GROUNDWATER IMPACTS ON A MOSTLY CLOSED, DISPLACEMENT DOMINATED ICOLL

P Haines[1], M Barry[1], R Holmes[1], J Crawford[2]
[1]BMT WBM, Brisbane, QLD
[2]Warringah Council, Dee Why, NSW

Abstract

Little is known regarding the impacts of groundwater on the unique hydrological cycles of ICOLLs. It is hypothesized that groundwater would play a relatively minor role in larger mixing-dominated ICOLLs, but could be potentially more significant in smaller and narrower displacement-dominated ICOLLs.

An example of the latter is Curl Curl Lagoon on the northern beaches of Sydney. Groundwater inputs and interactions for Curl Curl Lagoon have been deduced from analysis of rainfall and runoff data and corresponding water level data within the lagoon. For periods of low water level in the lagoon, groundwater inflows to the waterbody were found to be high. As lagoon levels increase (due to groundwater and periodic catchment runoff), the groundwater inflows to the lagoon subside due to reduced hydraulic gradient between groundwater and lake levels, as evidenced by the progressively decreasing rate of water level rise. Under very high water levels, there is even the potential for groundwater to be recharged from the lagoon via a reverse hydraulic gradient.

The implications of these findings are particularly important for Curl Curl Lagoon as the adjoining lands from which the groundwater is drawn are reclaimed land. In particular, the concept of maintaining an open lagoon entrance to maximise flushing of the estuary simply maximises the hydraulic gradient, which in this case may change the hydraulic character of the lagoon.

Two-dimensional modelling was used to investigate implication of modified hydrological behaviour at Curl Curl Lagoon, and associated ramifications for groundwater inflows. A scenario of lagoon dredging was considered to promoting tidal flushing, along with an option of maintaining higher water levels via a weir structure. Modelling found that neither option provided significant advantage for water quality within the lagoon.

While the Curl Curl Lagoon situation is considered to be relatively unique, this example highlights that ICOLLs continue to be one of the most complex but still poorly understood estuarine environments, and manipulation of their structure and hydraulic behaviour continues to be done with limited appreciation of the full impacts of such actions.

Introduction

ICOLLs in NSW

Intermittently Closed and Open Lakes or Lagoons (ICOLLs) are relatively common coastal features along the NSW coastline. ICOLLs are geomorphologically unique in that the entrances connecting them with the ocean are sometimes open and sometimes closed. There are about 70 ICOLLs in NSW of size greater than one hectare, of which approximately 70% are closed for the majority of the time (Haines et al., 2006). The majority of ICOLLs in NSW are located along the south coast, where the coastal character is dominated by small beach compartments, separated by rocky headlands, and relatively small catchments due to the proximity of the Great Dividing Range to the coast (Haines, 2006).

Displacement-Dominated ICOLLs

The waterway shape of an ICOLL can have a significant influence on its hydrodynamics, including tidal mixing and wind-driven circulation. Relatively linear ICOLLs are known as 'displacement-dominated' ICOLLs, whereas more circular ICOLLs have been termed 'mixing-dominated' (Haines et al., 2006).

Displacement-dominated ICOLLs are named as such because catchment runoff that enters the lagoon tends to push out, or displace, the resident water in the system. Haines et al. (2006) showed that tidal exchange was up to 10 times more effective in mixing-dominated ICOLLs compared to displacement-dominated ICOLLs for a comparable waterway area. This means that displacement-dominated ICOLLs are naturally more sensitive to inputs, with generally less capacity to accommodate and assimilate pollutants.

Curl Curl Lagoon, Sydney

Curl Curl Lagoon is a small ICOLL located within Warringah Local Government Area, in the Sydney northern suburbs. The lagoon's surface area is approximately 6 ha and sits within a catchment covering almost 440 ha. The predominant land uses in the catchment are residential and industrial. The majority of catchment runoff enters the upstream end of the lagoon through Greendale Creek but there are also a number of stormwater pipes that feed directly into the lagoon around the foreshores (BMT WBM, 2012).

From 1951 until the mid-1970s, the land immediately adjacent to the creek and lagoon system was reclaimed. The reclaimed areas around the lagoon now support a number of sports fields that are of regional importance. This modified the shape of the system, making it more displacement-dominated. Indeed, the resulting narrow and elongated shape of Curl Curl Lagoon makes it one of the most displacement-dominated in NSW, and as such, it is recognised as one of the most sensitive ICOLLs to external inputs (Haines et al., 2006; Haines 2006).

Water quality in Curl Curl Lagoon is generally poor, as a result of frequent stormwater runoff from the urbanised catchment as well as inflows from potentially contaminated groundwater (PBP, 2005).

Objectives of this Paper

This paper explores the impact of groundwater inflows on Curl Curl Lagoon hydrology. Groundwater is generally not considered to have a significant effect on ICOLL hydrodynamics because the groundwater inflows would generally be very small compared to the resident volume held in the waterway and the magnitude of catchment runoff. Curl Curl Lagoon is different in this regard, as its strong displacement-dominance means it has a small waterway area (and volume) compared to the potential for groundwater inflows (which is largely a function of the lagoon perimeter). Also, the progressive infilling of the lagoon has resulted in relatively steep banks, which provide an opportunity for significant groundwater gradients that can drive groundwater inflows to the lagoon.

Information presented in this paper is largely drawn from a stormwater and estuary modelling study of Curl Curl Lagoon, wherein it was discovered that groundwater contributions need to be included as modelling inputs in order to meet model validation requirements (BMT WBM, 2012). Modelling of Curl Curl Lagoon consisted of a stormwater model of the catchment using MUSIC, and a hydrodynamic model of the lagoon and Greendale Creek, using TUFLOW. Indeed special algorithms were incorporated into the TUFLOW software in order to represent the groundwater inflows using the relationships presented in this paper.

Assessment of Measured Hydrologic Data

Water Level and Volume

A water level gauge, located under Griffin Road bridge, is maintained by Manly Hydraulic Lab (MHL) and provides a record of lagoon water level, at 15 minute intervals, dating back to August 1991. A water level-volume relationship for the lagoon was calculated using a detailed hydrographic survey of the lagoon. The time-history of water level data was converted to a volume to enable a volumetric water balance assessment to be carried out.

From this dataset, it can be determined when the lagoon entrance was open and influenced by tides, when the entrance was closed and re-filling (referred to as a 'recovery', or 'fill period'), and when a breakout event occurs (Figure 1). For periods when the entrance is closed, the high-resolution data enabled quite accurate calculations of volumetric inputs to the lagoon over short timeframes.

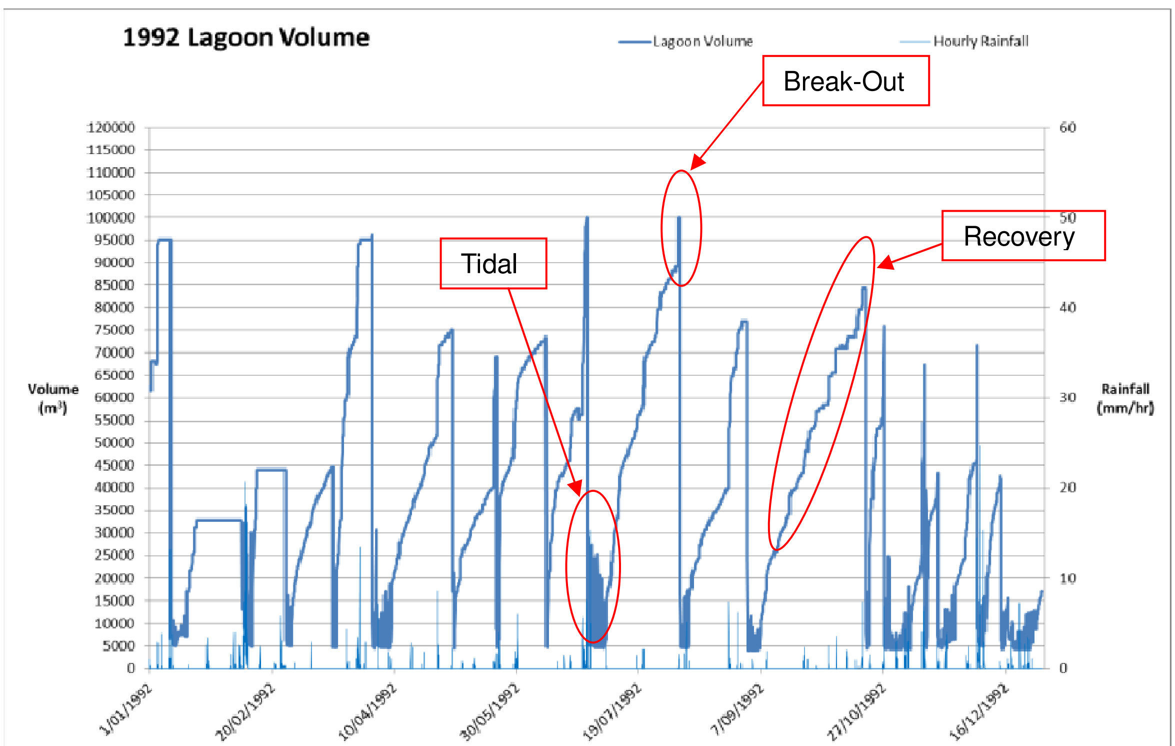

Figure 1 Time series of lagoon volume, with labels indicating a break-out event, a period when the entrance is closed (Recovery) and a period when the entrance is open (Tidal).

Groundwater

An assessment of groundwater flows was carried out by WSP Environmental Pty Ltd (WSP) over the period 2009 to 2010 (WSP, 2011). Twenty groundwater monitoring wells were drilled and samples were taken on three occasions: June 2009, October 2009 and March 2010. Groundwater flow was estimated using hydraulic conductivity measurements, and was found to vary from 0.332 to 161.7 m^3/day, varying temporally as well as spatially around the lagoon foreshores.

Sports Fields Irrigation

A potential source of surface runoff (and on-going recharge to groundwater inflows) to the lagoon system is irrigation of the sports fields adjacent to the lagoon system. A report into water usage at John Fischer Park was conducted by the Water Savings Section of NSW Public Works on behalf of Warringah Council. The report found that the average daily usage over the 12 months to July 2011 was 8.5 kL/day (0.35 m^3/hr) with higher usage in summer (0.88 m^3/hr) than winter (0.01 m^3/hr). These values are small in comparison to long-term averages of surface runoff and groundwater inflows (as determined in the following section) so were excluded from further consideration.

Determination of Groundwater Inflows

Lagoon Water Balance During Closed Periods

A water balance was carried out comparing the volume of lagoon with the inflows to the lagoon as determined through MUSIC catchment modelling for a fixed period where sufficient data was available. Only the time periods during “recovery” events when the lagoon behaved as a ‘terminal’ system could be used to compare the recorded lagoon volume change with modelled inflows. During breakout and tidal periods, the lagoon volume is influenced by other factors, such as tidal inflows and outflows.

The time periods during recovery events were identified throughout the period 1991 and 2008 (covering the period of high quality water level data) and a comparison was made between the total lagoon volume increase and the inflow volumes from direct rainfall on the lagoon surface, and the MUSIC modelled stormwater flows. The result of this comparison is presented in Table 1.

Table 1 Predicted Curl Curl Lagoon Volume Inflows during Recovery Events 1991-2008

Parameter	*Value*
Total Rainfall Volume Falling on Lagoon	198,536 m^3
Total MUSIC Predicted Stormwater Volume	4,207,109 m^3
Combined Stormwater and Rainfall Volume	4,405,645 m^3
Total Estimated Lagoon Volume Increase	5,635,066 m^3
Difference = Total Other Volume Contribution	1,229,422 m^3
Total number of Recovery Period Hours	56,387 hours
Estimated Other Flow Rate	22 m^3/hr

From Table 1 it can be seen that there is a deficit between the lagoon volume increase and the total inflows. This volume difference is represented by the total ‘other’ volume contributions. An estimate of the total other volume flow rate can be made by dividing the total other volume by the total number of recovery hours, giving an estimated residual flow of 22m^3/hr. This residual flow is assumed to come primarily from groundwater flow.

Based on this 'back analysis' a percentage distribution of the flows entering the lagoon is presented in Table 2.

Table 2 Percent Distribution of Predicted Inflow Volumes into Curl Curl Lagoon 1991-2008

Constituent	*Value*
Stormwater	75%
Other (assumed to be groundwater)	22%
Direct Rainfall	3%

An example of the impact of groundwater on lagoon volume can be seen in Figure 2, which is a time series graph of a recovery event during March 1992. The deficit between the blue and green lines is the contribution from groundwater. The shape of the curve is representative of a flow that decreases in magnitude with higher water level, a signature of groundwater flow.

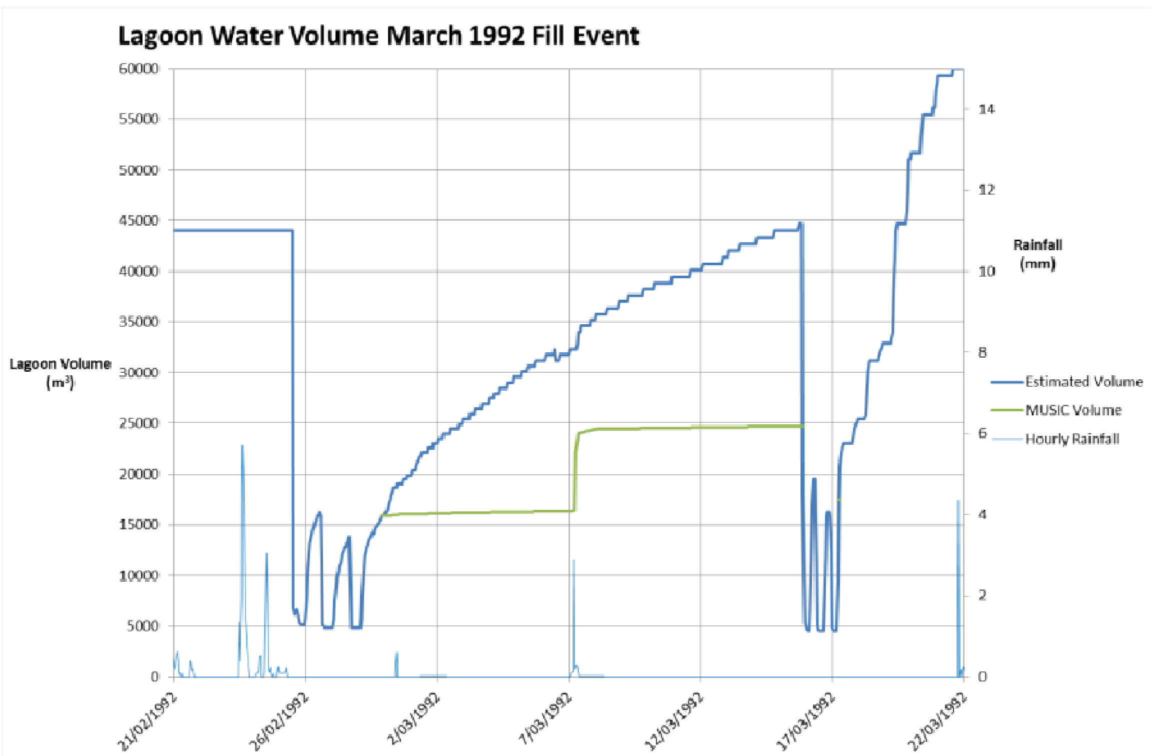

Figure 2 Time Series Graph of the Measured Curl Curl Lagoon Volume versus the volume contribution from catchment runoff for the March 1992 Recovery Event

Derivation of Groundwater Relationship

From the time-history results, the magnitude of the 'other' inputs to the lagoon tends to be inversely proportional to the water level in the lagoon. This suggests that the input is dependent on the hydraulic gradient, that is, the difference in level between the lagoon water level and the typical groundwater level (refer Figure 3).

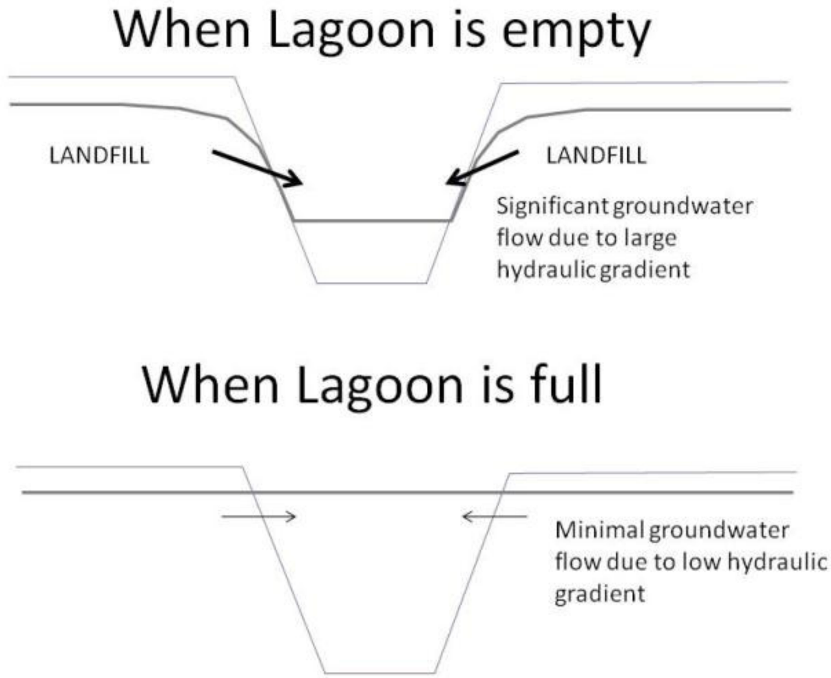

Figure 3 Conceptual diagram of groundwater flow based on hydraulic gradient

The relationship between water level and groundwater flow was derived by identifying a number of fill, or recovery, periods during which the lagoon entrance was closed. Eight periods were chosen that were considered representative, and during which few rainfall events occurred (Figure 4). Excluding outliers that are the result of surface runoff, the instantaneous rate of water-level rise was then compared against water level (Figure 5). Using the high-resolution bathymetry dataset, it was possible to convert the instantaneous rate of water level rise to a volumetric flow rate and thereby derive a relationship of flow rate to water level using a linear regression (Figure 6; note the high value of R^2=0.9363). Interestingly this relationship has a value of zero at approximately 2.0m AHD. Thus it can be inferred that water levels in excess of 2.0m AHD would indeed recharge groundwater aquifers, rather than draining these aquifers.

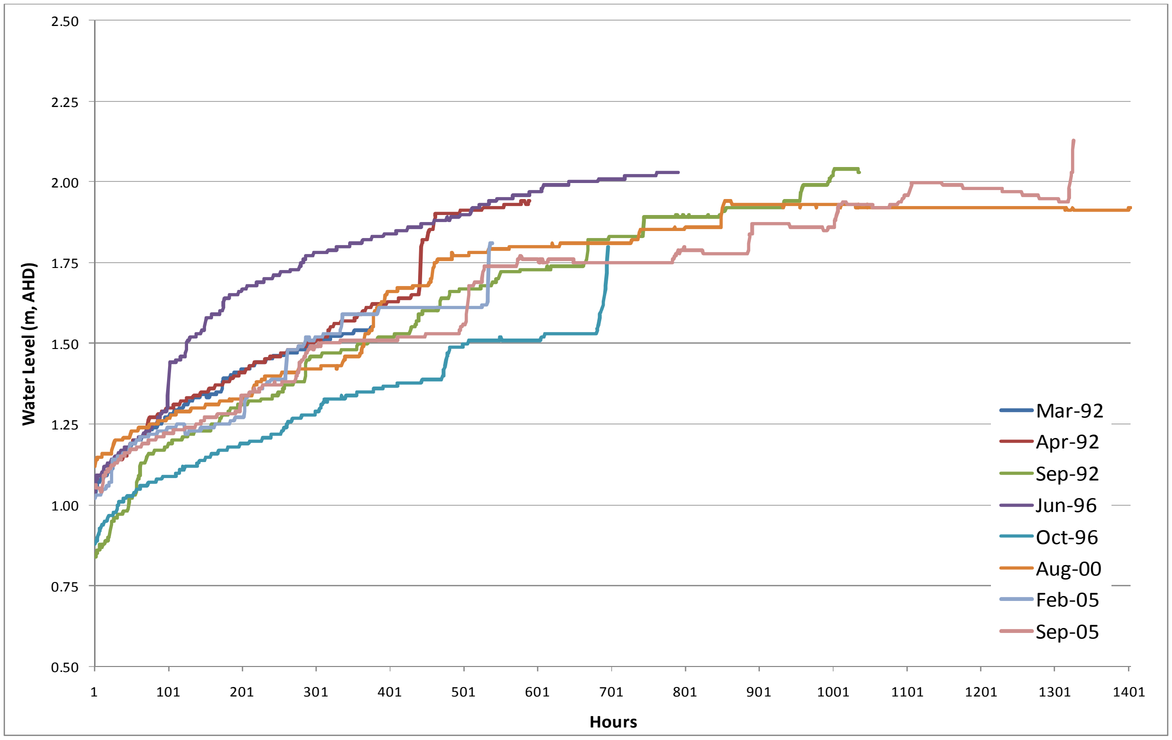

Figure 4 Eight fill periods chosen to derive relationship between groundwater flow and water level

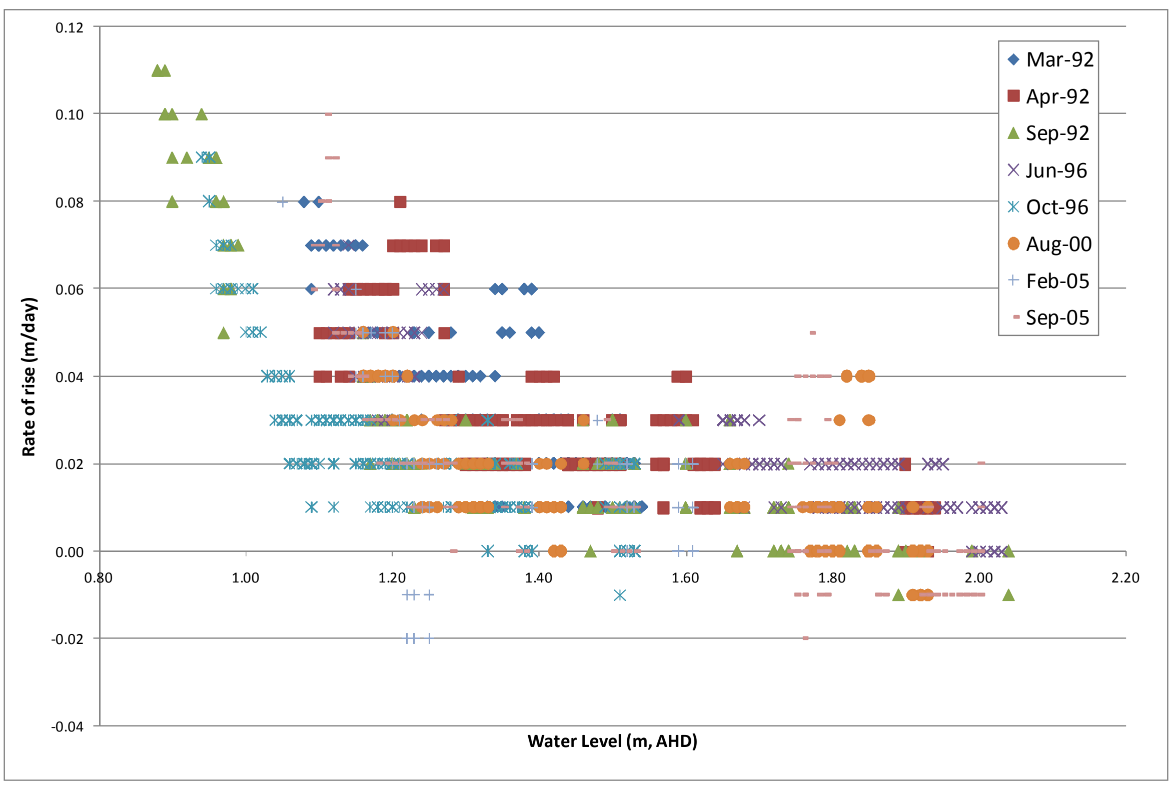

Figure 5 Instantaneous rate of water level rise versus lagoon water level

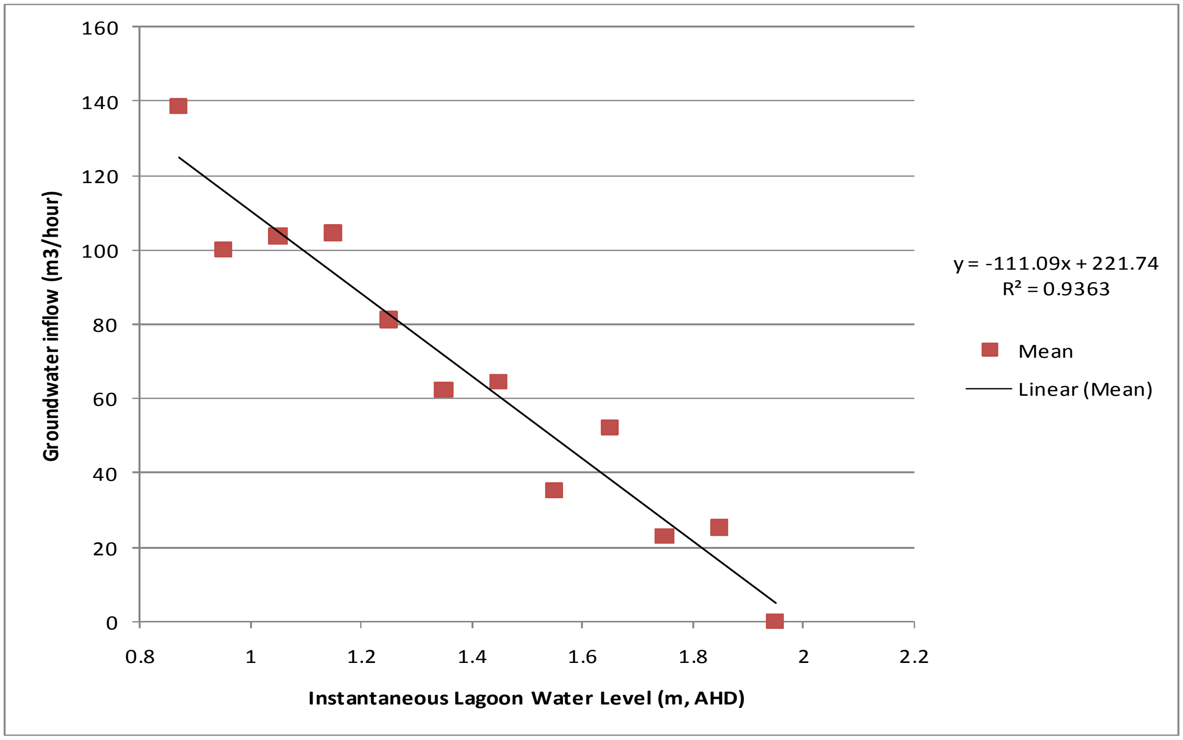

Figure 6 Relationship between groundwater flow and lagoon water level

Based on this analysis, it is clear that groundwater exerts much more of an influence on the lagoon system than previously thought based on flow estimates (WSP, 2010). Further work is required to identify the primary sources of groundwater flow along the lagoon (given that there may be differences in groundwater inflow rates due to the potentially inconsistent fill material) and estimates for associated pollutant loads.

Hydrodynamic Modelling Assessment of Lagoon Options

Model Set-up

TUFLOW is a 1D/2D hydrodynamic modelling platform, developed by BMT WBM, which is widely used for flood and tidal studies in Australia and abroad. In 2D mode, it solves the free-surface, shallow water equations and, coupled with the TUFLOW-AD module, can simulate the Advection and Dispersion (AD) of constituents within a flow. It has several features that make it ideal for assessment of Curl Curl Lagoon, including the ability to introduce variable bathymetry, which is essential for simulating the regular breakout events observed in entrance of Curl Curl Lagoon.

A computational grid with horizontal resolution of 7m was constructed for use with TUFLOW. The grid size of 7m was chosen as it had a sufficiently high-resolution to accurately represent the bathymetry of the lagoon system, while keeping model runtimes short enough to allow for a full year's simulation, noting that calculations are performed at a simulation timestep of 3 seconds (i.e. total number of timesteps simulated = 28,800 per day x 365 days = 10,512,000).

The simulation period 1 January 2006 to 31 December 2006 was chosen for the TUFLOW simulations based on the availability of water quality observations and the presence of a long fill period. Examination of the water level record determined that the period from May 2006 was typical in terms of breakout frequency but the period from January to May was a long fill period without breakouts, allowing for a detailed examination of the effects of groundwater during this time. Water quality samples were also collected during this time, allowing for comparison of model output against observations.

Inputs to the model consist of stormwater inflow, groundwater inflow and the ocean entrance. The stormwater inflow was primarily at Greendale Creek, although a further 25 pipes that drain directly into the lagoon were also included. The MUSIC model provides flow values and concentrations of total nitrogen and total phosphorous for these boundaries. Salinity was assumed to be zero for stormwater runoff. The groundwater inflows were based on the results of the groundwater analysis described above. That is, groundwater inflows to the model were based on the assumed relationship with water levels in the lagoon. To the authors' knowledge, this is the first application in a hydrodynamic model where groundwater inflows have been included as a function of water level within the waterway.

The open ocean boundary at the entrance to Curl Curl Lagoon takes tidal elevations from predictions at Sydney Harbour. Direct rainfall was excluded from the TUFLOW model, as it is such a small component in comparison to catchment runoff that it was considered inconsequential for the purposes of this study.

In keeping with typical breakout behaviour determined from the water level record, the bathymetry at the lagoon entrance was modified in the model to allow a breakout when the water level reached 2.12 m AHD. On average, a breakout event lasts three hours and the entrance remains open for a period of just over six days (145 hours). The entrance is then closed over a period of 6 hours. These conditions were hard-coded into the TUFLOW model for the purposes of this assessment.

In order to help identify the source of water within the lagoon, separate passive tracers were included into the respective stormwater and groundwater inflows in the TUFLOW model. A passive tracer was also added to the ocean inflows to help define the flushing characteristics of the lagoon under existing and potential future management conditions. All tracers had an input value of 1.0.

Management Scenarios Modelled

Two possible management scenarios were examined as part of this study. The first scenario was the "dredging option", which was the preferred option outlined in the Curl Curl Lagoon Rehabilitation Plan Statement of Environmental Effects (PBP, 2005). This involves removal of approximately 16,000 m^3 of sediment from the downstream section of the lagoon to an average depth of -0.2 m AHD, followed by removal of approximately 14,000 m^3 of sediment from the upstream section of the lagoon to an average depth of +0.2 m AHD. A mooring area dredged to -1.0 m AHD would be needed to moor the dredger in the event of a breakout, and a sediment trap just downstream of Greendale Creek dredged to -1.0 m AHD would also be included.

The second scenario was the "weir option" and involves creation of a permanent ponded waterbody through construction of a weir in the entrance channel. This scenario was not a preferred option in PBP (2005) but is included for comparative purposes. A weir of height 1.3 m AHD was included just downstream of Griffin Road bridge. This height was chosen as it allows for some tidal flushing during high spring tides in the event that the entrance is open, while still creating a permanent pond with an average depth of approximately 30 cm. Both scenarios were compared to the 'baseline' scenario, which represents current conditions.

Model Results

A time series of lagoon water levels for each of the three scenarios (baseline; dredged, weir) is presented in Figure 7. The timing of breakouts for the dredged scenario was very similar to the baseline case, indicating that dredging of the lagoon would not have a significant impact on breakout frequency. Introduction of a weir, however, would increase breakout frequency by approximately 2 events per year.

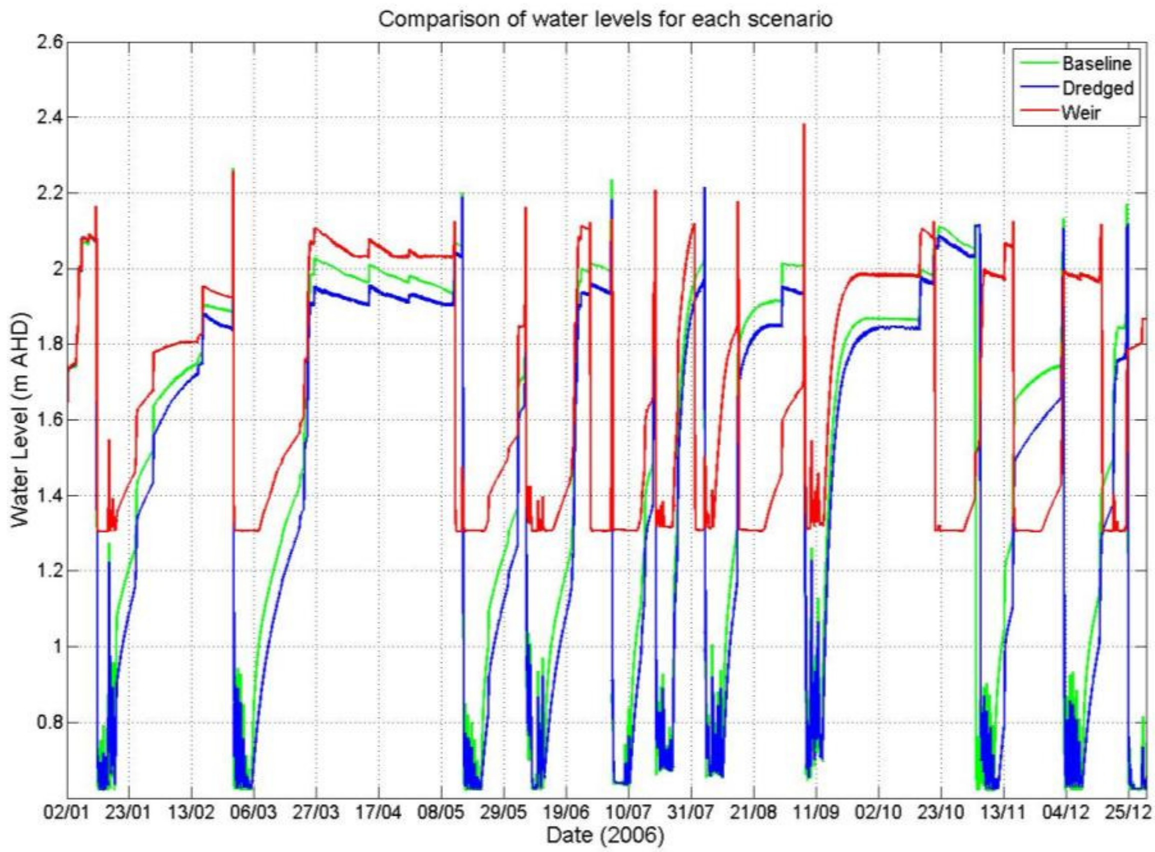

Figure 7 Comparison of water levels for each management scenario

The relative influences of stormwater, groundwater and seawater were determined using the passive tracers PT1, PT2 and PT3, respectively. For example, a concentration of 0.75 mg/L for PT3 indicates that 75% of the water at this point was made up of seawater. The tracer analysis has showed that when the entrance is open, ocean flushing of Curl Curl Lagoon does not extend far beyond Griffin Road bridge (Figure 8).

Figure 8 Influence of Seawater under Baseline Conditions when Entrance is Open

Time series of each of the groundwater passive tracer at the Griffin Road bridge for the period February to July 2006 is presented in Figure 9. As can be seen from this figure, at times up to 80% of the lagoon volume can be made up of groundwater, although approximately 25% is more typical for the baseline scenario, which agrees well with the long-term average calculated as part of the water balance assessment described previously. The relative influence of groundwater increases significantly for the dredged scenario, which is a reflection of the increased hydraulic gradient that would be introduced under these conditions. Conversely, construction of a weir, slightly reduces the influence of groundwater by decreasing the hydraulic gradient.

Dredging of the lagoon allows a slightly greater seawater intrusion (compared to the baseline as shown in Figure 7) during periods when the entrance is open, while the opposite is the case under a weir scenario, where the weir essentially prevents tidal flushing of the lagoon above the weir.

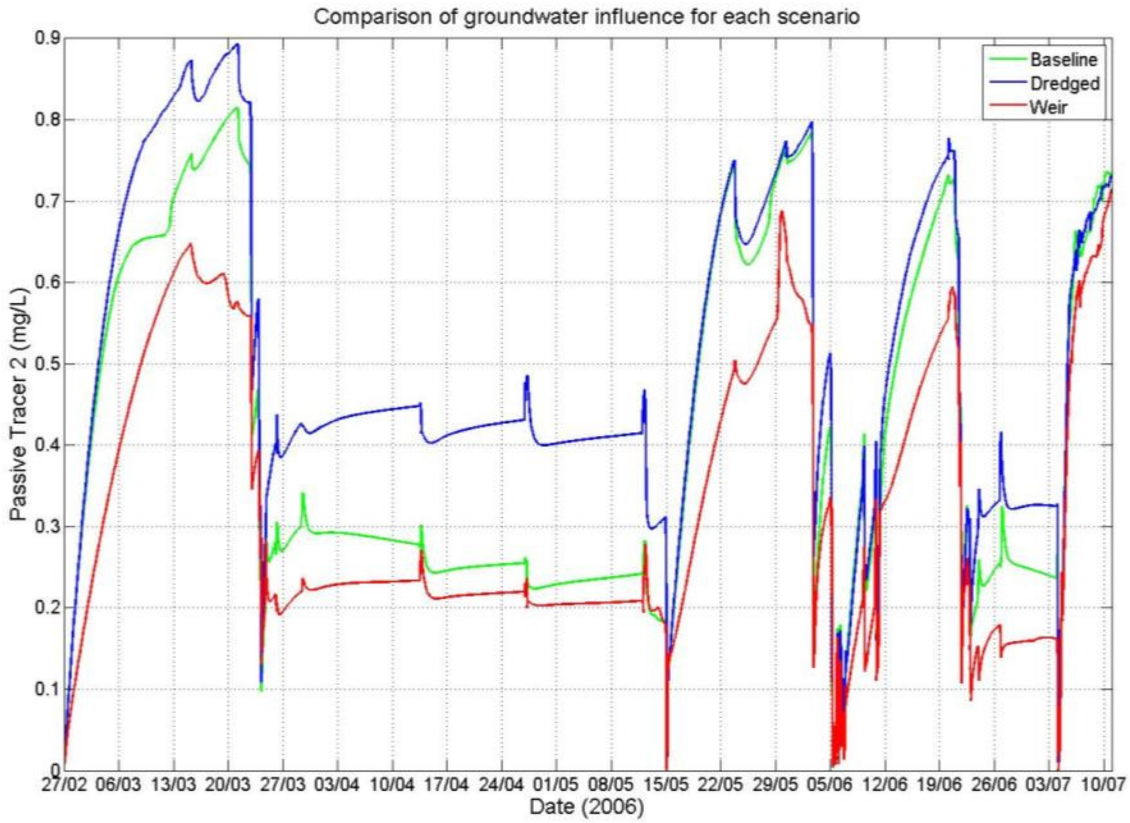

Figure 9 Concentration of groundwater passive tracer at Griffin Road Bridge for each scenario

Discussion and Conclusions

It is clear from the water balance assessment that groundwater plays a very important role in the hydrodynamic regime of Curl Curl Lagoon, contributing approximately 22% to the total volume discharged into the waterway. While this analysis demonstrates that groundwater contributes a significant amount of flow to the lagoon, the source of this flow is still largely unknown. Further work is required to identify the primary source of the groundwater, and complete a full water balance analysis of the lagoon.

The study demonstrated that the lagoon generally fills rapidly with a combination of stormwater runoff and groundwater inflows. Once full, the lagoon entrance breaks out, discharging the accumulated volume to the ocean. The entrance remains open for a few days before closing again. When open, the lower entrance channel of the lagoon is well flushed with tidal inflows and outflows. The tidal flushing is essentially restricted to the area downstream of Griffin Road bridge.

Dredging of Curl Curl Lagoon has been mooted as a concept for rehabilitation since the 1990s. Modelling of the dredging option presented here shows that it would not have a significant benefit to the flushing characteristics of the lagoon that would justify the large expense. Modelling results actually indicate that dredging of the lagoon would increase the relative influence of groundwater, because dredging has the potential to lower lagoon water levels, which would increase hydraulic gradient and induce a greater groundwater inflow into the waterbody. The modelling also showed that construction of a weir on the downstream side of Griffin Road bridge also had no benefit to lagoon water quality.

It must be recognised that Curl Curl Lagoon is a very harsh environment, given its high degree of catchment disturbance and highly dynamic hydrological regime. Rehabilitation of the waterway to a natural or pristine condition would be impossible given existing constraints. Poor water quality in Curl Curl Lagoon is due to a combination of catchment runoff (from a highly developed and urbanised catchment), and potentially from groundwater. Both of these conditions would be very difficult to modify.

Given the difficulties and questionable outcomes from modifying the lagoon receiving water conditions, it is considered more appropriate to pursue catchment-based works and initiatives as a way of reducing both the diffuse and point source pollutant inputs to Curl Curl Lagoon. Groundwater management within reclaimed land adjacent to the lagoon could also be considered, however, this would likely be expensive and the outcomes uncertain.

References

BMT WBM (2012) "Stormwater and Estuary Modelling for Curl Curl Lagoon", Prepared for Warringah Council

Haines, P. E. (2006) "Physical and chemical behaviour and management of Intermittently Closed and Open Lakes and Lagoons (ICOLLs) in NSW". Gold Coast, Queensland: Griffith University, Ph.D. thesis, 505p.

Haines PE, Tomlinson RB, Thom BG (2006) "Morphometric Assessment of intermittently open/closed coastal lagoons in New South Wales, Australia" Estuarine, Coastal and Shelf Science 67(1-2) 321-332

Patterson Britton & Partners Pty Ltd (1992) "Curl Curl Lagoon Rehabilitation Study", Prepared for Warringah Council.

Patterson Britton & Partners Pty Ltd (1994) "Greendale Creek Rehabilitation Project. Statement of Environmental Effects", Prepared for Warringah Council.

Patterson Britton & Partners Pty Ltd (2005) "Curl Curl Lagoon Rehabilitation Project – Stage 4. Statement of Environmental Effects", Sydney Water (2011) "Northern Beach Storage Project – Review of Environmental Factor".

WSP Environment & Energy (2010) "Curl Curl Lagoon Groundwater Assessment".