DOES DREDGING IN ICOLL ENTRANCES IMPROVE TIDAL FLUSHING?

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Abstract

Dredging of marine flood tide deltas in selected NSW intermittently closed and open lakes and lagoons (ICOLLs) is carried out by local councils for reasons including reducing foreshore flooding of infrastructure, improving tidal flushing and water quality, and enhancing aquatic biodiversity through increased recruitment. However, due to the difficulty and expense of monitoring these perceived improvements, there is little information available supporting the effectiveness of these dredging programs, with only potential flood mitigation benefits validated via modelling so far. Given the cost of these dredging operations and their potential to negatively impact on the lagoon, the importance of quantifying what improvements are obtained in terms of improving water quality, aquatic biodiversity, and flood mitigation is crucial to making decisions about the overall benefit of the dredging compared to other management alternatives.

As many ICOLLs now have continuous automatic water level recorders, the water level data obtained can be analysed using tidal harmonic analysis to provide a cheap and informative method of comparing tidal response before and after dredging operations to indicate changes in tidal flushing. Case studies from Manly and Narrabeen Lagoons on the northern beaches of Sydney are used to determine what effect dredging has on tidal flushing using the method of tidal harmonic analysis. Dredging programs at both these lagoons remove the intermittent marine sand build up that shoals the lagoon entrance and can eventually lead to closure. The dredging is carried out for the purposes of flood mitigation, enhancing tidal flushing to improve water quality, and increasing aquatic biodiversity. The results of the analyses and the importance of monitoring and review of management programs are discussed.

Introduction

Artificial opening of ICOLL entrances to provide a temporary connection to the ocean occurs at more than 50% of ICOLLs in NSW (Haines, 2006). Such artificial openings are mainly done to limit the impacts of flooding with other reasons including improving water quality and allowing for fish and prawn recruitment. These artificial openings occur through excavation of a pilot channel through the entrance sand bar, which then expands through the outflowing water scouring a larger channel that can remain open for days to months. An extension of this artificial intervention is the dredging (defined as the mechanical removal of sediments in a waterway and disposing of them at a different location) of marine flood tide deltas that build up in the entrance channel to increase the length of time an ICOLL remains open, and assist in successful breakout of the lagoon when the entrance closes. This is a practice that is employed at both Manly and Narrabeen Lagoons on Sydney's Northern Beaches for the purposes of flood mitigation, enhancing tidal flushing to improve water quality, and increasing aquatic biodiversity (Patterson Britton and Partners, 2003a; Cardno Lawson Treloar, 2006).

Although clear benefits in terms of reducing flooding impacts have been shown from modelling changes as a result of entrance dredging to lagoons such as Narrabeen (SMEC, 2002; WBM, 2002a), no information exists on whether the dredging has improved tidal flushing, water quality or increased aquatic biodiversity. Two of the main reasons for this are that it can be hard to gain meaningful results over short periods of time in such highly variable systems, and it can be very costly to rigorously monitor water quality and biota before and after dredging. However, it would be useful to more accurately quantify changes to tidal flushing/water quality and aquatic biodiversity to be able to weigh up the benefits against potential environmental impacts of entrance dredging practices (Box 1) and the high financial costs. One way to more accurately quantify before and after change in entrance tidal flushing is to analyse changes in tidal response though tidal harmonic analysis.

Box 1: Potential environmental impacts of ICOLL entrance dredging

There are a number of potential environmental impacts that can result from dredging entrances of predominantly closed ICOLLs to create predominantly open conditions, ranging from short-term to long-term. Many of these impacts have flow on effects and resultant ecosystem changes.

Short-term impacts can include (the first three points are dependent of the type of sediment and are less likely in predominantly marine sand):

- Increases in turbidity through suspension of sediments that can smoother seagrass beds and clog fish gills;
- Suspension of sediments placing an oxygen demand on the water column resulting in anoxic events and potential fish kills;
- Release of contaminants contained within sediments with resultant water quality and habitat toxicity implications (highly urbanised ICOLLs only);
- Changes in water circulation patterns, tidal conveyance and strength of currents e.g. increased velocities can lead to direct removal of seagrass beds through scouring, and lower low tide levels can impact upon seagrass through increased exposure; and
- Direct removal of bottom-dwelling animals (benthos) leading to a reduction in available food for other species and processes such as nutrient cycling.

Long-term impacts can include:

- Marinisation of the ICOLL and lower fluctuation and/or lessening of environmental extremes in parameters such as salinity that can lead to changes in seagrass and fish communities, such as an increase in species adapted to more stable marine ecological conditions;
- Introduction and establishment of mangroves at the expense of existing foreshore communities such as saltmarsh; and
- A contraction in the areal extent of fringing wetlands due to invasion of the fringes by dryland adapted species as a result of reduced periods of prolonged inundation.

Assessing the tidal response from the entrance dredging - tidal harmonic analysis

To determine whether or not the dredging of the marine sand deltas at the entrances to both Manly and Narrabeen Lagoons result in improved tidal exchange between the lagoon and the ocean, water level data from continuous automatic water level recorders in the lagoons was obtained from Manly Hydraulics Laboratory (Queenscliff Bridge Manly Lagoon, and Ocean St Narrabeen Lagoon). These recorders monitor the rise and fall in lagoon water levels as a response to tides, inflow from rainfall, and oceanic events. Because of the water level variations introduced from rainfall and oceanic events, the use of basic water level data to analyse ‘pure’ tidal variation (due solely to sun, moon and earth interactions and river tidal characteristics) in estuaries can be difficult, particularly if trying to compare differences before and after an event such as dredging. To obtain meaningful results from the water level data that removes the major rainfall and oceanic events, a technique called ‘Tidal Harmonic Analysis’ was used.

Tidal Harmonic Analysis is a technique applied to recorded water levels by which the various constituents or “building blocks” that make up the tide are calculated separately (see Box 2 on tides for details). If all the calculated constituents are added together, a close approximation of the original observed tide is produced. But it is useful to just look at the major tidal constituents that contribute most to the observed astronomical tide to compare how they vary between sites or with time. This provides an indicator of how tidal response may be changing, without the ‘noise’ associated with catchment and oceanic events.

To look at the dynamic behaviour of an estuary, the month to month changes in behaviour of the major constituents are best compared. As major tidal characteristics are related to the monthly lunar cycle, this is really the smallest period that is useful to consider for harmonic analysis. Even the monthly analyses involve a system that is changing over the month, which means that the harmonic results are still only an indicator of response, and not an exact measure. They indicate the average monthly tidal response. In this study, the method of harmonic analysis was extended by taking a monthly (30 day) analysis every 7 days. This provides a ‘moving average’ type set of results that reduce the errors due to non-tidal short-term changes on the water level. However, this method will not reduce errors due to long-term non-tidal effects where they occur over a significant proportion of the 30 day analysis periods.

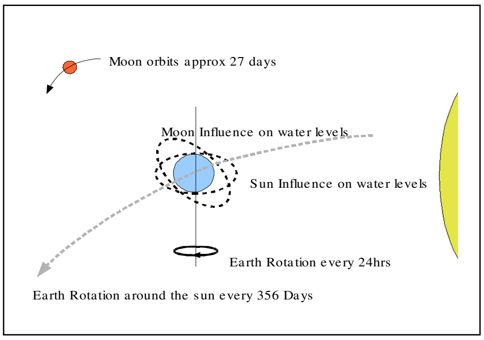
M_2 – the main tidal component

The major constituent of tides that was extracted from each analyses, that show the dominant changes in tidal behaviour is the “principal lunar semidiurnal constituent” (M_2) or main tidal component.

The M_2 constituent represents the dominant lunar influence in conjunction with the earth's rotation on the observed tide and is the major contributor to the tide. In the open ocean, the amplitude of this constituent is around three times the height of the next biggest constituent. Comparing the behaviour of M_2 over time provides an indicator of the tidal penetration into a system. For example, on the results graphs in the following sections, an increase in M_2 means an increase in tidal response and possibly increased tidal flushing.

Box 2: Tides

Tides are the end result of a number of astronomical interactions and the associated gravitational and inertial effects on the earth's surface water. The main influences being:



- the earth's spin,
- the earth's axis tilt,
- the moons orbit around the earth,
- the earth's orbit around the sun, and
- the combination and interactions between all these components and others.

These astronomical features and their interactions each represent a constituent or "building block", which when combined make up the observed tide. It is all these acting simultaneously that generate the tidal water levels we observe such as the twice daily high and low tides, fortnightly tides (where a lake system pumps up and down at spring and neap respectively) and the roughly six monthly King Tides, amongst others.

Understanding ICOLL entrance conditions and its control on tidal flushing

The condition (degree of openness) of the ICOLL entrance determines the tidal behaviour of the system, with maximum conveyance of the tide occurring in an open ICOLL when the entrance is well scoured. Increased tidal conveyance means that more water is moving in and out of the ICOLL every high/low tide cycle (i.e. the tidal prism is increased), which means that the tidal flushing capability is therefore also increased. However, whether or not this translates into improving ICOLL water quality greatly depends on factors such as waterway bathymetry, internal mixing, how much and for how long tidal flushing is increased (residence times), as well as the type and loads of pollutants entering the ICOLL from the catchment and how they are processed within a system (e.g. denitrification processes).

The condition of the ICOLL entrance is determined by four main factors: i) wave climate, ii) discharge of floodwaters, iii) flood tides, and iv) ebb tides. However, other factors such as longshore drift also play a role. To comprehensively understand a tidal harmonic analysis data series, it is therefore important to also have an understanding of wave climate and discharge of floodwaters over the same time period. Wave climate can be inferred by measured wave height. Flood discharge is expensive to measure, and therefore rainfall is used as an indicator of freshwater flow potential in this study. However, in other systems where a rain gauge may not be in close proximity, or for large river catchments where relatively uniform rainfall over the catchment cannot be assumed, this indication may not be as accurate.

Wave height data

Significant wave height data (designated as 'Hsig') for Sydney was obtained from MHL's waverider buoy located offshore of Sydney for the study period. Hsig is the average height of the waves which comprise the highest 33% of waves in a given sample period (typically 20 to 30 minutes). As the significant wave height is an average of the largest waves over a recording period, it should be noted that some individual waves might be much larger than this.

This value is used in coastal and marine engineering because it is close to what a person will 'measure' by observation, without the benefit of time series data. Also, in many applications of wave data, larger waves are more "significant" (important) than smaller waves. For example, the larger waves in a storm cause the most erosion on a beach and can be responsible for causing considerable infilling of ICOLL entrances with marine sand. Direct sand infilling from littoral drift is linked to wave height (climate), and the potential sediment infill due to flood tides is also enhanced with increased bed stirring, as increased wave height leaves sediment suspended and more easily transported. This process can greatly exacerbate the closure of ICOLL entrances. This then has implications for tidal flushing, which can be reduced as the entrance channel shoals up with sand.

It is important to note that the direction of wave climate and location of near shore sand bars can have an effect on the degree that storm waves exacerbate sand infilling of ICOLL entrances. For example, if the entrance is protected by a headland immediately north or south, waves from this direction will have reduced height and energy at the shoreline through losses associated with refraction around the headland. Hence, two separate storms of the same Hsig with wave climate from two different directions, may not lead to the same level of infilling.

Rainfall data

Daily rainfall data for Middle Creek located in Narrabeen Lagoon catchment, and Allambie Heights located in Manly Lagoon catchment, was obtained from MHL over the study period. Rainfall in an ICOLL catchment can have a considerable bearing on entrance conditions, with relatively large inflows from heavy rainfall having the ability to scour large quantities of marine sand and transport it back to the near shore ocean environment. Conversely, drier periods of below average rainfall, such as has been experienced over the past 5 years over much of south-eastern Australia, can result in ICOLL entrances filling up with marine sand due to a decrease in scouring floodwaters, leading to a greater frequency and longer duration of entrance closure, which has been the case at a number of south coast ICOLLs (e.g. Burrill Lake).

In the comparisons to follow, the daily rainfall was accumulated into weekly rainfall, allowing for the fact that generally a single day rainfall event will not cause extensive scouring of the entrance to an ICOLL unless of very high intensity. Large runoff events are associated with rainfall of sufficient duration to saturate the catchment, then continued rainfall that will result in a greater proportion of water moving across the land surface as runoff rather than infiltrating into the soil profile.

Narrabeen Lagoon entrance dredging

Entrance dredging works

Narrabeen Lagoon is the largest of four ICOLLs located on the northern beaches of Sydney, having a surface area of $2km^2$ and a catchment area of approximately $55km^2$. The lagoon lies entirely within the Warringah Local Government Area, with the northern foreshore forming the boundary with Pittwater Council. A narrow channel approximately

2km long and typically 150m wide links the main body of the lagoon to the ocean. The lagoon is divided geographically into three distinct areas: the western basin, the central basin, and the eastern channel (Figure 1) (WBM, 2002b). The entrance to Narrabeen Lagoon is intermittently filled with marine sediment when the amount of sand moved into the lagoon entrance by the incoming tide exceeds the amount of sand removed by the outgoing tide. Prior to development, it is thought the lagoon was mostly closed to the ocean (Gordon, 2006).

Due to increasing urbanisation leading to water quality problems and foreshore flooding of properties, a policy of opening the lagoon entrance through entrance dredging works has been practiced since 1975. Eight major entrance dredging works have occurred to date roughly every three to four years, with volumes of material removed up to about 45,000m^3 and costs up to $800,000. The entrance dredging operations are a key action out of the Narrabeen Lagoon Floodplain Management Plan to minimise flooding to surrounding properties. The works are carried out according to the Narrabeen Lagoon Entrance Management Policy (Warringah and Pittwater Councils, 1996), which is currently under review.

The entrance dredging works involve the excavation of marine sediment from the entrance area of the lagoon, on the eastern and western sides of Ocean Street Bridge (Figures 2 and 3). The marine sediment that is excavated is firstly stockpiled and left to drain, then transported by truck to Collaroy/Narrabeen Beach where it is spread as minor beach nourishment (Figure 2).

Narrabeen Lagoon results of tidal harmonic analysis

Continuous water level data was available for assessment for the last four entrance dredging episodes. All four dredging episodes show a clear increase in tidal response of up to 8cm in the main tidal component (M_2), indicating that the dredging improves tidal conveyance into the lagoon. This would improve tidal flushing of the lagoon, particularly the eastern channel and to some extent the central basin. However, it should be noted that an improvement in tidal flushing may have limited benefits to water quality in the western basin of the lagoon, due to long flushing times (75 days for a mean spring tide, 110 days for a mean neap tide) and water quality largely being controlled by the quality of catchment runoff (WBM, 2000).

Detailed explanations of results for each dredging episode are discussed over the following pages, while a complete data series is provided in Appendix A. For all analyses, the top graph shows raw water level data from the Ocean St recorder. Second graph shows 7-day accumulated daily rainfall from Middle Ck, third graph shows the dredging period, the fourth graph shows the M_2 tidal component calculated from a 30 day analysis every 7 days, and the last graph shows significant wave height (Hsig). Data gaps in the Hsig time series indicate failure of instrumentation.

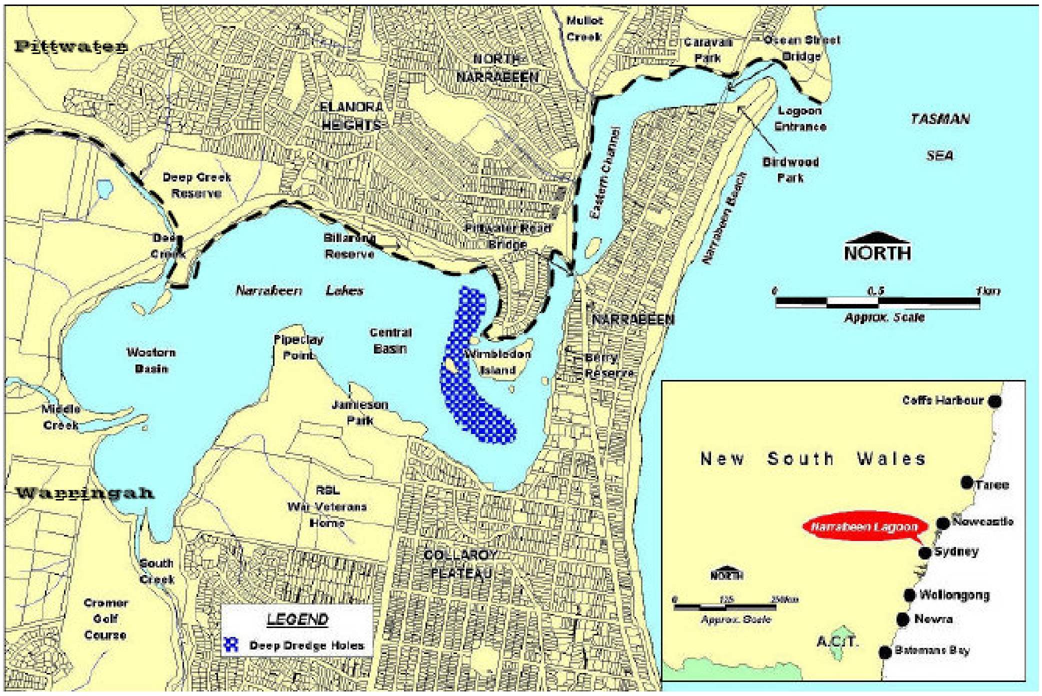


Figure 1: Locality map of Narrabeen Lagoon showing the three geographically divided distinct areas of the western basin, the central basin, and the eastern channel (figure from WBM, 2002b).

Figure 2: Extent of Narrabeen Lagoon entrance dredging area (left shot) (taken from the 2006 REF compiled by Cardno Lawson Treloar). The right photo is of sand nourishment on Collaroy/Narrabeen Beach supplied from the dredged marine flood tide delta.

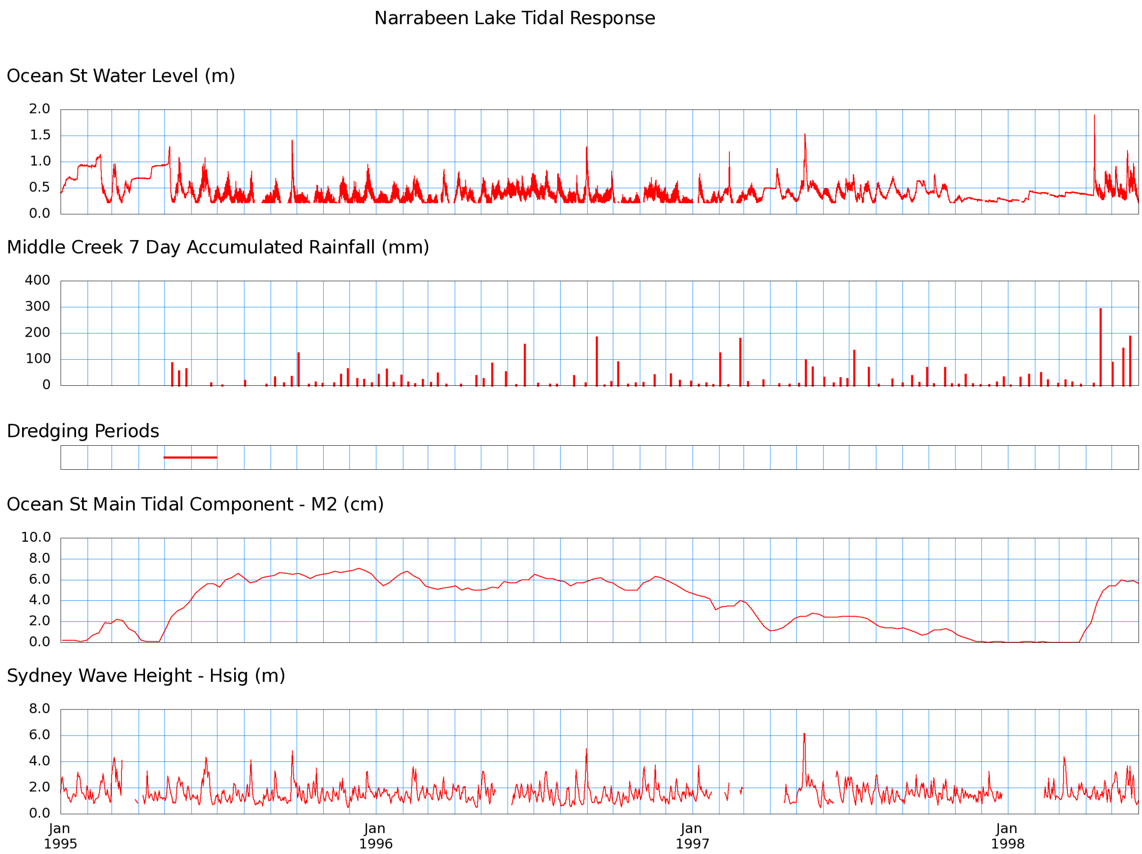
Figure 3: Dredging works in progress west (left photo) and east (right photo) of Ocean St Bridge in Narrabeen Lagoon.

1995 dredging

The 1995 dredging started in May and ran through till July. An immediate increase in tidal response is indicated by the rise in the main tidal component (M_2) from 0cm to over 6cm during and after the dredging. This indicates an improvement in tidal flushing. This improvement lasts till around November 1996, where M_2 starts to dip from 6cm until entrance closure in December 1997. The rise in M_2 in April 1998 associated with significant rainfall is discussed in the 1999 dredging analysis.

Two significant wave height (Hsig) events of about 4m in quick concession in November 1996, with a third event in January 1997, correlate with the dip in M_2. A large storm with a Hsig of over 6m occurred in May 1997, which corresponds to M_2 continuing to drop steadily afterwards until closure in December 1997. These storms would have been responsible for exacerbating the marine sand infilling of the entrance.

As the rainfall recorder only started operation at the end of April 1995, rainfall data could not be included before the dredging begun and correlations cannot be made between the rainfall and M_2. However, as the lagoon water level before dredging was significantly elevated, this would have helped to create a significant breach with associated scouring, most probably initiated by the dredging or significant possible rainfall not logged, which has helped raise M_2 during and after the dredging.



1999 dredging

The 1999 dredging (38,000m^3) started in April and was completed by July. After dredging was completed, M_2 significantly increased from around 2cm to just under 8cm, indicating a strong tidal response and likely improved tidal flushing. Significant rainfall and high water levels leading to breaching of the entrance occur in the months prior to dredging, which would have helped raise M_2 in conjunction with the dredging.

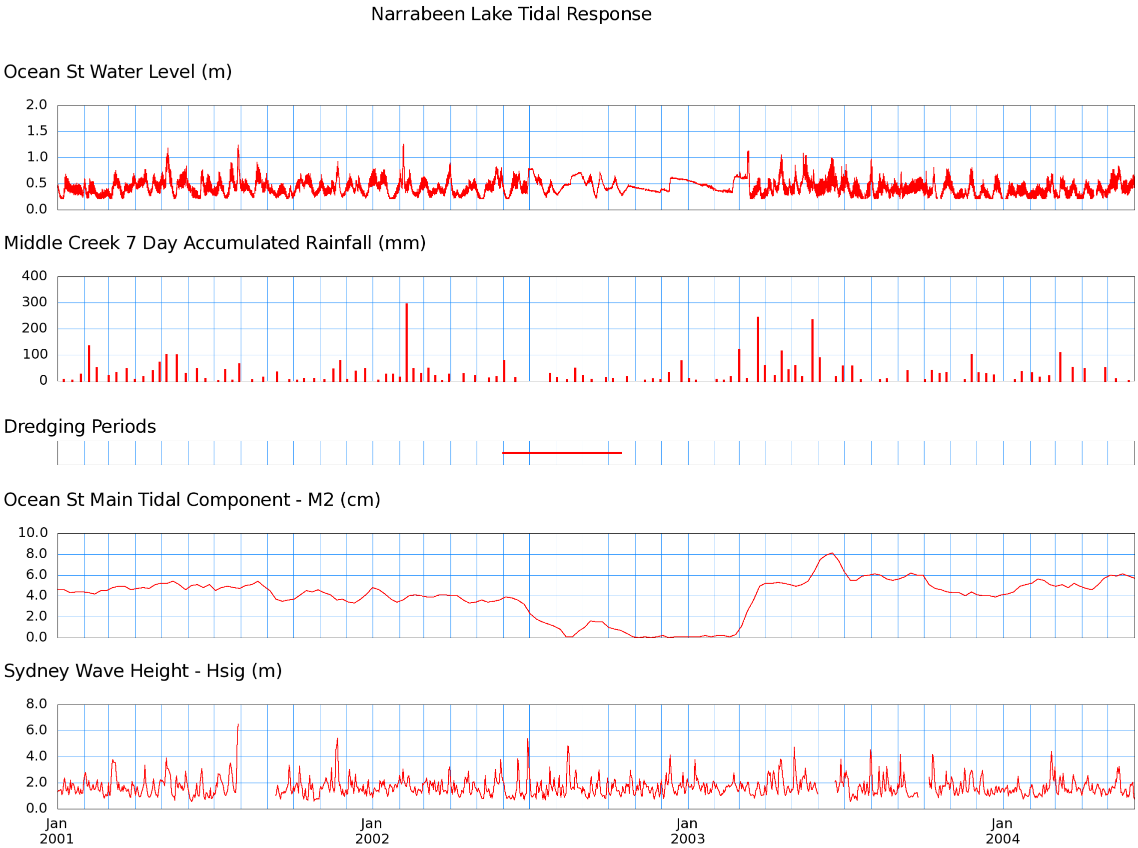
After the initial rise, three episodes of wave activity where Hsig is 4m or greater occur from July to September 1999, and appear to be responsible for a rapid decrease in M_2 from 8cm to 4cm. A period of high rainfall then corresponds to a recovery in M_2 of back to around 6cm, which lasts until June/July 2000. At this point lower rainfall conditions prevail and three Hsig events of 4m occur and M_2 drops to just under 2cm in November 2000. Significant rainfall events then correspond to a recovery in M_2 to around 4-5cm that is maintained until June 2002, which is the start of the next entrance dredging.

The other notable change to tidal response occurs in May 1998, where M_2 increases to 6cm as it did after the 1995 dredging episode. This corresponds to a period of significant rainfall and high water level of nearly 2m, which would have generated floodwaters and significant scouring potential resulting in removal of sand from the entrance channel. After the large rainfall events, M_2 drops to below 4cm but is again raised to just under 6cm by another significant period of rainfall in August. This is despite significant wave activity where Hsig is consistently 3-4m over a period of about four months. A period of low rainfall begins in September, which corresponds to a rapid drop in M_2 in October until entrance closure in December 1998. This shows that the scouring effects of heavy rainfall floodwaters can increase tidal response to the same degree as the entrance dredging, but in this case, the increase is short lived compared to the dredging.

2002 dredging

The 2002 entrance dredging (38,000m^3) started in June and was completed in October. During the dredging operation around the end of June 2002, significant storms with Hsig greater than 5m occurred. These storms correspond to a dip in M_2 from 4cm to 0cm with entrance closure around August 2002. The effect of the storms on causing the dip in M_2 is supported by documentation of significant infilling of the completed dredged area occurring, in the post completion report for the 2002 dredging (Patterson Britton & Partners, 2003b). A survey of the completed dredged area had been completed just prior to the storms and another survey was carried out after the storms to assess their impact. The surveys showed that about 4000m^3 of sand infilled the entrance as a result of the storms over one weekend (Patterson Britton & Partners, 2003b).

After completion of the dredging in October, the lagoon remained closed until enough rainfall occurred to raise the water level to the artificial opening trigger level. This occurred in March 2003 and was followed by consistent rainfall until June resulting in M_2 increasing to 8cm.



2006 dredging

The 2006 entrance dredging (45,000m^3) started in late September and was completed in early December. After completion of the dredging, M_2 initially decreased slightly from just under 6cm to just over 4cm in February 2007, before increasing in response to heavy rainfall to a maximum of 8cm in June.

The water level and M_2 show that the lagoon is predominantly closed from August 2005 to August 2006. The lagoon is opened through artificial breaching four times over this period, with the first three breachings at water levels of about 1.2m having no effect on M_2 due to rapid entrance closure. This correlates to a period of low rainfall with no significant rainfall events. It is only after the last artificial breaching in early September where rainfall raised the lagoon water level to about 1.5m, 0.3m above the normal opening trigger level, that a noticeable effect on M_2 is shown. This breaching was responsible for scouring about 6000m^3 of sediment from the entrance and resulted in the original entrance dredging amount proposed being reduced by the same amount (Warringah Council, 2006). This highlights the importance of setting opening trigger levels as high as possible to maximise scouring potential where this type of intervention is needed for flood mitigation purposes.

Significant storms, with Hsig up to nearly 6m, were experienced over the June 2007 long weekend and result in M_2 decreasing to below 6cm by August. Cameron and Morris (2007), who also are presenting a paper dealing with Narrabeen Lagoon entrance dredging at this conference, surveyed the entrance area shortly before and after these storms. Initial analyses report sediment infilling of around 2000m^3 on the flood shoal east of Ocean St Bridge (with corresponding shoal infilling west of Ocean St Bridge also found, but yet to be confirmed if all due to the storm), which would have been responsible for the drop in M_2. It is highly likely that the scouring effect of floodwaters from the significant amount of rainfall experienced at the same time as the storms would have countered the amount of infilling from large waves, which could have potentially negated the dredging.

Narrabeen Lake Tidal Response

Manly Lagoon entrance dredging

Entrance dredging works

Manly Lagoon is an ICOLL situated at the boundary of Warringah and Manly Council Local Government Areas in Sydney's northern beaches area. It has a catchment area of 18km^2 and a waterway area of 0.1km^2. The catchment is highly urbanised with about 60% of land use considered urban. The remaining land use is open space which includes two golf courses and playing fields adjacent to the lagoon. The Lagoon has a restricted outlet to the sea through a constructed low flow channel approximately 3.3m wide by 1.8m high at the northern end of Queenscliff Beach that allows permanent tidal exchange.

Historically, the lagoon's fringing wetlands where reclaimed for rubbish dumps and are now playing fields (Patterson Britton and Partners, 1995). This has resulted in a reduced tidal prism, and importantly flood storage volume. This reduced flood storage volume combined with the permanent tidal exchange through the low flow pipes, results in the loss of scouring potential that occurs when ICOLL water levels are raised high enough to breach the entrance berm and open the ICOLL to the ocean.

The Manly Lagoon Estuary Management Plan completed in 1998 describes the lagoons poor water quality as the fundamental environmental issue and as such water quality remediation is the primary focus of the Plan and its management strategies. One of the strategies outlined in the Plan to address water quality (and other) issues is for selective dredging/deepening of the lagoon. To implement this strategy, five sites within the lagoon have been identified for dredging works and are currently under consideration, including the entrance.

Since the adoption of the Plan in 1998, entrance dredging has occurred three times, with costs as high as $120 000 for dredging and disposal. The works involve the removal of marine sand (ranging from 1500m^3 to 6300 m^3) that has entered the lagoon under wave and tidal action upstream of the Queenscliff Bridge (Figure 3). Dredged sand is then used to nourish Manly Ocean Beach. The Statement of Environmental Effects (Patterson Britton and Partners, 2003a) for the works notes the benefits of the dredging as "The removal of marine sand would improve tidal exchange between the lagoon and the ocean, remove any restrictions to fish passage, and avoid continued sand migration upstream smothering aquatic vegetation".

Manly Lagoon results of tidal harmonic analysis

Continuous water level data was available for assessment of all three entrance dredging episodes. Unlike Narrabeen Lagoon, the dredging episodes do not show a clear increase in tidal response in the main tidal component (M_2). This indicates that the dredging is unlikely to improve tidal flushing of the lagoon. Patterns are evident for M_2 changing in relation to significant wave height (Hsig) events and large rainfall periods, but are not always as clear as they were for Narrabeen Lagoon. The low flow pipes that allow permanent tidal exchange into the lagoon appear to result in a fairly constant tidal regime, that is not noticeable effected by dredging, but can be lowered short term by sand infilling exacerbated by large waves, and increased short term by the scouring effects of heavy rainfall-induced flood discharges.

Detailed explanations of results for each dredging episode are discussed over the following pages, while a complete data series is provided in Appendix B. For all analyses, the top graph shows raw water level data from the Queenscliff Bridge recorder. Second graph shows 7-day accumulated daily rainfall from Allambie Heights, third graph shows the dredging period, the fourth graph shows the M_2 tidal component calculated from a 30 day analysis every 7 days, and the last graph shows significant wave height (Hsig). Data gaps in the Hsig time series indicate failure of instrumentation.

Figure 3: Marine sand built up in the entrance area of Manly Lagoon before dredging, August 2005 (Top left). Dredging is done through a bulldozer pushing sand up against the shore then piled up by an excavator (Middle left). After the marine sand has been dredged, August 2006, showing the sand stockpile on the shore. Discoloration is due to estuarine fines (Bottom left). Signage produced by Manly Council illustrating the location of dredging, scope of works and the benefits of the dredging (right).

2001 dredging

The 2001 dredging (1500m^3) started in August and ran through till early December. M_2 peaks twice over the displayed record indicating improvements in tidal flushing, both times corresponding with significant rainfall events (April/May 2001 and February 2002). There is a significant reduction in the tidal response in September after dredging started, but the cause has not been determined. There is no overall improvement evident comparing M_2 before and after dredging. On average over the graphed time period below, M_2 appears to fluctuate at around 4cm, such as from April to December 2000. It is slightly lower over the period from July 2002 to January 2003, possibly due to low rainfall and two Hsig events of about 5m over this period of time. Dominant increases in M_2 correspond to rainfall events only.

2003 dredging

The 2003 dredging (1500m^3) started in September and ran through till early December. M_2 peaks twice over the displayed record. The first corresponds to a significant period of rainfall in May 2003, where M_2 rises to over 6cm, with the second in May 2004 where M_2 rises again to about 6cm but does not correlate with any significant rainfall or dredging. There is no change in M_2 evident when comparing before and after dredging, which stays fairly constant at around 3cm. The three times when M_2 drops to about 2cm or under (March and July 2004, and April 2005) are all associated with Hsig events of 4-5m.

Over this period, we see the only closures/significant tidal restriction of the lagoon, which occur in March 2004 and August 2005 as shown on the Queenscliff Rd water level data plot. Due to the short term of the closure/restriction, a zero M_2 is not recorded due to a month long analysis period.

2006 dredging

The 2006 dredging (6300m^3) commenced mid April and was completed in two stages, the last finishing at the beginning of October. M_2 peaks twice over the period, corresponding to the start of the dredging in April 2006 (M_2 = 7cm) and towards the end of the data series in June 2007 (M_2 = 7cm), which corresponds to significant rainfall. It is doubtful that the dredging is responsible for the increase in April, as M_2 peaks right at the start of dredging, and throughout the first stage of dredging M_2 decreases to 4cm and remains at this level after the dredging. After the second period of dredging, that also coincides with a significant rainfall event, M_2 decreases to 2cm in November 2006, possibly due to a period of about six medium Hsig events. As with Narrabeen Lagoon, the significant storms over June where Hsig reaches about 6m and subsequent Hsig event of well over 4m in July correlate with M_2 decreasing to about 2cm.

As with the other two dredging episodes, it appears unlikely that the dredging has lead to any increase in tidal response.

Conclusions

The results from the tidal harmonic analysis illustrate the differences in response to dredging, as well as from rainfall and storm events, between Narrabeen and Manly Lagoons. While a clear pattern of improvement in tidal response can be seen after the dredging at Narrabeen Lagoon, this is not demonstrated for Manly Lagoon. Hence, the entrance dredging program at Narrabeen Lagoon is likely to have tidal flushing as well as flooding benefits (albeit these can be short lived). However, at Manly Lagoon tidal flushing benefits are not apparent, as the low flow pipes are a major control on tidal response and limit the variation as a result of disturbances such as dredging and storm waves.

Another important result is that rainfall events which result in significant floodwaters and high lagoon water level, have the ability to increase tidal response to the same degree as the dredging at Narrabeen Lagoon, and appear to be the only means of increasing tidal response at Manly Lagoon. This also highlights the importance of setting ICOLL opening trigger levels as high as possible to maximise scouring potential where this type of intervention is needed for flood mitigation purposes.

Monitoring the effectiveness of a particular management approach is crucial to determining whether or not the desired outcomes are being met. The results from this study will help both the Narrabeen Lagoon and Manly Lagoon Estuary Management Committees weigh up the benefits versus costs and potential benefits and impacts of the dredging programs.

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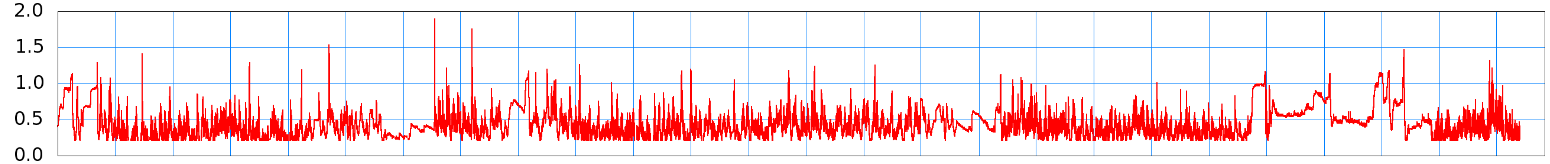
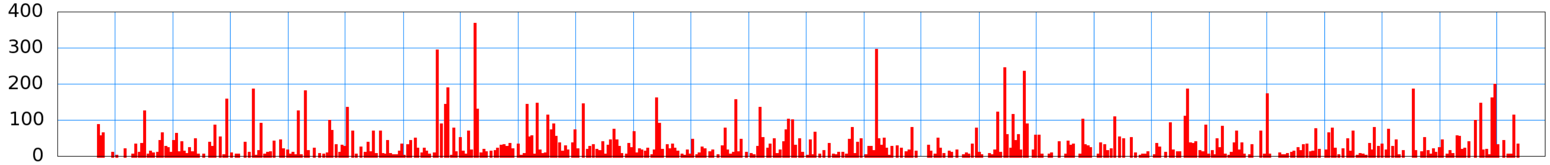
Appendix A – Complete data series for Narrabeen Lagoon

Ocean St Water Level (m)

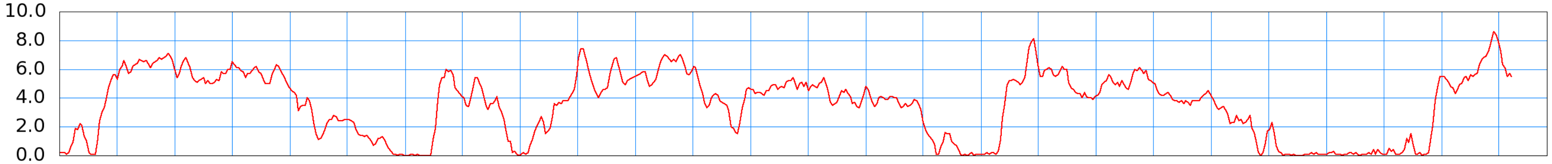


Middle Creek 7 Day Accumulated Rainfall (mm)

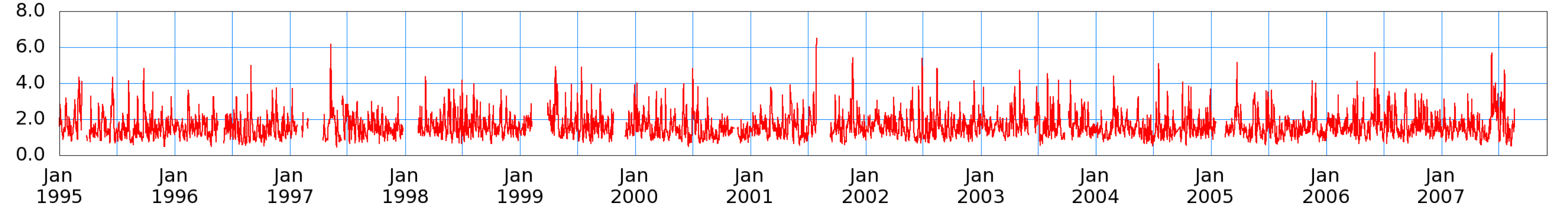


Dredging Periods

Ocean St Main Tidal Component - M2 (cm)

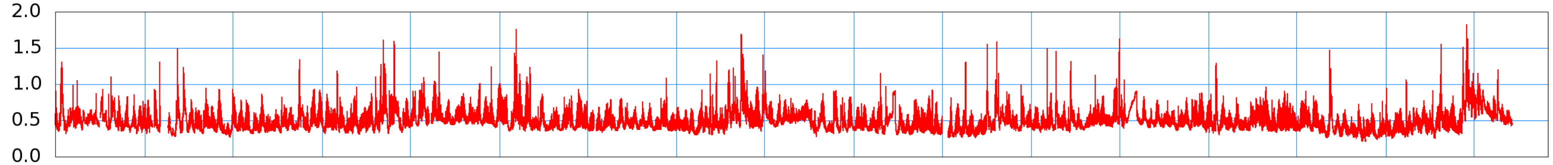


Wave Height - Hsig (m)

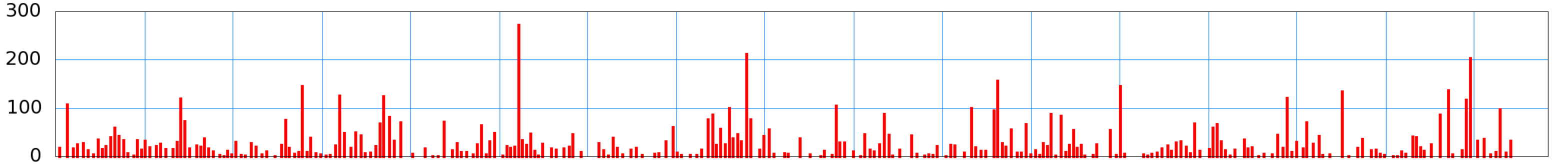


Appendix B - Complete data series for Manly Lagoon

Queencliff Rd Water Level (m)

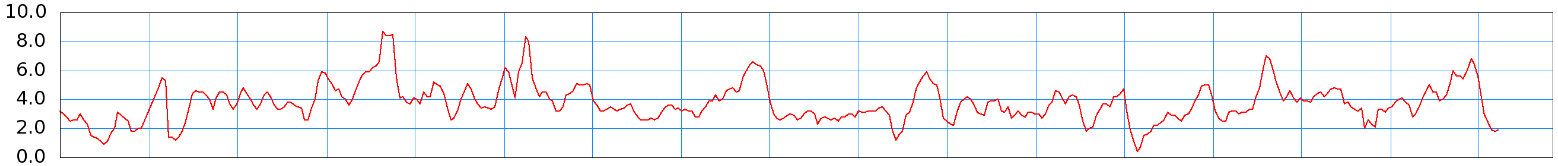


Allambie Heights 7 Day Accumulated Rainfall (mm)



Dredging Periods

Queenscliff Main Tidal Component - M2 (cm)



Sydney Wave Height - Hsig (m)