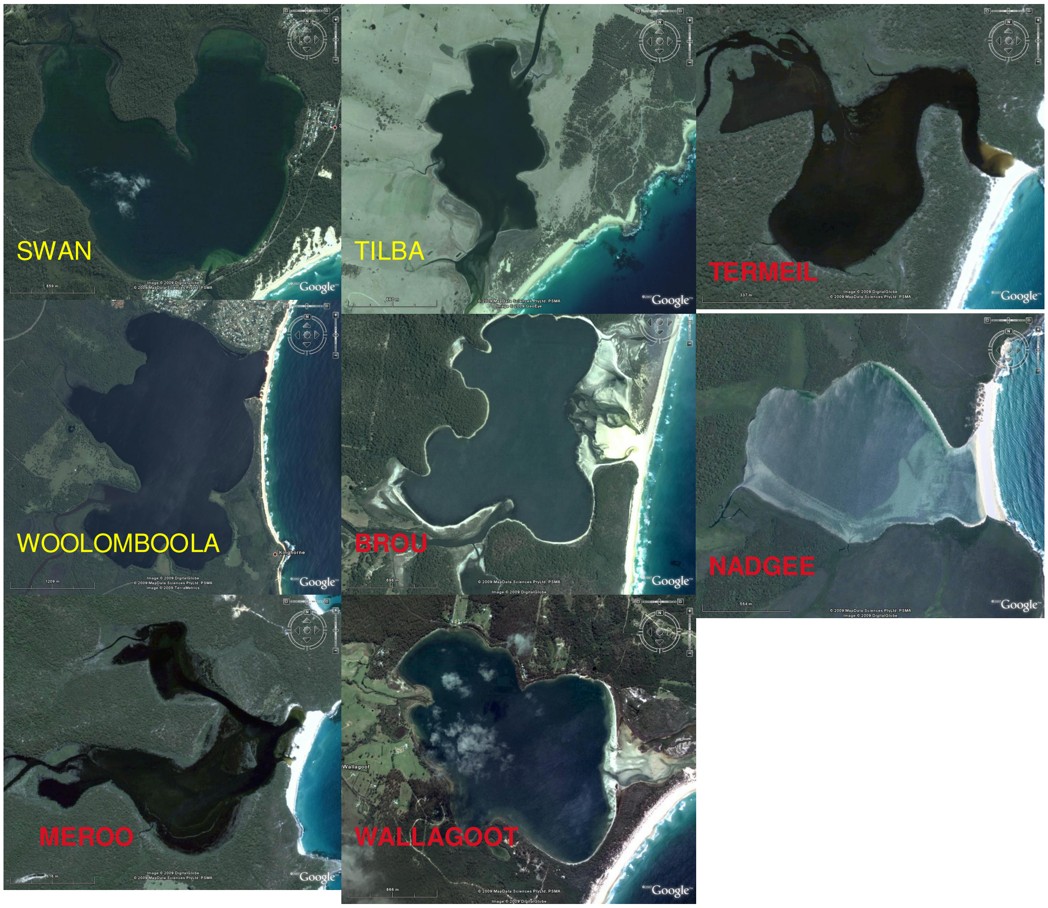


Figure 2 – Examples of the Back-dune Lagoon biotype.

Most estuaries tended to clump together in the MDS, but there were several that were separate (Figure 3; see Appendix 1 for abbreviations). Separation was not according to estuary type (symbols in Figure 4). When the additional class was added (AT in Figure 4) 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 5). 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).

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 2).

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 4), 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, Lake Tabourie, Termeil Lake, Meroo Lake, 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.

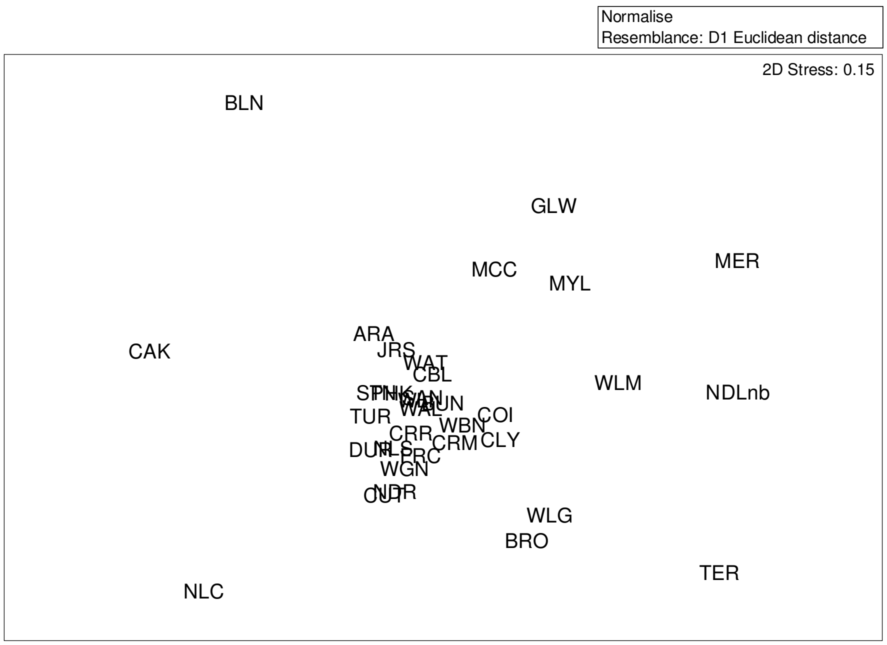


Figure 3 2D representation of MDS for estuaries based on physical, chemical and biological data. WLM represents Lake Wollumboola. Key to other Estuary Site Codes is in Appendix 2.

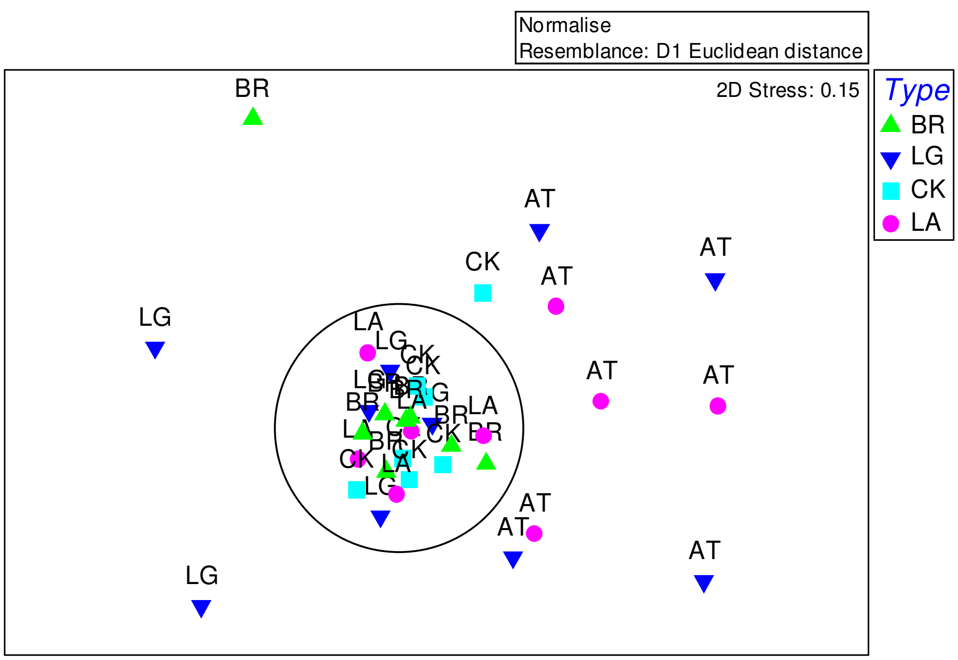


Figure 4 2D MDS plot showing distribution of CERAT estuary types (coloured symbols; BR – Barrier Rivers, LG – Lagoon A, CK – Lagoon B, LA - Lake) and modified typology (which now includes “AT” type; lettering on plot). AT type is clearly distinguished from other types (circled). There are no “AT“ within the circle.

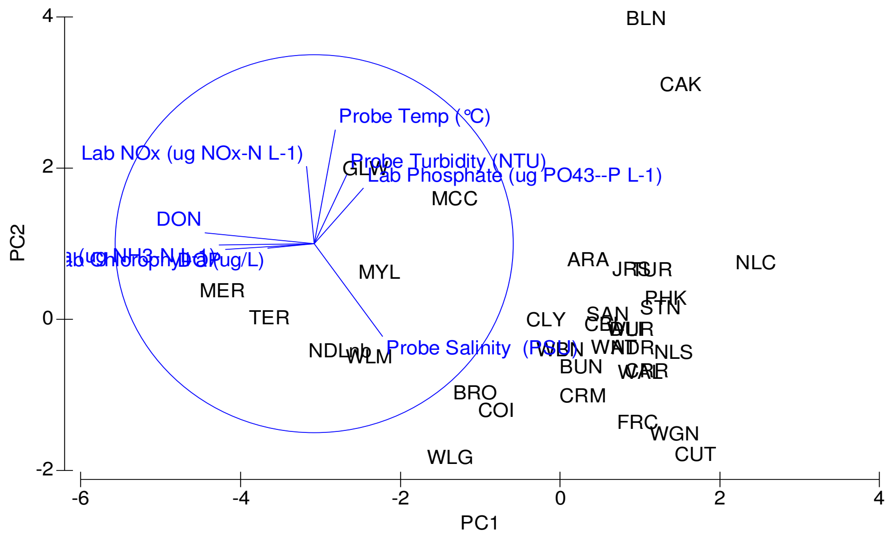


Figure 5 PCA showing main factors determining spread in 2D space.

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 do Back Dune Lagoons 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 above that Back Dune Lagoons in near natural condition are intrinsically different from other types of estuary, however there is currently no comprehensive description of the linkages between catchment inputs, lake biogeochemistry, and lake ecology. This section attempts to summarise what is known using Lake Wollumboola as an example.

Conceptual model of Back Dune Lagoon function

Back Dune Lagoons are always shallow estuaries 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. BDLs consist 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. Entrances of BDLs 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, BDLs shift between two very distinctly different states which are illustrated in Figure 6.

Under open entrance conditions, the BDL 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.

In Lake Wollumboola, 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.

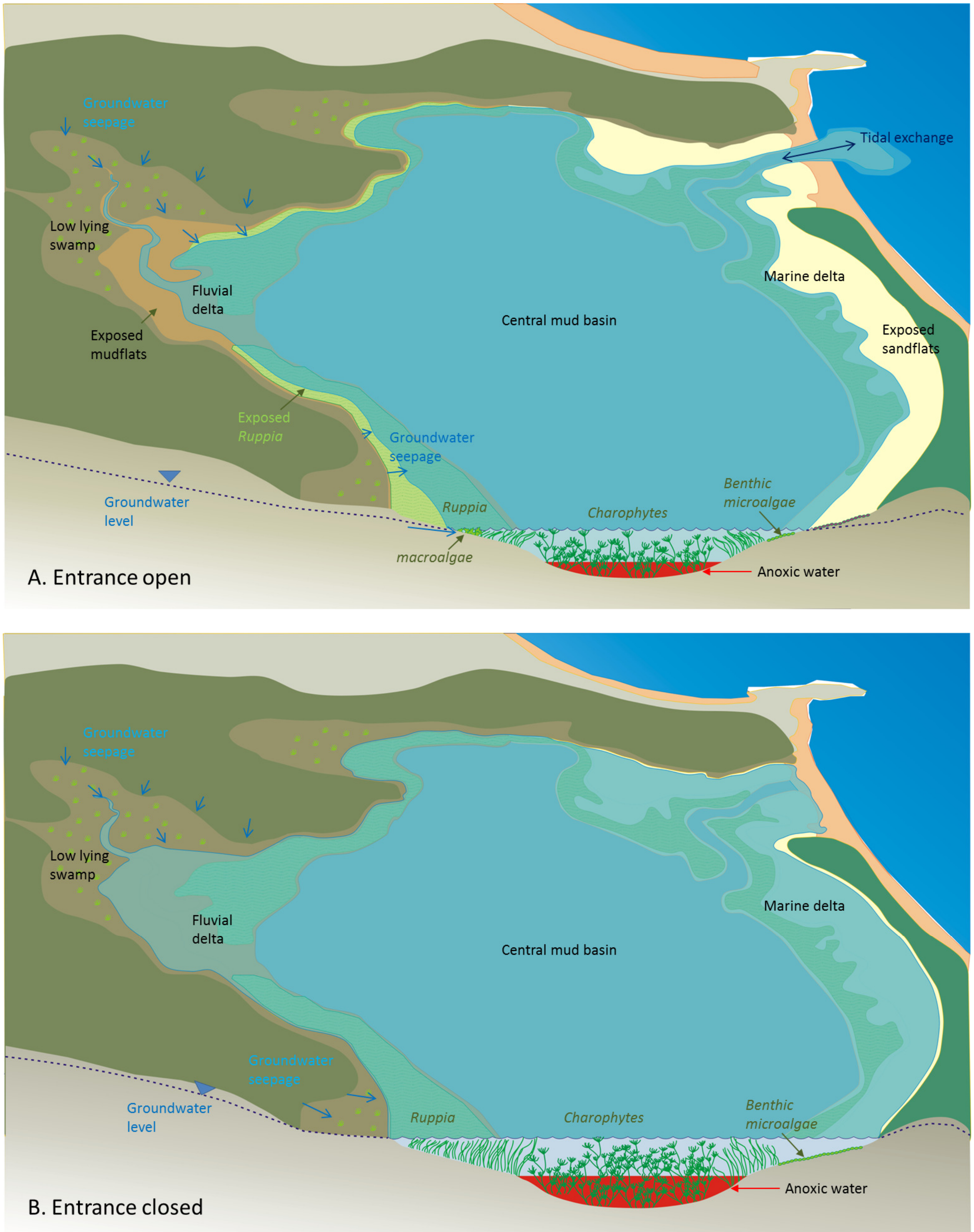


Figure 6 Conceptual model of Lake Wollumboola under A) entrance open; B) entrance closed conditions

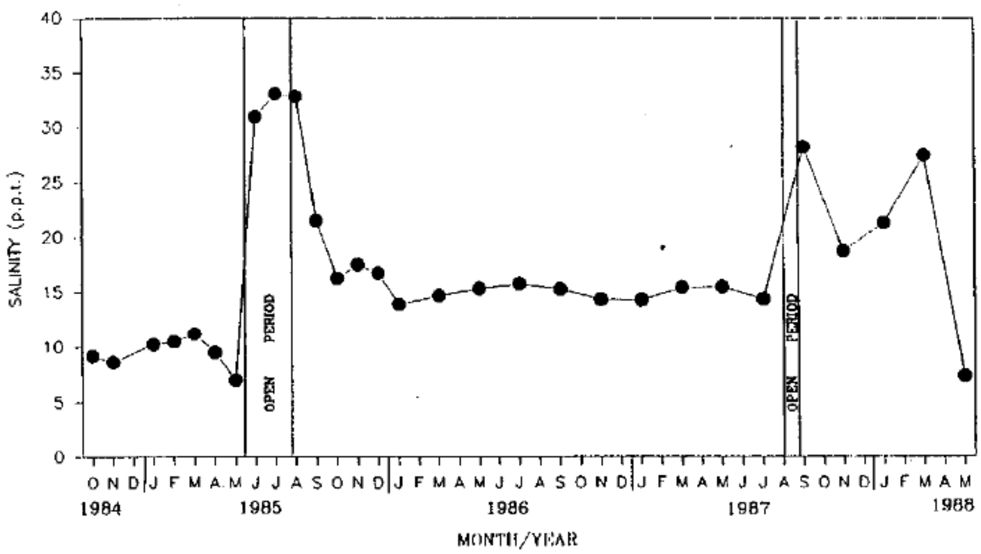
Entrance opening and salinity regime

Salinity is very variable in BDLs, ranging from near fresh to hypersaline. In Lake Wollumboola, salinites range between 1 or 2 and 45 PSU according to entrance state and rainfall

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 is the normal maximum (seawater is 35 PSU). This is comparable with BDLs such as Lake Brou and Wallagoot Lake, though others such as Nadgee, Meroo and Termeil never become hyper-saline.

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.



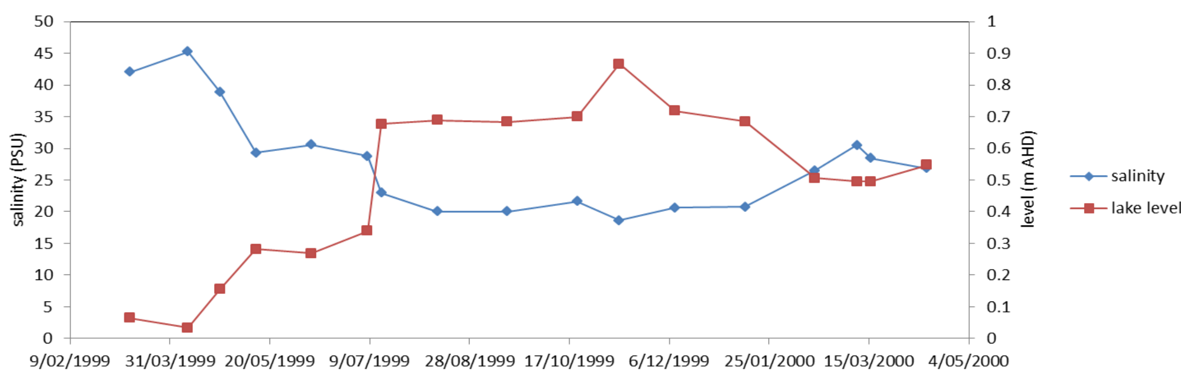


Figure 7 Salinity and lake levels in Lake Wollumboola

Stratification

Data from water quality loggers deployed between 1999 and 2001 (MHL 2001) show that Lake Wollumboola 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 presence of thick *Ruppia* and *Lamprothamnion* stands most likely dampens mixing between surface and bottom layers, however extended strong wind events can eventually lead to the breakdown of stratification.

The occurrence of such dramatic stratification 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.

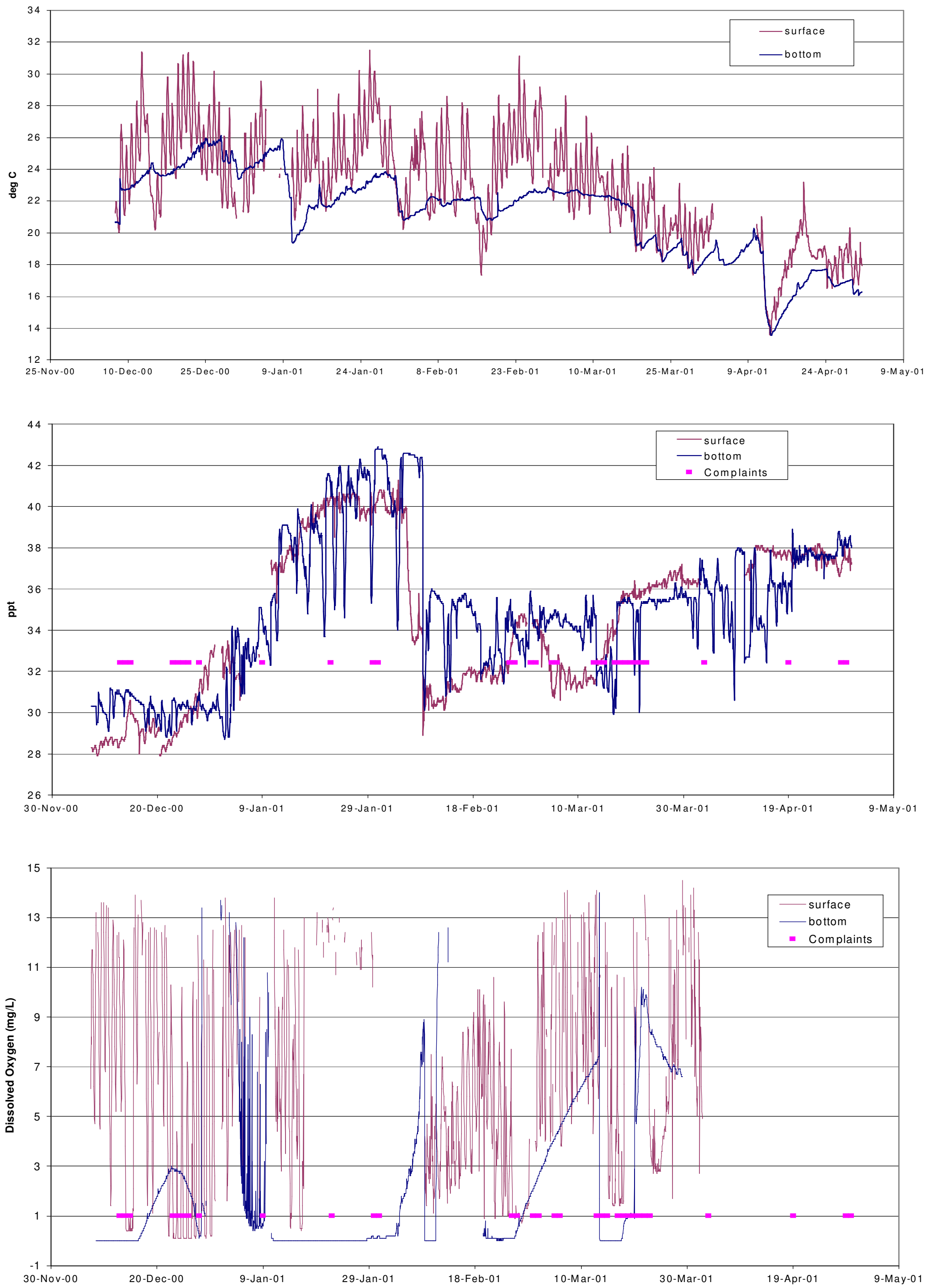


Figure 8 Variation in temperature, salinity and dissolved oxygen (DO) in surface and bottom waters of Lake Wollumboola. Periods where DO rises indicate the breakdown of stratification caused by wind driven mixing.

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

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) is 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 a BDL.

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.

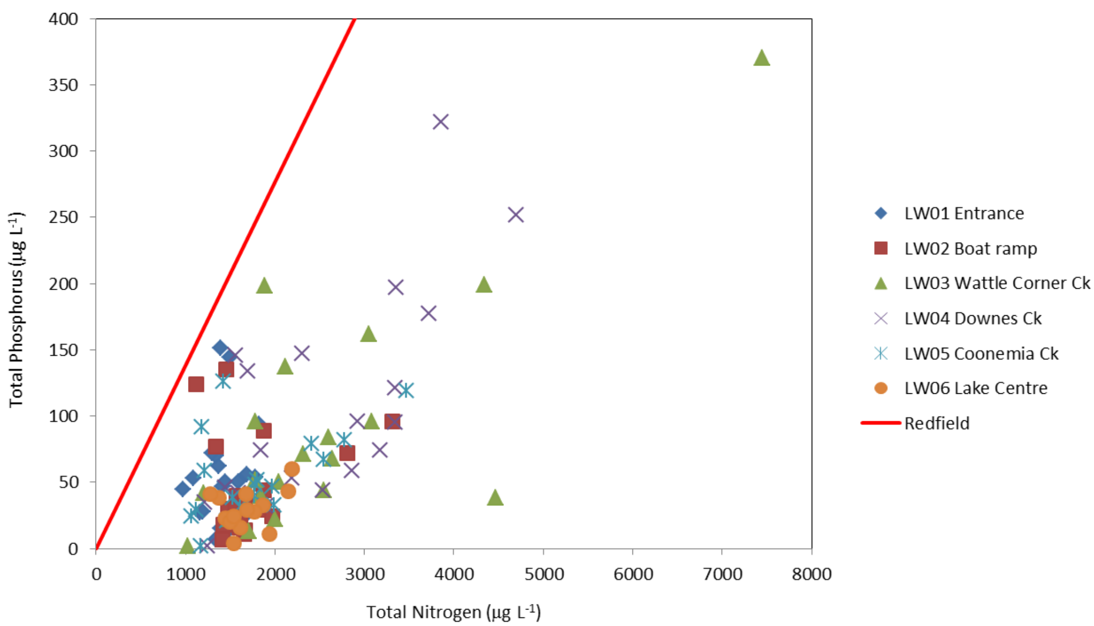


Figure 9 Comparison of total nitrogen and phosphorus in Lake Wollumboola with the Redfield N:P ratio (see text for explanation). Points falling below the Redfield line indicate potential phosphorus limitation.

Water column N:P ratios

Water quality data from Lake Wollumboola indicate that N:P ratios are consistently below the Redfield ratio (Figure 9), 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 10).

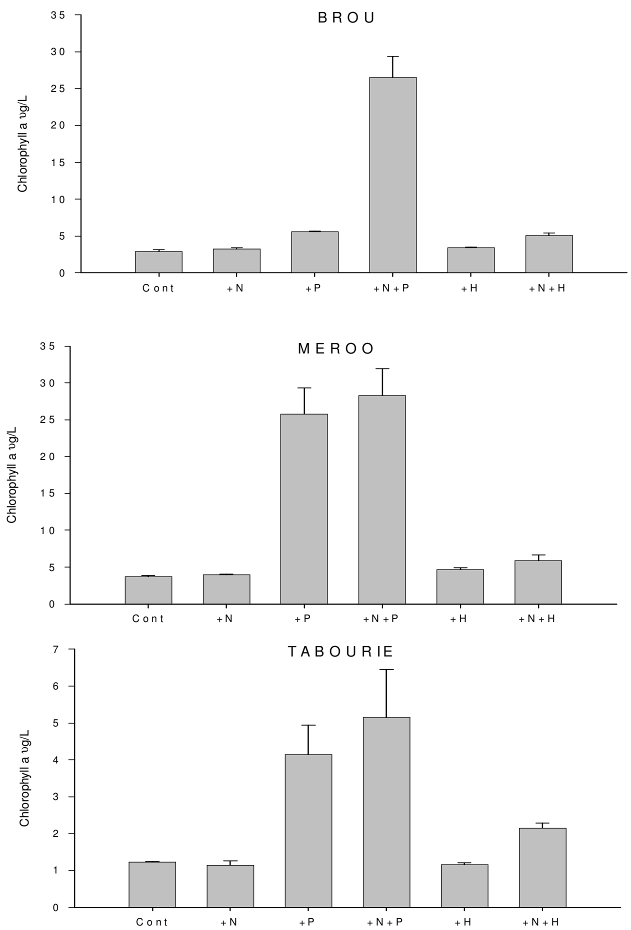


Figure 10 Results of experimental nutrient additions in three back dune lagoons. Phytoplankton productivity was consistently stimulated by P addition.

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.

Figure 11 Typical form of charophyte beds – example from northern hemisphere

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) (Figure 11).

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 µg L^{-1} in the water column and total phosphates (TP) are about 100 µg 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 12).

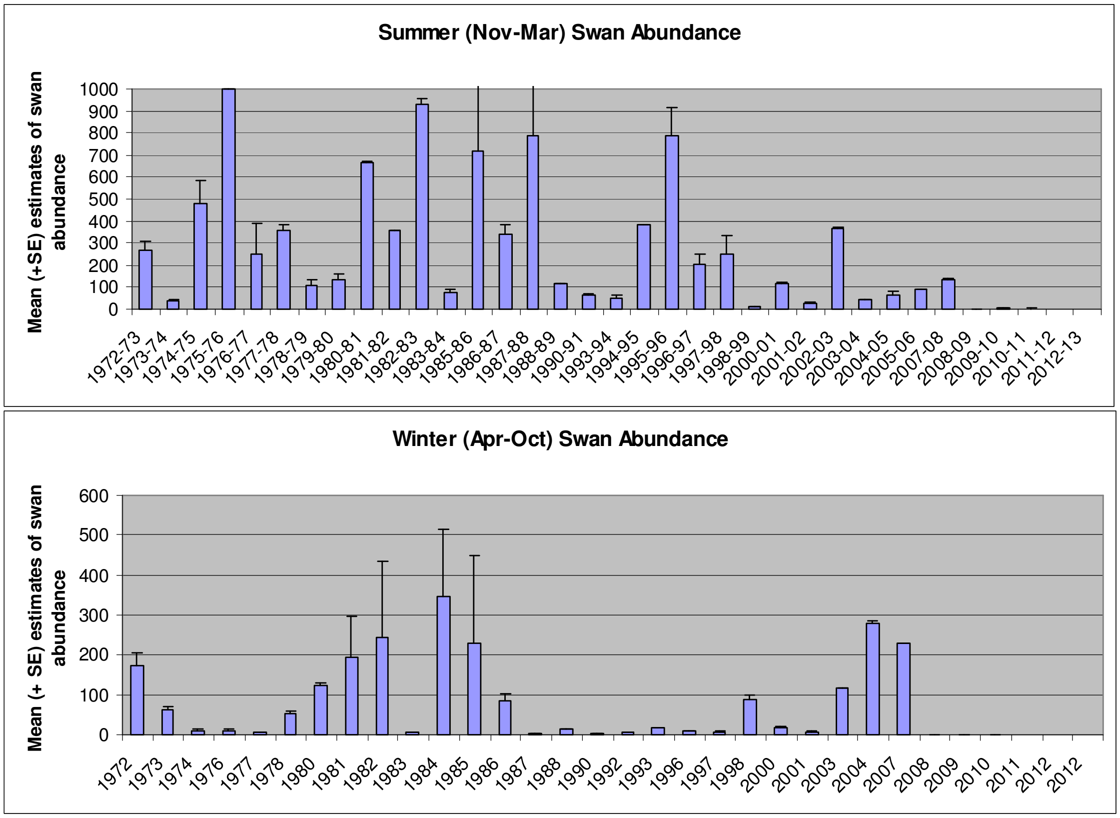


Figure 12 Swans ceased to utilise Nadgee Lake following the loss of charophyte beds after storms in June 2007

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 (Figure 14). 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).

Sensitivity

Tilba Tilba lake is an estuary that is physically very similar to the identified back dune lagoons and was most probably similar to the other BDLs. It's catchment is, however, highly disturbed . Data from Tilba Tilba can show how sensitive BDLs are to disturbance. The data available show that turbidity, chlorophyll (Fig 13) and other variables (not shown) are significantly different in Tilba.

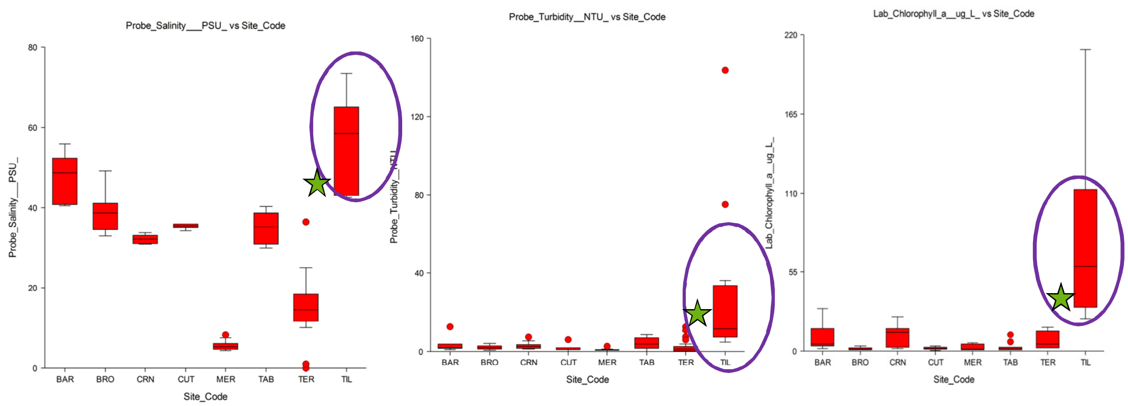


Figure 13 Back dune lagoons are very sensitive to catchment disturbance

Conclusions

- Traditional river-focussed definition of estuaries do not work for Australia and South Africa (and many other places)
- IN NSW, there is a sub-group of ICOLL type estuaries that are chemically and biologically dis-similar to all other types – back dune lagoons.
- This types comprises less than 5% of NSW estuaries sampled
- They are often ecologically dominated by charophyte algae or other macrophytes which results in characteristic physical and chemical signals, though those signals can occur without macrophytes
- Surface waters have naturally high nitrogen but are phosphorus limited with low (and occasionally high) algal concentrations
- Infrequent breakdown of stratification in vegetation leads to natural blooms of algae
- They appear very sensitive to disturbance, disturbed examples seem to be in poor condition (Tilba, Kianga)
- Management decisions need to acknowledge that we do not have an effective conceptualisation and therefore can't make quantitative predictions
- 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.

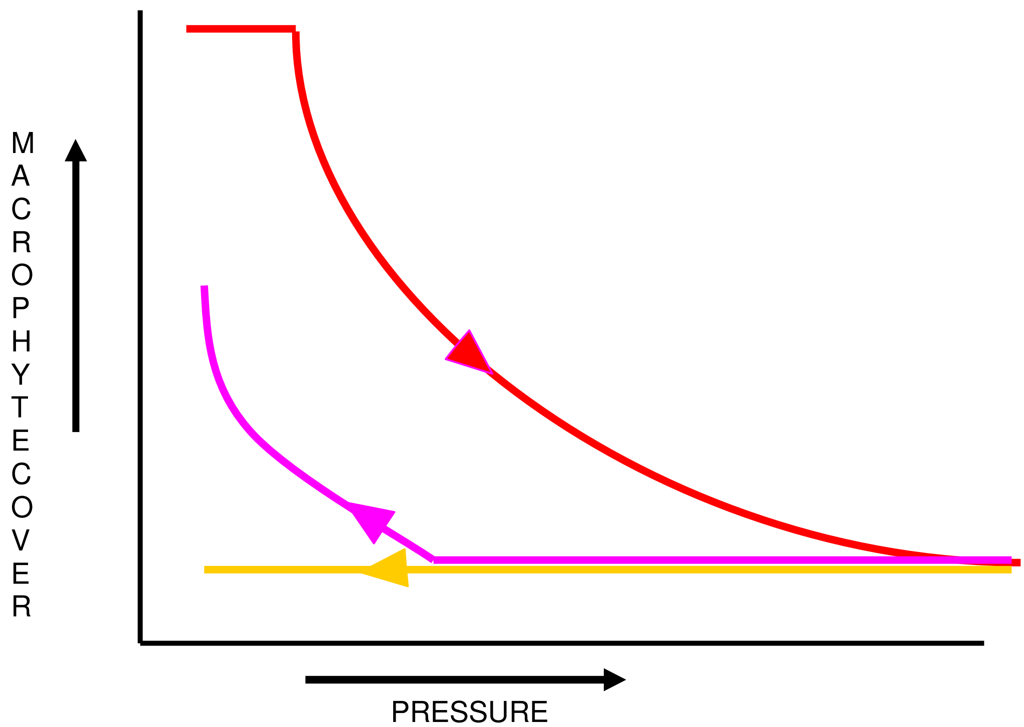


Figure 14 A conceptual diagram of system response ('macrophyte cover') to an increase in some pressure (red line), and recovery trajectories as the pressure is reduced. In most cases, perturbed systems never recover to the same state (pink line), while others never recover at all (yellow line). This is because of the loss of fundamental ecosystem services provided by the macrophytes which maintained tolerable or competitive conditions to ensure their survival.

Acknowledgements

This paper is an extract from an OEH Technical Report that has been reviewed by Dr Jocelyn dela-Cruz and Ms Kerryn Stephens.

We wish to thank Jocelyn and Kerryn for their constructive comments on the manuscript.

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Appendix 1 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