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Marine and Freshwater Studies

Review of Benthic Fauna Studies in Manly Lagoon

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Executive Summary

Manly Lagoon is situated in a catchment that has been significantly impacted by urban development and the lagoon has been considered to be in a degraded state for many years. Cardno Ecology Lab was commissioned by Warringah Council to undertake a review of studies of benthos in Manly Lagoon and other similar intermittently open coastal lakes and lagoons (ICOLLs). The review would advise Council on the state of the benthic community and its sensitivity to disturbance as a basis for management actions aimed at improving the condition of the benthic community and hence of the lagoon as a whole.

This report reviews the available literature on the ecology of macrobenthos in Manly Lagoon and compares this with Australian and international literature on intermittently closed/open coastal lakes and lagoons (ICOLLs).

The purpose of the review is to provide information to assist Council in:

- Developing appropriate management activities for reducing impacts on the lagoon benthos; and
- Assessing the appropriateness of undertaking future benthic monitoring programs in terms of benefits to Council's management strategies for improving the condition of the lagoon.

Macrobenthos plays several important roles in the ecology of estuarine systems. These animals ingest and mechanically break down organic matter which is then colonized by microbes and decomposed. In the absence of macrobenthos, nutrient cycling is impaired which reduces the capacity of the system to process inputs of organic matter from the catchment. This is a particularly acute problem in urbanised catchments which contribute large amounts of organics and other contaminants. Low diversity and abundance of macrobenthos is, therefore, a strong indicator of a potentially dysfunctional system.

Macrobenthos also stimulates nutrient recycling by reworking the sediment through burrowing and other movements. This enhances the flow of oxygenated water into the sediment and speeds up microbial decomposition. In general, the more abundant and diverse the macrobenthos, the greater their role in trophic dynamics and nutrient recycling. Systems with impoverished macrobenthos have less capacity to support higher levels in the food web and less capacity to initiate the process of decomposition of organic matter and nutrient recycling. This leads to an accumulation of organic matter in sediments and low oxygen concentrations in overlying water.

Macrobenthos is also an important food source for higher levels in the estuarine food web, such as larger crustaceans and fish. Low abundance of macrobenthos results in fewer resources for other animals.

Macrobenthos in predominantly open systems is generally more abundant and diverse than that in closed systems. Studies show that this component of the benthos is sensitive to anthropogenic disturbance (physical and chemical) typical of urbanised areas, which exacerbated in small systems like Manly Lagoon. The available information of Manly Lagoon indicates that it most closely resembles Curl Curl Lagoon in that it has chronically low macrobenthic diversity. It is less diverse than other comparable urban lagoons in this region, including Dee Why, Narrabeen and the Gosford Lagoons. It is concluded that the benthos is so impoverished that there is little or no scope for tolerance to further disturbance. This being the case, remediation involving structural changes to the lagoon, may be the only viable management option for improving the ecology of the system.

Possible management strategies to improve the ecological condition of benthos (and the aquatic system in general) in Manly Lagoon include:

- Dredging and deepening the channel and entrance to ensure frequent and effective tidal circulation and exchange within the lower reaches of the lagoon.
- Removal of organically enriched sediment from the main body of the lagoon may also allow better tidal flow and oxygenation of the system which would enhance recolonisation by macroinvertebrates.
- Improve the water quality of run-off from the catchment.
- Since macrobenthos is a sensitive indicator of ecosystem health, monitoring the state of benthic assemblages will not only provide further insights into its role in the ecology of this system, but should be an important component of any post-rehabilitation management strategy.

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1 Background

Cardno Ecology Lab was commissioned by Warringah Council to undertake a review of studies of benthos in Manly Lagoon and other similar intermittently open coastal lakes and lagoons (ICOLLs) in order to advise Council on the state of the benthic community and its sensitivity to disturbance as a basis for management actions aimed at improving the condition of the benthic community and hence of the lagoon as a whole. This review synthesises the available information on benthos in Manly in relation to selected international literature and data from similar urbanised lagoons in New South Wales. The purpose of the review is to provide information to assist Council in:

- Developing appropriate management activities for reducing impacts on the lagoon benthos; and
- Assessing the appropriateness of undertaking future benthic monitoring programs in terms of benefits to Council's management strategies for improving the condition of the lagoon.

2 Introduction

Intermittently closed and open lagoons and lakes (ICOLLs) are significant features on the Australian coast and there are about 130 of them in New South Wales. They have highly variable geomorphology and hydrology and their intermittent connection with the sea makes them ecologically complex (Roy *et al*. 2001). These lagoons are often centres of economic development, supporting light and heavy industry and substantial recreational and tourist activities. As a result, many have become highly urbanised. Urban development in the catchments and along the shorelines of coastal lagoons introduces a variety of stresses additional to those imposed by their intermittent nature. These include contamination, sedimentation, nutrient enrichment and habitat modification or loss due to shoreline development. A common activity, which in many cases has fundamentally altered the ecology of these lagoons, is the practice of artificially opening the mouth in order to mitigate the threat of flooding.

The ecological health of a coastal lagoon depends on the interaction of a large number of physical and biological factors including frequency and duration of tidal flow, quantity and quality of freshwater input and inputs of nutrients and sediment. One of the most important processes relates to how efficiently the lagoon system processes nutrient inputs. While the lagoon is open much of this material is flushed out to sea and is replaced by tidal inflow. During periods of closure, which can be of substantial duration, excess nutrients cause rapid growth of micro- and macroalgae which form blooms. When these plants die they are decomposed by bacteria in the water which remove much of the available oxygen in the process. This in turn can lead to fish kills and to the build up of dead plant material and poor water quality.

The principal way in which such a system can process nutrients is by recycling the organic matter in a process known as remineralisation, which occurs primarily in the sediments. The primary agents of remineralisation are the macro- and meiobenthos (the latter are animals smaller than 0.5 mm which are very numerous) living in the sediment. These animals feed on the organic matter and excrete it in a form that enhances its subsequent breakdown by sediment microbes such as protozoa and bacteria (Dye 2006a). Factors that tend to diminish the abundance and activity of the benthos, such as pollution, can have significant consequences for the overall health of the system by impairing nutrient processing. Management could therefore be informed through an understanding of the ecological function of benthos and the factors that influence it. Although there have been studies of meiobenthos in urban lagoons in New South Wales (Dye 2004, Dye 2005, Dye and Barros 2005a, Dye 2006b), there have been no studies of this component of the benthos in Manly Lagoon and therefore no basis for comparison. In this review, therefore, the emphasis is on macrobenthos for which comparable data are available for Manly Lagoon.

Manly Lagoon is a small coastal lagoon located on the boundary of Manly and Warringah Councils. It extends approximately 3 km north-west from its entrance at the northern end of Queenscliff Beach and has a water area of 8.6 ha. As such it is considerably smaller than Narrabeen Lagoon (218.1 ha), about half the size of Dee Why Lagoon (23.8 ha), but somewhat larger than Curl Curl Lagoon (5.8 ha) (The Ecology Lab 2002). Under natural conditions, Manly Lagoon would be intermittently opened to the sea, but the installation of a large pipe system maintains this entrance (Patterson Britton and Partners 1998). In times of flooding, the lagoon is also drained by bulldozing a channel across Queenscliff Beach. A recent analysis of the effect of dredging the entrance on tidal flow in Manly and Narrabeen lagoons indicated that dredging may not noticeably improve tidal flow in Manly, although it does in Narrabeen (Wiecek and Floyd 2007). This was ascribed to the pipe system that maintains the open status of Manly lagoon. Manly Lagoon has several creeks flowing into it from the surrounding catchments (18 km^2). Most flow through highly urbanised areas, including residential properties, commercial and light industrial areas and golf courses. There is also a relatively large dam in the upper catchment. A recent review of estuary condition in New South Wales rated Manly Lagoon as in very poor condition (Roper *et al.* 2010).

3 Studies of Macrobenthos in ICOLLs

Soft sediment benthic communities play important roles in the functioning of coastal ecosystems over a range of spatial scales from embayments to microtidal estuaries (Tenore *et al*. 2006). Arguably, the two most important roles that macrobenthos plays in the ecology of estuaries and coastal lagoons are as a food source for higher trophic levels, including commercially important fisheries species (Gee *et al* 1985, Flint and Kalk 1986) and as agents for nutrient recycling (Frasco and Good 1982, Menendez *et al*. 1989, 2004, Zimmer *et al*. 2004, Dye 2006a). In view of the importance of these ecosystem functions, it is not surprising that there is an extensive literature on the ecology of macrobenthos in transitional waters. Many of these studies have focussed on the structural aspects of macrobenthic ecology, i.e. the number and abundance of species, in relation to the physical and chemical environment, while others address functional aspects, such as trophic dynamics and decomposition. Several methodological studies into ways of characterising the health of estuarine systems using macrobenthos have also been published over the last twenty years (Warwick and Clarke, 1993, 1995, Clarke and Warwick 2001, Clarke *et al*. 2006).

The structure of macrobenthic assemblages in lagoons is strongly influenced by physical and chemical conditions which can be subject to extreme fluctuations resulting from periodic opening and closing of the mouth and episodic flooding (Millet and Guelorget 1994). Factors that are important in structuring macrobenthic assemblages include characteristics of sediments (Whitlach, 1981, Thrush *et al*. 1996, 2003, Wu and Shin 1997), hydrodynamics such as evacuation and dilution factors (Haines *et al*. 2006) and rates of water exchange (Gamito 2006), nutrient enrichment (Tsutsumi 1990, Hadwen and Arthington 2006), water chemistry (Geddes and Butler 1984, Shimeta and Jumars 1991, Attrill, 2002, Magni *et al*. 2005) and isolation from the sea *per se* (Castel *et al* 1990, Guelorget and Perthuisot 1992, Blanchet *et al*. 2005, Carvalho *et al*. 2006).

Early studies on the ecology of macrobenthos in coastal lagoons in Australia include a survey of benthos in Gosford lagoons by Weate and Hutchings (1977), who found that the benthos comprised a reduced marine fauna in which several typical estuarine species, including molluscs, polychaetes and crustaceans, were absent. Similarly, species diversity in Smiths Lake decreased when the system closed (Hutchings *et al*. 1978). Benthic fauna in Myall Lakes was strongly influenced by salinity (Atkinson *et al*. 1981), as is the case in similar systems in many parts of the world (de Kroon *et al*. 1985, Teske and Wooldridge 2003). Benthic communities in the Gippsland Lakes, Victoria, were strongly influenced by distance from the sea, sediment characteristics and salinity (Poore 1982), while extreme salinity fluctuations reduced diversity in the Coorong Lagoons, South Australia (Geddes and Butler 1984). In Western Australia, the composition of benthos in Wilson Inlet was strongly influenced *inter alia* by low salinity and absence of recruitment from the sea during periods of closure (Platell and Potter 1996).

The extent to which the intermittent nature of opening of coastal lagoons influences the structure of macrobenthic assemblages has received increasing attention in recent years. Dye and Barros (2005b) studied macrobenthos in eight ICOLLs in New South Wales in relation to their medium-term open/closed status and the degree to which their mouths were artificially manipulated. They found that macrobenthic assemblages in open lakes were consistently different from those in closed systems, mainly due to differences in the composition of polychaete assemblages, which are known to be indicators of stress (Cardoso *et al*. 2006), although oligochaetes and amphipods were also important (Dye 2006b). Taxonomic diversity was higher in open lakes because closed systems tended to be dominated by a small number of taxa. While there were differences between lakes where the mouth was artificially opened periodically and those which opened or closed naturally, these differences were largely confined to the mouth area and were smaller than the differences between open or closed systems *per se*.

Differences in the structure of macrofaunal assemblages between permanently open and intermittently open estuaries in the Solitary Islands Marine Park were attributed to differences in the number of taxa, in particular the absence of an amphipod species from the latter (Hastie and Smith 2006). Similar patterns have been found elsewhere, for example in South African intermittent estuaries, where loss of species can be one consequence of isolation from the sea (Teske and Wooldridge 2003).

While clear patterns of difference in macrobenthos between open and closed systems can be seen over long time periods, the response of macrobenthos to individual disturbances such as particular opening events may not be apparent. This was the case in a study of opening events in Gosford Lagoons where temporal fluctuations in macrobenthos in the entrances did not differ between artificially opened and unopened lagoons (Gladstone *et al.* 2006), possibly indicating short-term resilience to such disturbances.

In their “natural” state, coastal lagoons in New South Wales tend to be poor in nutrients and dominated by seagrass because there is relatively little import of nutrients from the ocean and rainfall is generally low and sporadic. However, anthropogenic influences including pollution, nutrient enrichment and physical disturbance can drastically alter the environment in lagoons with severe consequences for macrobenthic assemblages and ecosystem function (Weston 1990, Gaston *et al*. 1998). Webster and Harris (2004) modelled the biogeochemistry of coastal lagoons in south-east and south-west Australia and found that they can adopt alternative stable states depending on their rates of loading of nutrients. Beyond a certain critical level recycling of nutrients, in particular denitrification, which is the process by which nitrogen is recycled in sedimentary systems, shuts down, reducing oxygen levels at the sediment surface to zero. This results in a severely degraded and dysfunctional system. Similar “dystrophic’ crises have been recorded in lagoons subject to human impacts in the Mediterranean (Sorokin *et al*. 1996, Koutsoubas *et al*. 2000, Marzano *et al*. 2003).

The decomposition of organic detritus in marine sediments is enhanced by the activity of invertebrates that ingest the litter and produce fine fragments in their faeces that become colonised by bacteria and fungi which break it down into its basic chemical constituents (Fenchel 1970, Mann 1988). The grazing activity of amphipods has been found to increase the rates of decomposition of *Zostera marina* leaves (Harrison 1977) and those of *Spartina alterniflora* (Lopez *et al*. 1977), while the decomposition of *Ruppia cirrhosa* is retarded in the absence of macroinvertebrates (Menendez *et al*. 1989). In contrast to the above, a study of the decomposition of *Zostera capricornii* in Tuggerah Lakes, Dye (2006) found that macrobenthos inhibited the initial stages of decomposition, possibly due to their grazing on microflora that had colonised the leaf surfaces. There was, however, a positive correlation between loss of the organic fraction of the litter and the abundance of macroinvertebrates.

Macrobenthos are largely responsible for another important process in sediments, that of bioturbation, in which sediment is turned over and made more porous by the burrowing activities of invertebrates. In areas with large populations of burrowing animals such as prawns, the circulation of water in the upper layers of the sediment is increased which, in turn, enhances microbial populations and contributes to decomposition of organic matter (Kristensen 1985, Hunter *et al*. 2003). Smaller macroinfauna, such as polychaetes and crustaceans, have a similar effect. Where benthic populations are impoverished, the sediment becomes more anoxic and decomposition is inhibited (Kristensen *et al*. 1995).

It is clear from the above that macrobenthos play crucial roles in the functioning of lagoon systems and that they are influenced by anthropogenic activities. In general, human impacts on lagoonal systems tend to exacerbate the effects of closure by increasing the inputs of nutrients and pollutants, often to levels which threaten the ecological integrity of the system. In view of this it is reasonable to ask whether the structure of such assemblages can indicate the environmental status or “health” of a system. A number of studies, including several of the above, have shown that stressed systems have characteristic benthic assemblages and several recent studies have developed this idea and shown the potential of macrobenthos as indicators of ecosystem health (Olsgard *et al*. 2003, Cardoso *et al*. 2007, Hale and Heltshe 2008). In general, the more abundant and diverse the macrobenthos, the greater their role in trophic dynamics and nutrient recycling. Systems with impoverished macrobenthos have less capacity to support higher levels in the food web and less capacity to initiate the process of decomposition of organic matter and nutrient recycling. This leads to an accumulation of organic matter in sediments and low oxygen concentrations in overlying water.

4 Studies of Macrobenthos in Manly Lagoon

There have been few studies of the benthos of Manly Lagoon. Early studies of water quality concluded that the lagoon was stressed from pollution, in particular eutrophication, sedimentation, low oxygen and contamination by heavy metals and hydrocarbons (Cheng 1985). Data from surveys carried out in the main body of the lagoon between 1985 and 2009 are summarised in Figure 1 and Figures 2 and 3 show the spatial distribution of macrobenthos (total abundance and number of taxa, respectively) in the lagoon between 1992 and 2002 (The Ecology Lab in 2002). While there are no comparable data from the inner reaches of other lagoons, it is worth noting that The Ecology Lab (2002) recorded the greatest density of macrobenthos from a location adjacent to Nolan Reserve. However, family-level diversity at this location was close to zero as the fauna comprised >99% spionid polychaetes. As far as possible, comparisons in Figure 1 and in the discussion below are made among similar seasons.

One of the earliest studies was by Cheng (1985). Unfortunately, this study suffered from inadequate replication and can therefore only provide an indication of the state of macrobenthos at that time. Subsequent studies done by The Ecology Lab and Cardno Ecology Lab (see below) were better designed and provide a more robust assessment of macrobenthos. Cheng (1985) found an impoverished benthic fauna dominated by polychaetes. Only 3.8 ± 1.9 taxa were found on average at each of five locations, with mean total abundance of 211 ± 131 individuals. Based on the original data, the mean Shannon-Weiner diversity index at that time was 0.7 ± 0.4. However, a subsequent survey (The Ecology Lab 1995) found that the macrobenthos was in fairly good condition, although polychaetes were again numerically dominant. The mean number of taxa in summer was 7.4 ± 0.9, the mean total abundance was 66 ± 17 individuals and the Shannon-Wiener diversity was 1.3 ± 0.1. Following a fish kill in the lagoon in summer 2001, The Ecology Lab again surveyed macrobenthos and recorded an impoverished fauna. At this time, the mean number of taxa was 4.4 ± 0.7, the mean total abundance was very low at 13.4 ± 2.9 and diversity was 0.6 ± 0.1. They concluded that the fish-kill had had no significant effect on the benthos. This is not surprising as benthos would respond more slowly to disturbances in the water column due to the time needed for the effect to penetrate into the sediment.

The latest survey of macrobenthos was conducted in July 2009 (Cardno Ecology Lab 2009). This revealed the most impoverished fauna recorded in the lagoon. While the mean number of taxa was similar to previous surveys (7.4 ± 0.9), the mean total abundance was again very low at 6.3 ± 4.1 individuals and diversity was only 0.2 ± 0.1. It should also be noted that these data were obtained in winter when numbers would be somewhat greater than at other times due to recruitment and higher levels of oxygen (Platell and Potter 1996).

Figure 1 also includes comparable data from three urbanised lagoons close to Manly Lagoon, i.e. Curl Curl, Dee Why and Narrabeen. The data are adapted from Dye and Barros 2005b whose findings in relation to opening regimes of ICOLLs have been discussed above. These data show that Manly Lagoon is most similar to Curl Curl in terms of abundance, number of taxa and Shannon-Weiner diversity, but is impoverished in comparison to Dee Why and Narrabeen. These data accord with the conclusions of Dye and Barros 2005b that the macrobenthos of systems that are frequently open (either naturally or deliberately) is richer than that in closed systems. In addition, both Curl Curl and Manly Lagoon are highly disturbed systems in which the benthos is stressed (Cheng 1985, Healthy Rivers Commission 2002, Roper *et al*. 2010) and as such they would be expected to support impoverished faunas (Warwick and Clarke 1993, 1995). Low diversity and abundance of macroinvertebrates in Curl Curl was also reported by The Ecology Lab (2004).

In Manly Lagoon, the number of taxa recorded in the main body of the lagoon over the last 25 years has varied from 10 (Chen 1985), to 15 (The Ecology Lab 1995), to 8 (The Ecology Lab 2002) and to 5 (Cardno Ecology Lab 2009). A wide range in number of taxa was reported in the Gosford Lagoons (Weate and Hutchings 1977) where the total number of taxa varied from 13 in Terrigal, to 10 in Wamberal, 16 in Avoca and 14 in Cockrone. A recent study of macrobenthos in these lagoons reported an average total number of taxa of 15 across these four lagoons (Gladstone *et al.* 2006). In Wallis and Smiths Lakes, the total number of taxa in muddy sediments was 22 (Hutchings *et al*. 1978). A survey of macrobenthos in muddy sediments in Myall Lakes carried in late winter revealed a total number of taxa of 11 (Atkinson *et al*. 1981). In Curl Curl, the total number of taxa was 8, in Dee Why it was 15 and in Narrabeen it was 22 (Dye and Barros 2005b). On this basis, Manly Lagoon is not only less diverse than in the past, it is also less diverse than the Gosford Lagoons, Dee Why or Narrabeen.

5 Conclusions from the Review

Water quality and macrobenthic studies in Manly Lagoon clearly indicate that this lagoon is highly degraded and compares poorly with other coastal lagoons, with the exception of Curl Curl, which is in an equally parlous state. Low numbers of benthic invertebrates have been recorded consistently over many years and there is a trend of decreasing abundance and taxonomic diversity. Even allowing for the fact that the latest survey was done in winter, the fauna is so depauperate that the sediment system can be described as dystrophic. Under these conditions, it would be expected that the sediment/water boundary layer and the sediment itself will be largely anoxic. Such conditions not only inhibit recruitment of species, but will also substantially reduce the capacity of the system to process organic matter and recycle nutrients. This, in turn leads to a build-up of organics and a dysfunctional system.

It is clear from the review, that macrobenthos is sensitive to a variety of disturbances. In highly disturbed or stressed systems, such as those impacted by urban development, macrobenthos becomes less diverse. In this respect, Manly Lagoon most closely resembles Curl Curl in that both are relatively small and significantly impacted by urban developments, although the latter has additional problems due to leachate from old land fill sites (Patterson Britton and Partners 2005) requiring special management considerations (Enviroaware 2006), and both have chronically low macrobenthic diversity.

The sensitivity of macrobenthos to a range of impacts, including excess nutrients and contamination by heavy metals and hydrocarbons, both of which are common in urbanised systems, makes this component of the benthos useful as an indicator of ecosystem health. Monitoring the status of macrobenthic assemblages provides important information on the capacity of the system to process nutrients. While monitoring water quality is important in assessing, for example levels of nutrients and pathogens, in the water column, this gives no information about the levels of these contaminants in the sediments. This is important because many contaminants, including nutrients, are bound to fine silt particles which settle out onto the bed of the lagoon. This means that there is only a weak correlation between water quality and the capacity of the system to process inputs of nutrients. Keeping track of the abundance and diversity of macrobenthos can give an early warning of problems. By the time a significant impairment of water quality is detected, the system is already in trouble.

It is worthwhile, at this point, to return briefly to the use of meiobenthos in assessing ecosystem health. Despite their demonstrated utility as indicators of sediment condition (Somerfield *et al*. 1994, Schratzberger *et al*. 2000), very few studies have been done on meiobenthos in coastal lagoons in Australia (Dye 2004, Dye 2005, Dye and Barros 2005a) and, as mentioned in the Introduction, there have been no studies of meiobenthos in Manly Lagoon. The main reason for this is the technical complexity involved in processing the sediment in order to identify and enumerate the animals. Few laboratories are equipped to deal with this and it would be very expensive. This, together with significant taxonomic (species identification) difficulties, makes meiofauna impractical as a routine indicator of sediment condition.

Given the degree of impact on the macrobenthos in Manly Lagoon, extensive rehabilitation of the lagoon would be an effective way of improving the sediment ecosystem and thus the health of the lagoon. Under the present conditions, it is likely that the macrobenthos is largely dysfunctional as regards its role in trophic and nutrient dynamics.

6 Management Considerations

In the brief for this project, Warringah Council sought answers to several important questions regarding benthos in Manly Lagoon. The following responses are based on the above review and our experience in research on this issue.

6.1 Role of Benthic Fauna in Manly Lagoon

As discussed above, benthos plays several important roles in the ecology of lagoons, including as a food source for larger animals and, crucially, as the primary agent initiating the breakdown of organic matter and recycling of nutrients brought into the system primarily by stormwater inflows. In Manly Lagoon, however, the benthos is so impoverished that it cannot effectively fulfil these roles. Consequently there will be an accumulation of organic matter on and in the sediments and very low to zero levels of oxygen, ultimately leading to a decline in water quality in the lagoon. Moreover, the downward trend in abundance over time suggests that the lagoon condition is deteriorating and that intervention is required reverse this.

6.2 Sensitivity and Robustness of the Benthos

Benthos living in the sediments of ICOLLs are generally adapted to conditions of fluctuating temperature, salinity and oxygen. However, they are not indestructible and under stressed conditions (e.g. high organic loads and contamination) the abundance and diversity of benthos will decrease, sometimes to the point of local extinction. Benthos living at the limit of their tolerance are very sensitive to any additional stresses, such as those resulting from increased organic inputs or contamination by heavy metals. Unfortunately these are the very conditions that often occur in urbanised lagoons. The data from Manly Lagoon indicate that the benthos is at or past the limit of tolerance and has been declining for some time. This decline may be punctuated by sporadic increases at certain locations and/or times, as seen at Nolans Reserve in October 2001 and at Hinkler Park in 1992.

6.3 Disturbances that may Impact on Benthos in Manly Lagoon

The most significant forms of disturbance that may affect benthos are related to the quality of water inputs to the lagoon. Organic inputs in the form of sewage and other plant and animal particulate matter arguably pose the greatest threat. Poor tidal circulation in the lagoon ensures that this material for the most part remains in the lagoon and ultimately settles on the bottom where it can form a persistent anoxic layer. Recruitment of benthos from elsewhere is not only limited by the lack of adequate tidal exchange, but even if such animals do enter the lagoon, it would be unlikely that viable populations would become established under such conditions. Indeed, if this were happening to any significant extent, the benthos would not be so impoverished.

6.4 Tolerances of the Benthos in Manly Lagoon to Further Disturbance

Recent surveys clearly show that the benthos in Manly Lagoon is in a degraded state and the situation appears to be worsening. So impoverished are the benthic assemblages that there is effectively little or no scope for tolerance to further disturbances. Dredging the lagoon will have the obvious consequence of largely removing the benthos. However, if dredging results in improved conditions, specifically improved sediment and water quality, then recolonisation of the benthos, mainly from undredged areas but also via water-borne propagules and tidal inflow, will be enhanced.

6.5 Possible Management Actions

Possible actions aimed at improving the ecological condition of benthos (and the aquatic system in general) in Manly Lagoon include:

- Dredging and deepening the channel and entrance to ensure frequent and effective tidal circulation and exchange with the lower reaches of the lagoon, particularly below Pittwater Road and possibly up to the vicinity of Addiscombe Rd. The existing arrangement for maintaining tidal flow would appear to be inadequate for flushing the system to the extent that is required to balance inputs of nutrients from stormwater and to allow development of a healthy macrobenthic community (Webster and Harris 2004, Gamito 2006). It should be noted, however, that dredging the entrance may not result in significantly increased flow into and out of the lagoon (Wiecek and Floyd 2007). Nevertheless, any increased tidal flow will not only flush the lower part of the lagoon, but will also significantly dilute the load of organic matter entering the system via stormwater. This would help to restore the efficacy of nutrient cycling which is probably significantly impaired at present. A controlled release from Manly Dam after completion of dredging should be considered to flush the lagoon. Additionally, an improved tidal flow will increase the rate at which the benthos recolonise, as benthic larvae are carried into the lagoon with the tide.

- More important for the improving the condition of the lagoon would be removal of organically enriched sediment from the main body of the lagoon which may also allow better tidal flow and oxygenation of the system and would enhance recolonisation by macroinvertebrates.

- While tidal exchange would be important in any rehabilitation process, it would be insufficient on its own and should be complemented by managerial actions to improve the water quality of run-off from the catchment. The main problem here is excess nutrients contributed by stormwater although other contaminants, such as heavy metals and hydrocarbons (primarily from roads), may also pose problems. Decreasing the nutrient load in the lagoon would also address other known problems, such as high bacterial counts that currently limit recreational use. A combination of management approaches to nutrient reduction is recommended. These would include (but be not limited to):

1. identification and repair of leaking sewerage pipes
2. identifying and rectifying sewage overflows during rain periods
3. installation and maintenance of gross pollutant traps to reduce the amount of organic matter that accumulates on the lagoon bed
4. Where feasible, construction of sediment traps/stormwater settlement ponds to reduce the amounts of particulate and dissolved organic matter entering the lagoon
5. Management of run-off and discharges from industrial and residential sources in the catchment.

While it cannot be denied that this is a difficult problem to solve given the extent of urban development in the catchment, continued monitoring of water quality in stormwater and in the lagoon is essential if this problem is to be tackled effectively.

- As discussed above, monitoring of water quality on its own will not provide information on the state of benthic assemblages. Since a major objective of rehabilitation would be to improve the state of the benthos and thus the lagoon as a whole, it is essential that the condition of the benthos is monitored. This would not only provide further insights into its role in the ecology of this system, but would provide the information needed to assess the success of rehabilitation works and ongoing management strategies. It is, therefore, recommended that a monitoring program is developed for macrobenthos in Manly Lagoon to complement ongoing water quality monitoring. Such a program would entail regular sampling in at least four locations (two sites within each location) in the main body of the lagoon where the greatest proportion of nutrient processing occurs. The sampling should be done twice a year in the first three years after rehabilitation works and then possibly less frequently thereafter (e.g. every three years).

7 Acknowledgements

This report was written by Dr Arthur Dye and reviewed by Dr Peggy O'Donnell.

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9 Figures

Figure 1: Mean abundance, number of taxa and diversity of macrobenthos in urban ICOLLs in Sydney.

Figure 2: Mean total abundance of macrobenthos in Manly Lagoon from 1992 to 2002.

Figure 3: Mean number of taxa of macrobenthos in Manly Lagoon from 1992 to 2002.

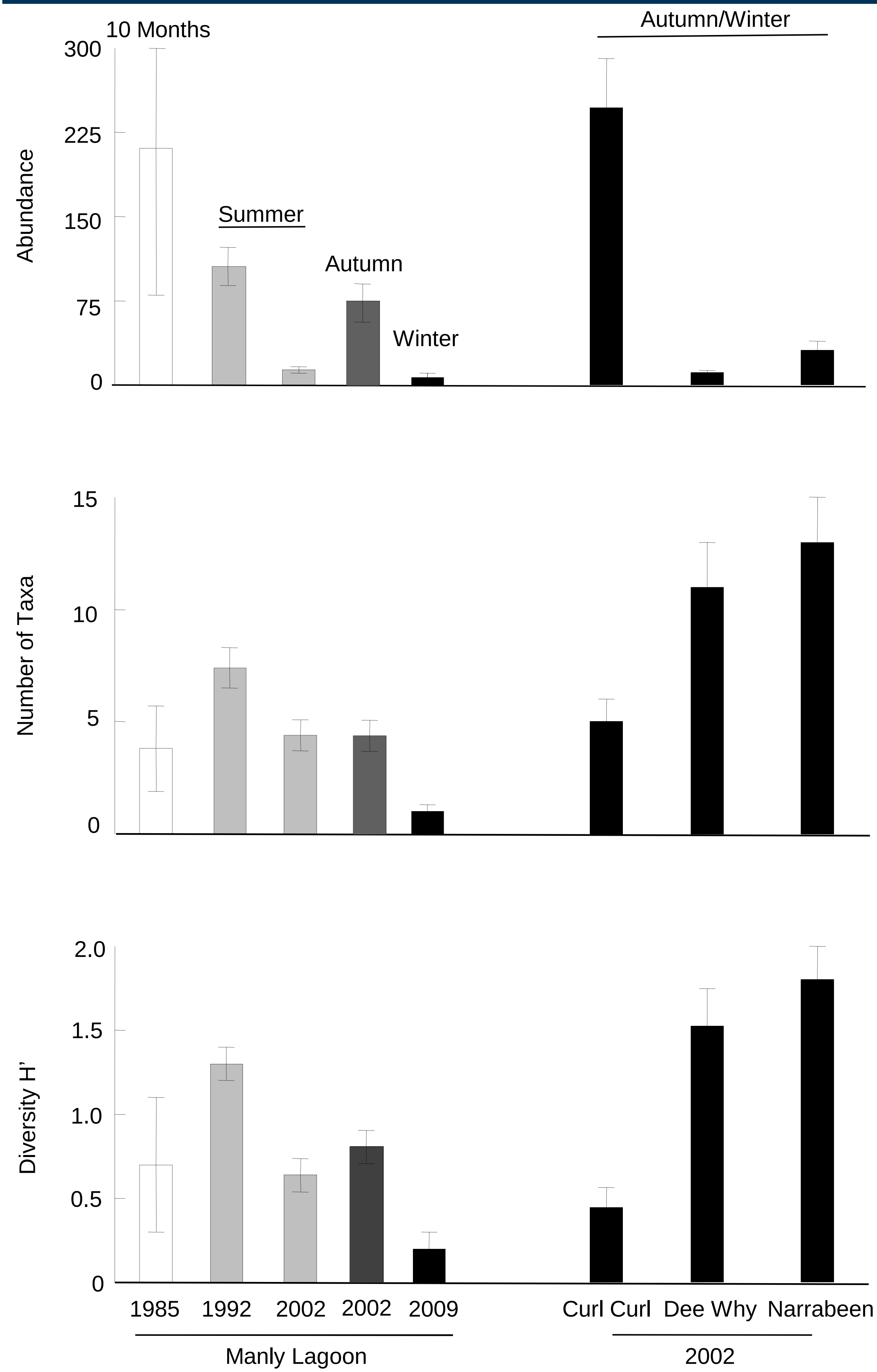

Figure 1: Mean (±SE, n = 5 - 12) abundance, number of taxa and diversity of macrobenthos in urban ICOLLs in Sydney. (Manly data: see text; other lagoons: after Dye and Barros 2005b).

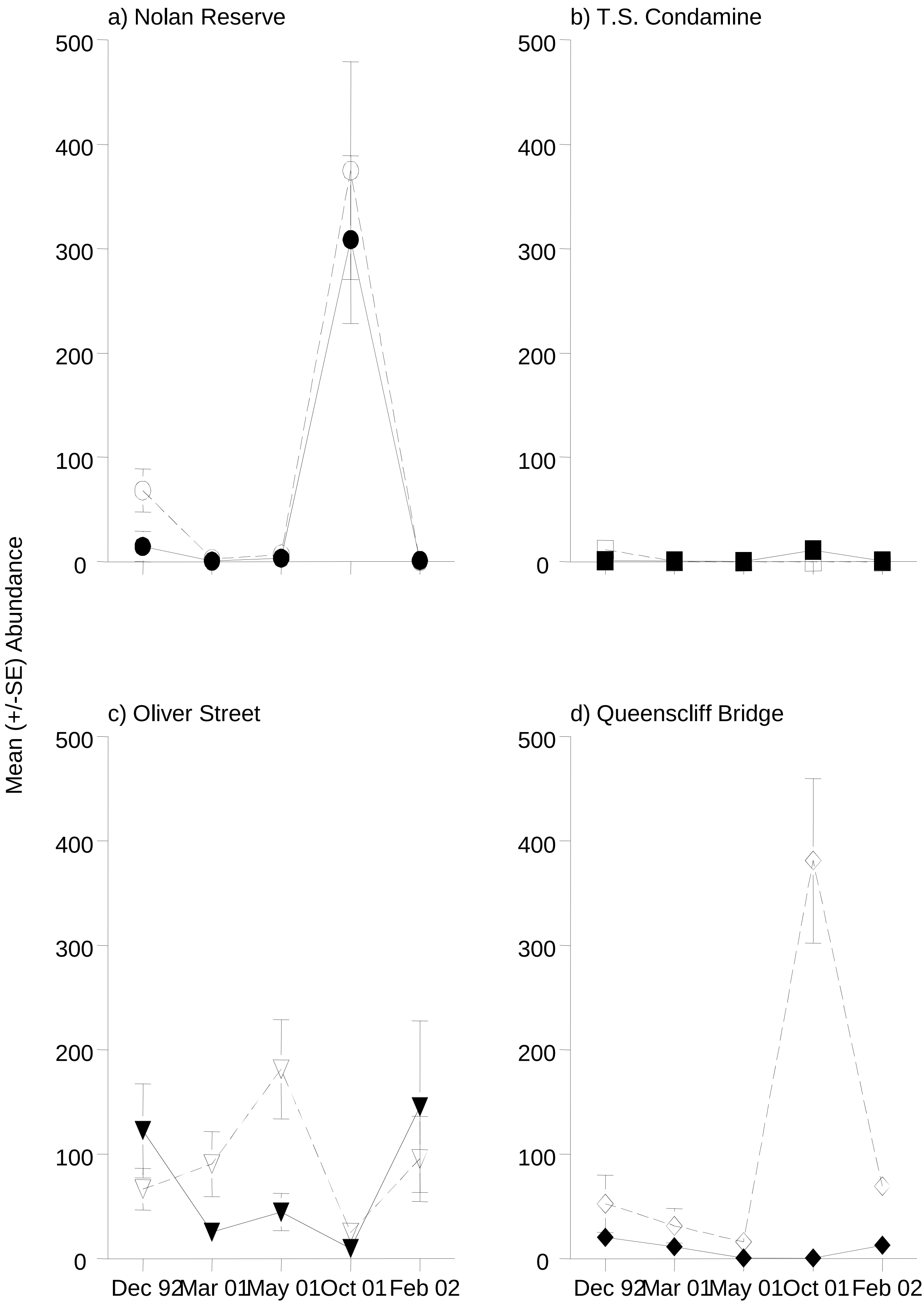

Figure 2: Mean (±SE, n = 8) total abundance of macrobenthos at two in four locations in Manly Lagoon from 1992 to 2002 (The Ecology Lab 2002).

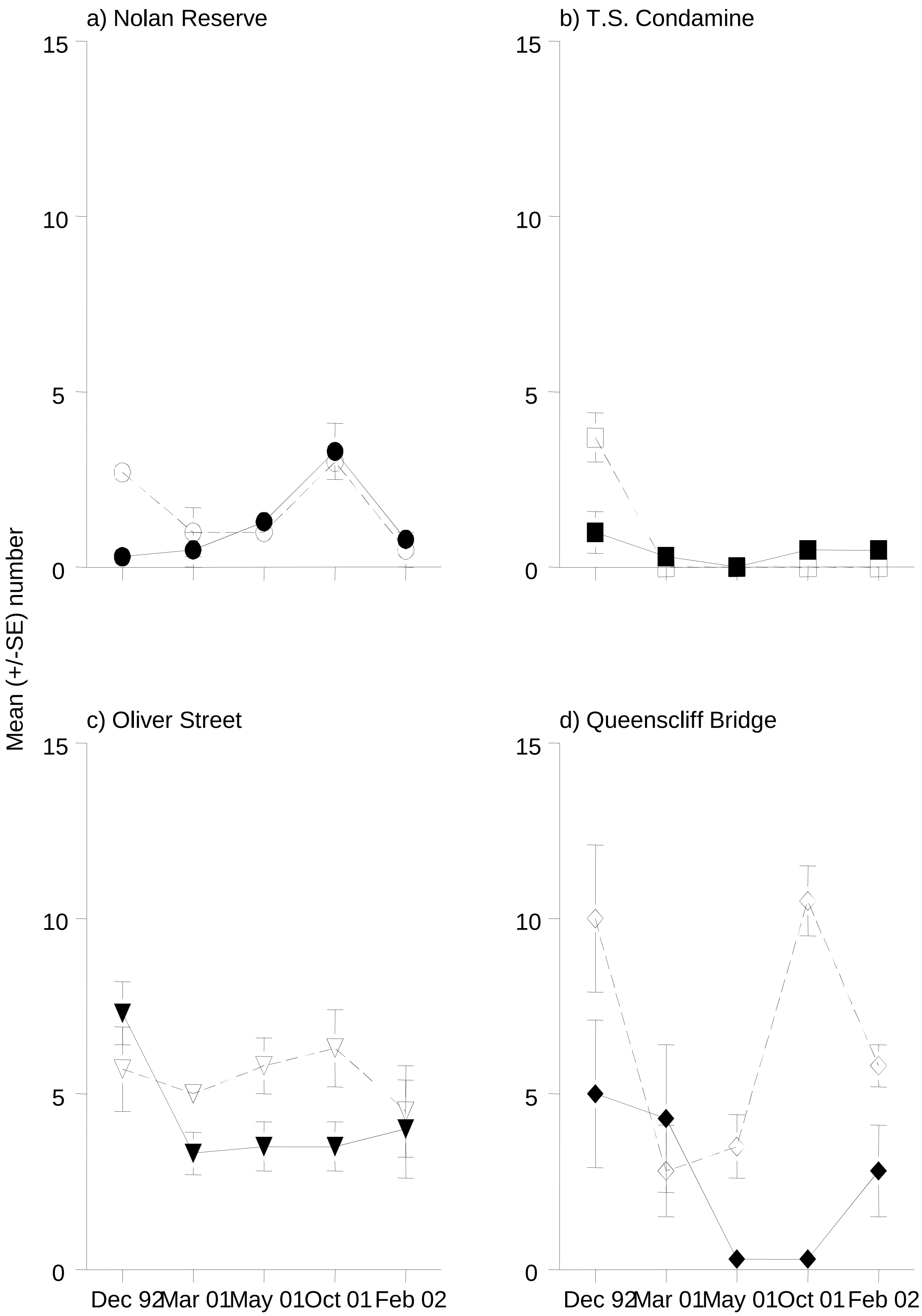

Figure 3: Mean (±SE, n = 8) number of taxa of macrobenthos at two sites in four locations in Manly Lagoon from 1992 to 2002 (The Ecology Lab 2002).

10 Appendices

Appendix 1: Responses to Warringah Council comments on the final report (August 2010).

Appendix 1: Responses (in bold) to Warringah Council comments on final report (August 2010)

- Need an Executive Summary – which should include the last 5 lines of paragraph 3 on Page 5 after (Hale and Heltshe 2008 reference) **Heading amended and additional lines inserted.**
- Second sentence of first paragraph in Summary is too long - **revised**
- "low diversity and abundance of macrobenthos is therefore a strong indicator of a potentially dysfunctional system." – Can you provide some evidence of this as Manly, although heavily impacted by urbanisation seems still relatively functional, ie. supports good fish abundance and diversity – good pop of estuary which is unusually for this type of "polluted" lagoon, some seagrass, support wading bird populations. Eg. we have seen large flocks of cormorants actively feeding in the upper reaches of Brookvale creek on large schools of fish. No algal blooms etc. – **See Page 5 for references**
- **Wiecek and Floyd paper** (Does dredging in ICOLL entrances improve tidal flushing)- In summary where its is stated that dredging and deepening of channel would improve circulation – refer to the Wiecek paper where it was shown that dredging of the entrance did not improve tidal exchange. **Reference inserted in main body of text (see Pages 2 and 10).**
- First paragraph Page ii of Summary - Provide examples where other lagoons that have similar "**impoverished"** benthos have collapsed i.e. gone eutrophic, had algal blooms , fish kills etc. – **see Page 4 for references**
- Page ii of Summary - Provide examples where removal of enriched sediment has improved flow and enhanced recolonisation by macroinvertebrates**. – examples of where removing sediment (enriched or not) has improved flow include Narrabeen Lagoon. This is recommended as a possible course of action for Manly.**
- By dredging we would be increasing the depth which may lower oxygenation and accelerate a decline in ecological condition especially if flow and exchange is not enhanced as Wiecek suggests. --- **dredging depth too shallow for this effect**
- Part 2: Introduction - When discussing the importance of tidal flushing and the cycling of nutrients (in intro) Manly is constantly open to the ocean yet it is suggested that water cycling very poor. If this was true then why have we not seen any algal blooms? Fish kills due to drop in DO or signs of eutrophication. **Numerous studies indicate that tidal exchange is an important factor in flushing of nutrients (e.g. Roy *et al.* 2001). However, it is not the only factor because nutrient loads, prolonged dry periods and other sources of pollution all play a role.**
- Page 2 - 1800 ha? Is this correct -- **corrected to 18 km^2**
- Page 6 paragraph 2 last sentence – "they (Ecology Lab) concluded that the fish kill had no sig effect on the benthos".
    - How is this possible if the benthos was "impoverished". In 1995 it was regarded as "quite good" then in 2001 as impoverished but still it managed to be unaffected by the fish kill episode. Previously in the summary it is suggested that an impoverished benthos is less likely to recover or has very little tolerance for disturbance thus ecological collapse is a valid concern.

Short-term "episodic" events such as that which apparently caused the fish kill, would not necessarily affect benthos since exchange between water and sediment takes longer than the time the event lasted. Prolonged pollution, however, would eventually affect the benthos. It is quite feasible, therefore, for a fish kill to happen without obviously affecting benthos.

- Pg 6 paragraph 3 – provide reference that validates benthos numbers are "somewhat lower in winter than at other times). **This statement was incorrect (numbers may be greater in winter due to recruitment and increased oxygen) and has been corrected with reference in the text.**

- Page 6, last paragraph – Dee Why is not permanently open and Curl Curl opens more frequently than Dee Why. If the argument is that frequency of opening leads to better flushing and nutrients cycling and thus better benthos, then Dee Why with its less frequent flushing, should have more impoverished benthos than Curl Curl. Furthermore Manly is permanently open so its benthos should be in a better condition than Curl Curl and Dee Why as propagule recruitment greater? **The "condition" of any biotic component of a lagoon is the result of a complex of factors of which regular opening is one. Local hydrology, recruitment, nutrient input and pollution levels also play a role and are likely to differ among lagoons.**

- Page 7 paragraph 2 – Expand with more of a discussion on the Central Coast lagoons, eg. how the greater number of taxa etc. defines their ecological condition as "better" or more "robust" than Warringah's lagoons. Do these lagoon cycle nutrients better because of their more diverse benthos or is it because of the nature of the flushing regime or physical entrance management? **This paragraph does not make a judgement as to whether the Central Coast lagoons are ecologically "better" than Manly, only that benthos in Manly is less diverse that it used to be and less than in the other lagoons. As no studies of nutrient cycling have been done in these particular lagoons, it is difficult to make comparisons. However, the extremely impoverished state of benthos in Manly suggests that nutrient cycling may well be less efficient relative to the other lagoons.**

- Page 7 – Conclusion – Will the lagoon collapse? And if it id so impoverished why hasn't it collapsed already? Last sentence says the macrobenthos is largely dysfunctional in its role in trophic and nutrient cycling yet we haven't seen an ecological collapse? **It is not possible to say with certainty that the system will collapse. The benthos data suggest that there is little capacity for absorbing nutrient inputs above their current levels. The system could continue in this state for some time before suddenly entering a distrophic crisis given the right combination of factors**

- Can we do a trial on the benefits of replacing the sediment?
    - Can we investigate the effectiveness of removing the high organic sediments (the dredging of sites 1 and 2) by assessing the degree of recruitment or recolonisation of the "fresh" marine sands exposed by the dredging program by new benthic fauna.? **It is possible to conduct experiments on recolonisation of sediments by benthos. Similar experiments have been done for example in Hong Kong (Wu and Shin 1997, Lu and Wu 2000).**

- 6.3 – Line 3 **"Poor tidal circulation………"** are there any hydrodynamic studies that this assumption is based on and can it be referenced? **No hydrological**

studies on the main body of the lagoon. Wiecek and Floyd (2007) refer only to dredging in the entrance.

- **** 6.4 – Dredging will enhance tidal flow and improve benthos through recolonisation of newly exposed marine sands with incoming propagules from undredged areas and water borne propagules from tidal flow……..this is speculative so can we test it? Assess benthos improvement over time after dredging has occurred? **This can certainly be done by monitoring benthos post-dredging.**

- 6.5 – Doesn't deepening an estuary have negative impacts?

    - **Line 8 in first dot point "good tidal flow will not only flush the lower part iof the lagoon….."** From observations, tidal flow in and out of the low flow pipes is quite "vigorous" it really flows quite strong so how would dredging improve this, would it improve tidal penetration up Brookvale creek? **Dredging may allow a greater total volume of water to be exchanged on each tidal cycle and may increase landward penetration of tidal flow.**

    - Would deepening the lagoon create areas of even lower DO and hence put further pressure on the system? **This would not be expected at the shallow depths proposed for dredging.**