A Field Investigation into the Groundwater Dynamics of Raine Island

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Abstract

Raine Island is the nesting site for the world's largest remaining population of the green turtle (*Chelonia mydas*) and the most significant seabird rookery in the Great Barrier Reef World Heritage Area. Surveys of turtle nesting conducted by the Queensland Parks and Wildlife Service have indicated that the nesting success rate may be reduced due to flooding of the nests by groundwater. An expedition to the island in November-December 2006 was undertaken to investigate the beach groundwater dynamics. The field data was analysed and used to develop a simple mathematical model of the watertable response to tidal oscillations. When combined with sand surface survey data this information enables the estimation of the depth of sand available for green turtle nesting above the high tide inundation level.

1. Introduction

Raine Island

Raine Island (11°36' S, 144°01' E) is the largest coral cay on the outer reefs of the far northern Great Barrier Reef, approximately 80km north east of Cape Grenville, see Figure 1. The island lies at the leeward (northwestern) end of the Raine Reef, which is a detached reef located seaward of the main chain of ribbon reefs that run along the continental shelf. The reef abruptly rises out of water at least 200 metres deep and sits on a terrace approximately eight metres deep. The reef flat is approximately three kilometres long and one kilometre wide and no more than three metres deep at mean high water spring (MHWS) tide level. A stone tower was built on the island in 1844 to mark the reef entrance.

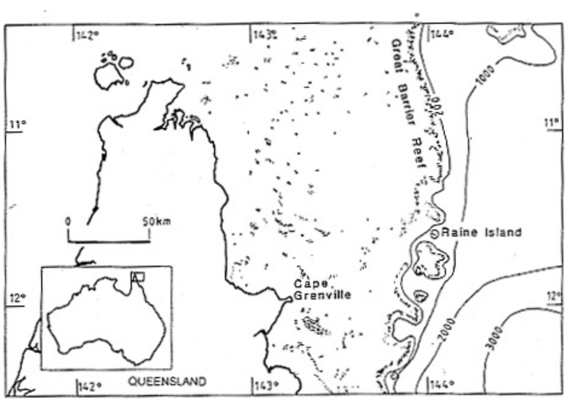

Figure 1: Raine Island locality map (from Baker et al., 1998)

The island is approximately 800 metres long and 370 metres wide at its broadest point. It is composed of a central phosphate rock platform surrounded by a beach which ranges in width from approximately 15 to 90 metres, excluding the small area near the tower where the rock platform extends to the MHWS level. The berm crest is approximately one to two metres above the mean MHWS tide level. Behind the berm there is a lower swale area of variable width which rises to the base of a small cliff that marks the edge of the central rock platform. The beach is composed of calcium carbonate sand comprising coral, molluscan detritus and foraminiferan skeletons (Gourlay and Hacker, 1991).

Extended periods of human habitation occurred during construction of a navigation beacon tower in the 1840s and phosphate mining in the 1890s. The island has since remained uninhabited and general public access is prohibited. Raine Island provides crucial habitat for several species of sea bird and the green turtle *Chelonia mydas.*

Green turtles

Raine Island and adjacent Moulter Cay support one of the few remaining large *Chelonia mydas* rookeries in the world (Figure 2). However concerns have been raised about the viability of Raine Island as a productive rookery due to regular flooding of nests by groundwater. Since at least 1996, incubating eggs have been regularly flooded by elevated groundwater levels associated with spring tides and rainfall (Limpus et al., 2002, 2006). Summer rainfall also appears to have increased over the last nine breeding seasons since 1996 (Limpus et al., 2006).

Flooding of eggs is catastrophic because an egg drowns after a few minutes of immersion. A single flooding event can drown two months accumulation of incubating eggs. The number of eggs killed by flooding has not been quantified but a paucity of hatchlings has been observed crossing the beach in December and many nests contain dead eggs (Limpus et al., 2006). Flooding not only reduces hatchling production but also the effective area of beach available for successful nesting. Nesting success on Raine Island can also be reduced by an insufficient depth of sand overlaying rock layers, dry sand that collapses easily and turtle interactions on high density nesting nights. The reduced nesting success and hatchling production observed during the past nine years, together with hunting of turtles in some parts of their range, is predicted to bring about the decline of the Raine Island - Moulter Cay population in the foreseeable future (Limpus et al., 2002, 2006).

Figure 2: Intensive nesting of *Chelonia mydas* observed at Raine Island in December 2006

Climate and weather
Raine Island lacks a weather station. However, the three closest Bureau of Meteorology weather stations (Horn Island, Willis Island and Lockhart River) are characterised by relatively uniform maximum and minimum air temperatures throughout the year, with mean monthly temperatures above 25°C and mean monthly maximums below 35°C (Limpus et al., 2002). Rainfall appears to be highly variable and correlated with the Southern Oscillation Index (SOI), with periods experiencing a negative SOI usually characterized by low rainfall and positive SOI generally producing high rainfall (Limpus et al., 2002). The ten year period since 1996 has experienced four years of negative SOI values, four years of positive values and two years of variable values (Bureau of Metrology, 2006). No rain was experienced during the 2006 expedition.

From April/May through September/October the island is generally subjected to seas and swells generated by the persistent southeast trade winds over the Coral Sea. Winds are probably more variable throughout the remainder of the year although the summer months are under the influence of the northwesterly monsoon.

Cyclones generally increase rainfall, tide heights and winds. The island is probably further north than the majority of cyclone tracks (Gourlay and Hacker, 1991); however two cyclones during early 2005 (Cyclones Kerry and Ingrid) are thought to have had a major impact on the island (Limpus et al., 2006). Furthermore, climate change may increase cyclonic activity in the region.

Morphology
It has been proposed that the increase in frequency of flooding of nests may be due to a loss of sand from the swale area of the beach. Limpus et al. (2006) investigated the proposition that the sand removed from the island on the backs of turtles may be important. The 2004 expedition to the island found that each turtle carried a mean 422mL (SD=635.6, range=0-4100mL, n=100) of sand to the sea and estimated that 23 cubic metres of sand was removed from the island during the 2004-5 breeding season. This amount of sand is not large in the context of the overall sediment transport budget of the island. It was also suggested that sand loss is enhanced by the low point in reef flat at the anchorage where a jetty was once constructed as part of the phosphate mining operation (Limpus et al., 2006). Gourlay (1999) noted on the basis of aerial photography analysis that the total volume of sand on the island increased from 1984 to 1995 by 10,000 cubic metres. It was noted that this measured long term change is comparable in magnitude to the errors resulting from inaccuracies in the photogrammetry and probably smaller than the magnitude of seasonal variations and changes due to significant meteorological events. The observed loss of sand over the western edge of the reef near the anchorage may not represent a net loss of sand to the island if the amount of sediment production on the reef

flat is enough to compensate. Quantification of sediment production rates is difficult to achieve. However, detailed surveys of the sand surface carried out on the 2006 expedition will enable comparisons with previous surveys and help to quantify a net loss or gain of sediment.

Wave-generated currents play an important role in the formation and morphological development of the island and have been the subject of detailed laboratory investigations (Gourlay, 1995).

Groundwater

The groundwater dynamics of the Raine Island aquifer are dominated by the influence of the tide. The propagation of the tide-induced groundwater wave into the aquifer is affected by the hydraulic conductivity and porosity of the substrate.

The only previous groundwater study at Raine Island reported that tidal water intrusion occurs throughout much of the swale area in a predictable and systematic manner (Neil, 2003). The present investigation includes a more comprehensive array of wells and a more detailed mathematical model than any previous effort.

2. Methodology

Thirteen wells were installed to measure groundwater levels and four offshore stilling wells were set up to record the tidal oscillation (Figure 3). Inshore wells were dug to a depth of one to two metres below the sand surface using an auger. Offshore stilling wells were installed with the base of the well at the sand surface supported by a star picket. All wells were made of 40 millimetre diameter clear plastic tubing. Groundwater levels were recorded at 15 minute intervals using a dipmeter and offshore water levels were read from a tape measure attached to the outside of the well. Conductivity was measured at each well as a gauge of the relative salinity. The elevations of the top of the wells were surveyed daily using a total station and tied into the lowest astronomical tide (LAT) datum using Permanent Survey Mark (PSM) 79041 (7.566m above LAT) as a reference. The position of each well in the horizontal plane was recorded using a differential GPS receiver.

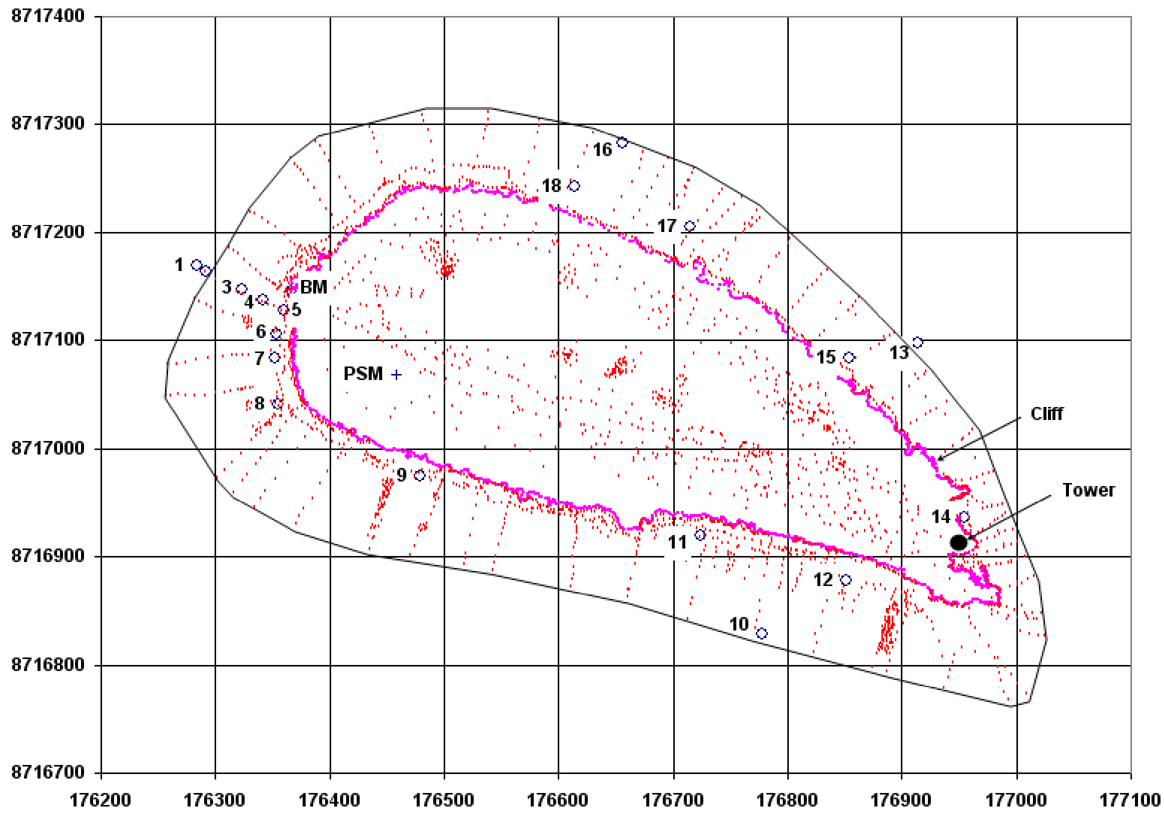

Figure 3: Raine Island map (WGS84 coordinates in metres) with location of groundwater monitoring wells (circles), survey data points (dots) and the Permanent Survey Mark 79041 (cross).

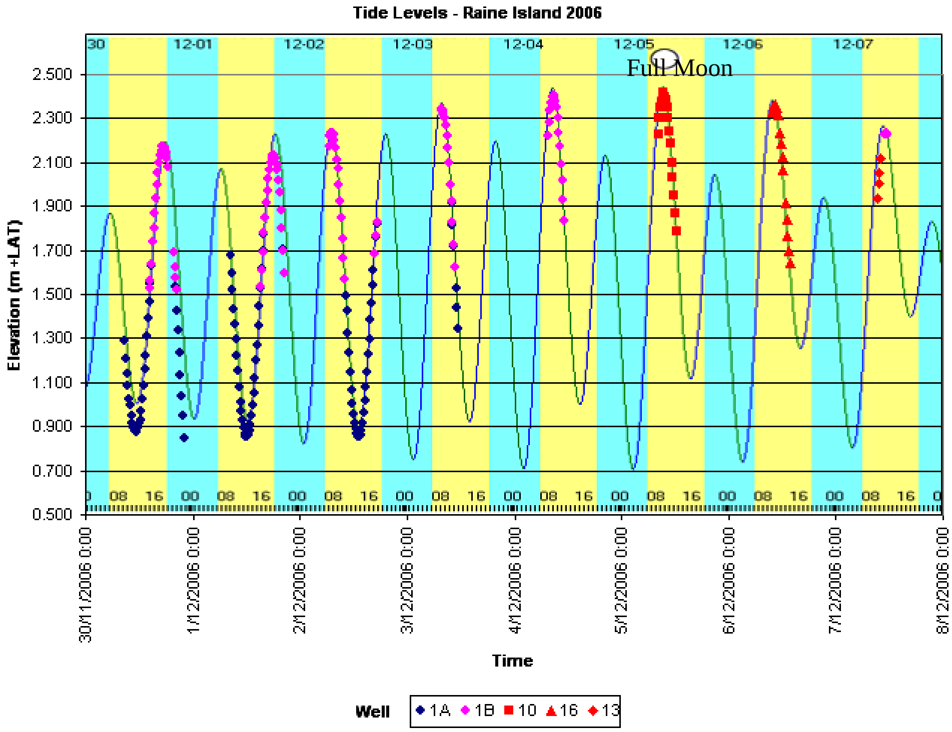

Figure 4: Tide measurements from the offshore wells 1,10,13 and 16 (dots) with the predicted astronomical tide level from WXTide32 (line).

Wells 1A, 1B and 3-5 formed a cross-shore transect, which was located adjacent to the anchorage at the western end of the island. Well 2 was not installed because it was located at the beach crest and it was not possible to reach a useful depth due to repeated wall collapse. Other wells were located throughout the swale (40-80 metres from the shoreline), together with adjacent offshore locations, to quantify spatial and temporal groundwater level variation.

Wells 6 and 7 were located toward the southwestern corner of the island. Well 8 was installed within the area experiencing the greatest degree of inundation, referred to by observers on previous expeditions as ‘the swimming pool’. Well 9 was located approximately 200 metres from well 8 and was installed into a layer of indurated sand (immature beach rock). Well 10 was located offshore to wells 11 and 12, which were located within the only region of the swale where green vegetation was observed. Well 13 was offshore to wells 14 and 15. Well 14 was installed within the rocky section of beach adjacent to the tower and well 15 was approximately 150 metres to the northwest, in the dry region of the swale referred to as ‘the dust bowl’. Well 16 was offshore to wells 17 and 18, which were located approximately 100 metres apart along the straight section of the northeastern beach. Wells 14, 15 and 17 were bound by exposed beachrock on the adjacent shoreline. Well 17 was located at the northeastern boundary of the 2006 turtle nesting success study area.

3. Field Measurements and Results

The tide conditions for the duration of the field campaign were monitored by manual readings of offshore well numbers 1, 10, 13 and 16. These measurements are shown in Figure 4, together with astronomical tide predictions from the software package WXTide32.

The field campaign included two major components. The first of these involved continuous daytime measurement of water table levels along a transect defined by wells 1 through 5 during the period 1/12/06 to 3/12/06. During this time the tidal oscillation was approximately sinusoidal. The objective was to measure the propagation of the groundwater wave so that a mathematical model could be developed and calibrated.

The second part of the field effort was directed towards measurement of the peak response of the water table to the high tide signal at various locations around the island at a distance of approximately 40-80 metres from the shoreline. These measurements were carried out at wells 8, 9, 11, 12, 14, 15, 17 and 18 during the period 4/12/06 to the 7/12/06. The objective was to assess the spatial homogeneity of the aquifer and to develop a model to estimate of the peak water table elevation at any point around the island for a given high tide level.

To investigate the propagation of the groundwater wave along the cross-shore transect (wells 1-5) the data from the 2/12/06 was used since it was the most comprehensive. The recorded water levels (metres above LAT) at each of the wells are shown in Figure 5. It can be seen that the response of the water table at each of the inland wells is delayed relative to the tidal signal and the amplitude of the oscillation is reduced. The time between the peak offshore high tide and the peak water table elevation increased with distance inland, from 1.5 hours at well 3 to 1.75 hours at well 5. The peak water table elevation measured at each of wells 3, 4 and 5 was approximately 1.97m above LAT compared to the high tide level of 2.24m above LAT. A profile of the cross-shore transect is shown in Figure 6, together with the approximate water table elevation at intervals around high tide on the 2/12/06.

A further effort to properly measure the propagation of the tidal wave into the aquifer was carried out by the installation of a self-logging pressure transducer in well 6. This well was deeper than wells 3-5 and was therefore able to make continuous recordings through low tide on several occasions. The water level recorded by the pressure transducer was in good agreement with the manual recordings at the same location (well 6). The results of this comparison are shown in Figure 7, as well as results from the simple mathematical model developed in the next section.
The second stage of the field campaign involved measurement of the peak water table elevations at various locations around the island. The chosen locations were between 40 to 80 metres from the shoreline, in the swale area in front of the phosphate rock cliff. The results from the monitoring at wells 8, 9, 11, 12, 17 and 18 carried out over the period 4/12/06 to 6/12/06 are shown in Figure 8. Wells 14 and 15 were monitored on 7/12/06, but the wells were not deep enough to record the water table response.

Table 1 includes a summary of all of the peak water table level measurements. An estimate of the response to a mean high water spring tide was obtained by multiplying the measured response by the ratio of tidal amplitudes. The results of the mathematical model developed in the next section are also included.

Table 1: Peak water table levels in response to high tide signals and relative conductivity

Well	Distance from shoreline (m)	High tide measured (m above LAT)	Peak water table level measured (m above LAT)	Estimated response to MHWS 2.07m tide (m above LAT)	Model results for MHWS 2.07m tide (m above LAT)	Ratio of average conductivity to seawater conductivity
5	72	2.24	1.97	1.87	1.84	0.64
8	78	2.41	2.21	1.96	1.83	0.83
9	74	2.41	2.07	1.87	1.84	0.62
11	77	2.42	2.02	1.84	1.83	0.33
12	71	2.42	2.12	1.90	1.85	0.46
14	43	2.24	< 2.13	Uncertain	1.94	-
15	46	2.24	< 2.11	Uncertain	1.93	-
17	48	2.36	1.93	1.80	1.92	-
18	51	2.36	2.11	1.91	1.91	-

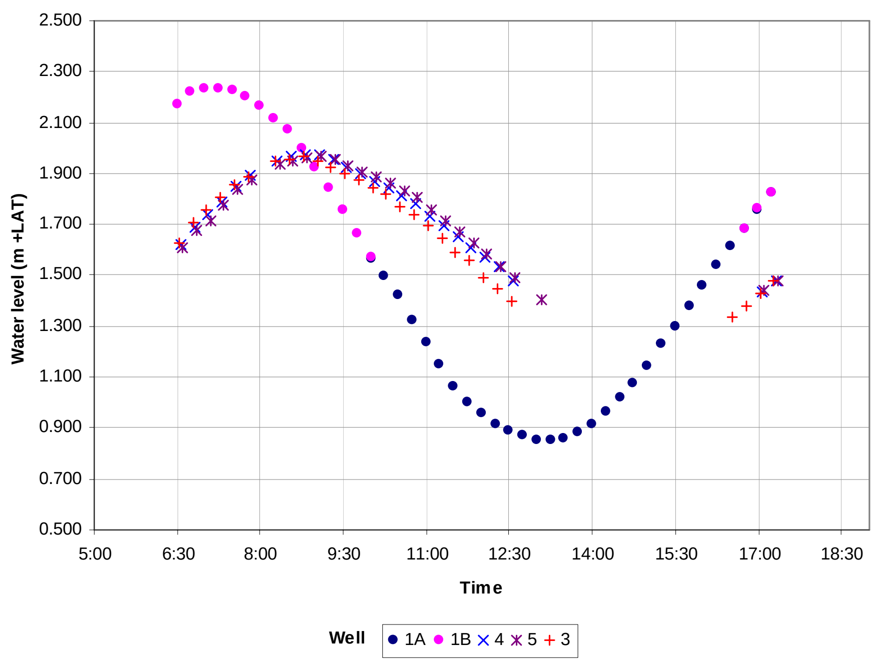

Figure 5: Water levels recorded along cross-shore transect (wells 1-5) on 2/12/06

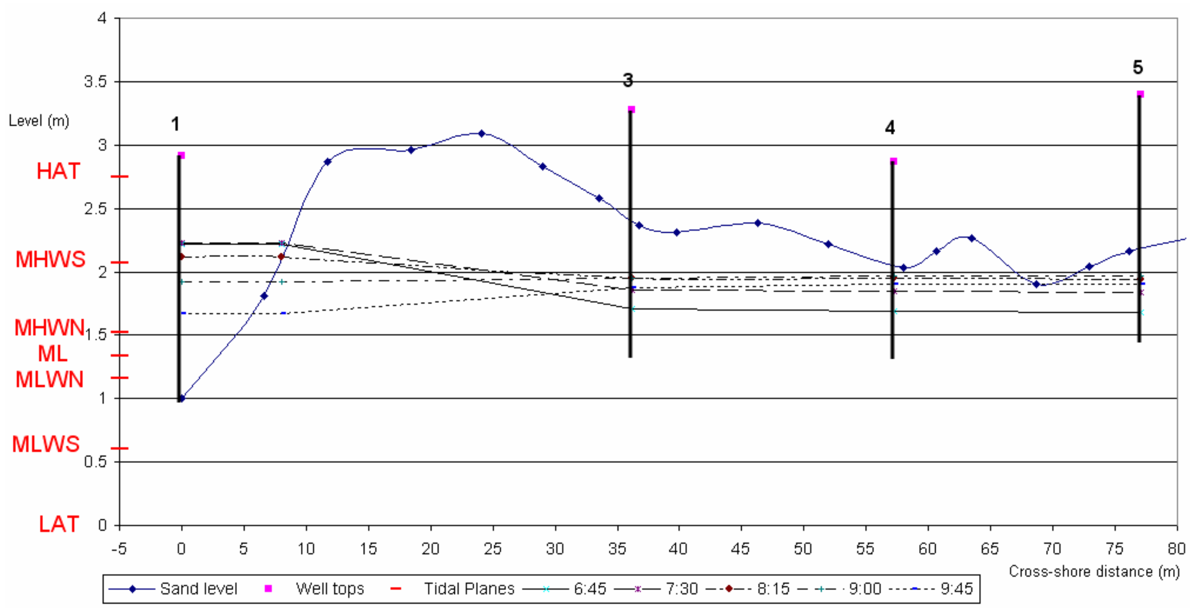

Figure 6: Main transect – wells 1 through 5. Water table levels are displayed for 2/12/06

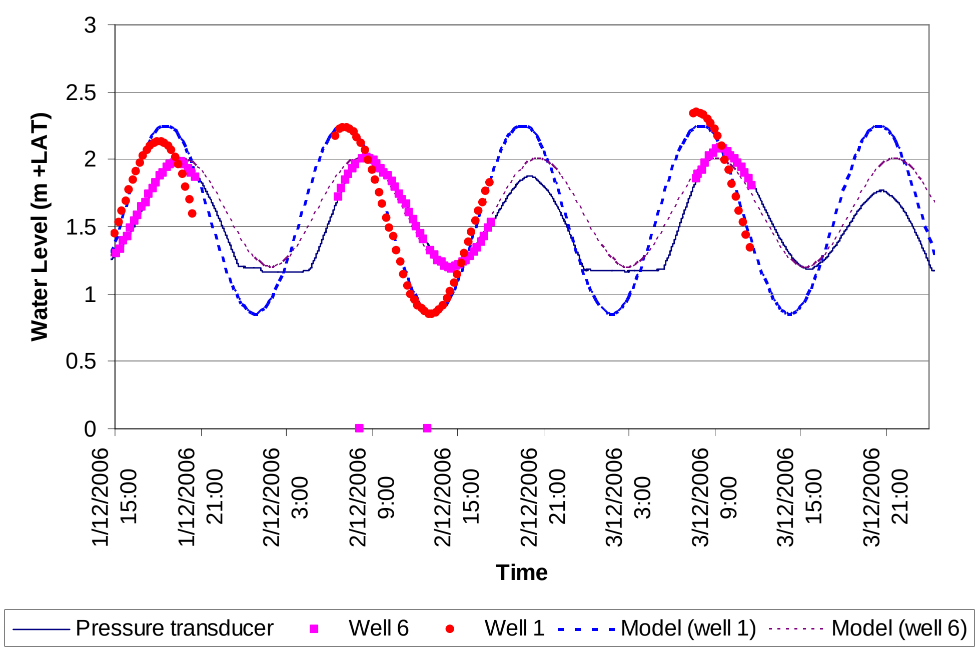

Figure 7: Pressure transducer recordings of water levels at well 6, compared to manual readings at wells 1 and 6 and simple model results for wells 1 and 6

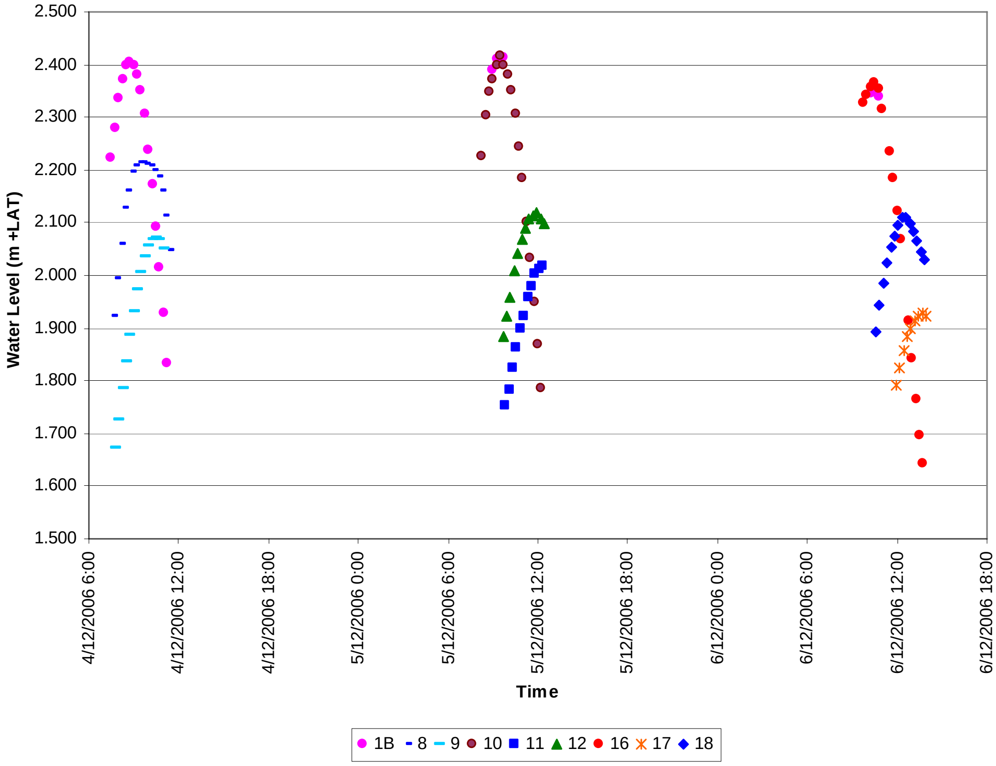

Figure 8: Measured water table response to high tide signal (offshore wells 1, 10 and 16) at wells 8, 9, 11, 12, 17 and 18

4. Mathematical Model

A simple mathematical representation of the propagation of the tidal wave into the aquifer is obtained by assuming that the beach is straight and uniform, taking the beach face to be vertical and adopting Dupuit's assumption that the flow is essentially horizontal. Then the water table elevation can be described by Boussinesq's equation

$$\frac{\partial h}{\partial t} = \frac{K}{n}\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) \qquad (1)$$

where n is the porosity, K is the hydraulic conductivity, x is the distance from the shoreline and $h(x,t)$ is the water table elevation. If we assume further that the tidal amplitude is small compared to the depth of the aquifer D this simplifies further to the diffusion equation

$$\frac{\partial h}{\partial t} = \frac{KD}{n}\frac{\partial^2 h}{\partial x^2} \qquad (2)$$

The application of boundary conditions $h(0,t) = D + A\cos(\omega t)$ and $h(\infty,t) = D$ leads to solutions of the form

$$h(x,t) = D + A\cos(\omega t - kx)e^{-kx} \qquad (3)$$

with the wave number k given by the dispersion relation

$$k = \left(\frac{n\omega}{2KD}\right)^{0.5} \qquad (4)$$

Nielsen (1990) noted that the nonlinear term in (1) and the fact that the beach face is not vertical both have the effect of producing an inland over-height C such that the time average water table elevation is $\overline{h(x,t)} = D + C$. Thus our modified simple model becomes

$$h(x,t) = D + A\cos(\omega t - kx)e^{-kx} + C \qquad (5)$$

The parameters of the model may be determined using the measurements at wells 1 and 6 on the 2/12/06. The amplitude of the first harmonic of the tidal signal was A = 0.7m and the dominant tidal frequency was $\omega = 1.4\times10^{-4}\text{s}^{-1}$. Well 6 was located 80 metres from the shoreline (x = 80m) and the observed over-height C was 0.05m. The wave number k based on the observed phase shift and amplitude decay was $\text{k} = 7\times10^{-3}\ \text{m}^{-1}$. Thus the adopted expression for the water table level (in metres above LAT) as a function of time and distance from the shoreline is

$$h(x,t) = 1.55 + 0.7\cos(1.4\times10^{-4}t - 7\times10^{-3}x)\, e^{-0.007x} \qquad (6)$$

Based on the empirical observations equation (4) can be used to determine the diffusivity

$$\frac{KD}{n} = \frac{\omega}{2k^2} = 1.43\text{m}^2\text{s}^{-1} \qquad (7)$$

Note we have neglected any time-averaged flux of water out of the beach caused by rainfall which may also contribute to the observed over-height. The results of the simple mathematical model for the time series of water table level at wells 1 and 6 are shown in Figure 7.

5. Discussion

The field measurements indicate that the water table dynamics of Raine Island were dominated by tidal influence during the period of the field campaign. The amplitude decay and phase shift of the tidal signal within the aquifer were modelled successfully using a simplified analysis. The collection of the data and development of the model enables us to consider the likely water table response to a given high tide event, and determine the implications for green turtle nesting success.

Table 1 included two estimates of peak water table levels for a mean high water spring tide at each of the well locations around the island. The first is a simple linear scaling based on the ratio of tidal amplitudes, and the second is the results of the mathematical model developed in Section 4. The two estimates are generally consistent, with a couple of exceptions. Well 8 was near the south-west corner of the island, leading to greater exposure to the tidal signal and a higher response than predicted by the mathematical model (one modelling assumption was that the beach was straight). Well 12 was similarly located close to a corner of the island and therefore had a higher than expected response. Well 17 was affected by an outcrop of beach rock along the corresponding stretch of shoreline which dampened the response compared to the model prediction.

Table 1 shows that the average measured conductivity of the aquifer at wells 11 and 12 was much lower than at wells 5, 8 and 9, indicating lower salinity consistent with the observation of green vegetation in the surrounding swale area.

The observed responses and model predictions can be combined to produce an estimation of the maximum level of tidal inundation for a mean high water spring tide at any point on the island. This estimate is shown in Figure 9.

The estimate of the peak water table response may be combined with surface survey data to provide an estimate of the total available depth of sand available for turtle nesting. Here it is assumed that turtle nests will be drowned if the depth of sand above the peak water table level is less than 0.82m, which is the average depth to the bottom of egg clutches according to Limpus et.al (2003).

Unfortunately, the surface survey data collected during the 2006 expedition was unusable due to technical problems. An estimate of depth available for nesting has been made based on 1994 survey data (Figure 10). Clearly this is not an ideal comparison due to the likely changes in beach morphology since that survey was carried out. Therefore no conclusion has been drawn at this stage, except to comment that based on 1994 survey data large areas of the beach berm and swale areas did provide sufficient depths for successful turtle nesting.

6. Conclusion

The water table dynamics on Raine Island were investigated by monitoring wells installed on the island between the 29/11/06 and 7/12/06. An analysis of the tidal wave propagation into the aquifer was carried out. The peak water table levels at various locations in the swale area were estimated for a mean high water spring tide. A mathematical model was developed that describes the propagation of the tidal signal within the aquifer. On the basis of the observed water table dynamics and the mathematical model a contour plot of the peak water table level for a mean high water spring tide was developed for the entire island. The contour plot of peak water table response (Figure 9) was combined with 1994 survey data to estimate the depth of sand available for turtle nesting above the peak water table level (Figure 10).

A thorough attempt to map the rock layers within the beach would be a worthwhile future task. This would allow a clearer picture of the available depth of sand for turtle nesting to be developed.

A conclusion on the viability of turtle nesting has not been made due to the insufficient availability of surface survey data. However, if the topography of the island had not changed substantially since the 1994 surface survey (ie negligible net sand movement in the last 12 years) it could be concluded that the groundwater dynamics do not present a significant barrier to the nesting success of *Chelonia mydas.* Additional groundwater measurements and survey data should be collected to allow a more detailed and accurate estimation of the depth of sand available for successful turtle nesting.

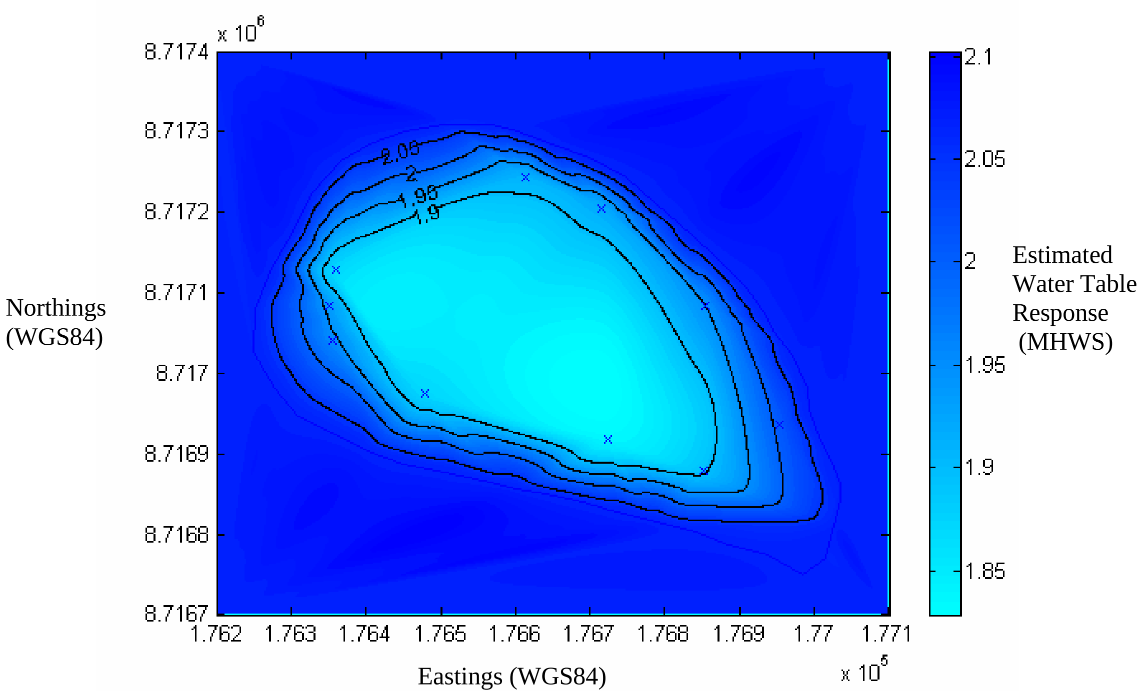

Figure 9: Estimated peak water table response (m above LAT) for a MHWS tide of 2.07m. Well locations are marked as crosses.

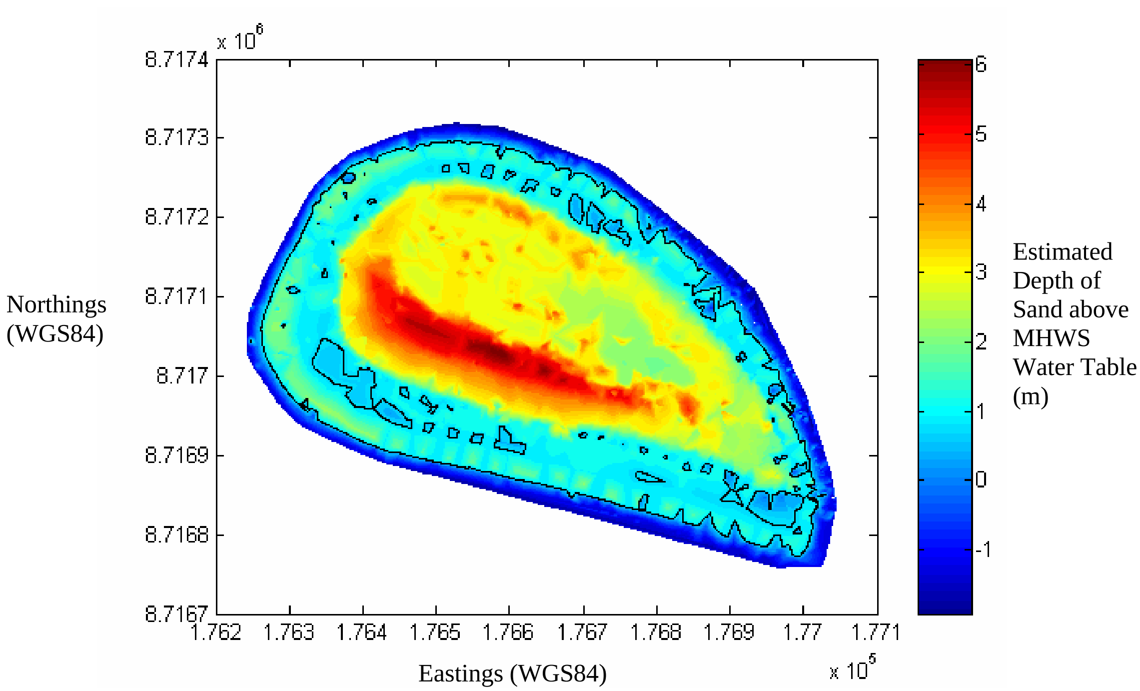

Figure 10: Estimated depth of sand available for turtle nesting above the MHWS water table elevation based on the 1994 survey data. The solid line indicates the 0.82m depth contour, which is representative of the minimum required depth for successful nesting

7. Acknowledgements

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8. References

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