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Tides, Waves and the Super-elevation of Groundwater at the Coast

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ABSTRACT

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The action of tides and waves results in a net super-elevation of the mean groundwater surface above the elevation of mean sea level at the ocean boundary to unconfined coastal aquifers. A comprehensive review is presented of recent analytical, laboratory and field research that investigates ocean-groundwater interactions at the coast. Groundwater over-height is shown to be a function of three principal factors: (1) the sloping beach face favoring vertical infiltration relative to horizontal outflow, (2) a 'decoupling' between the ocean and watertable around low tide, and (3) wave setup and runup further elevating the region of ocean infiltration above the elevation of the tide.

To exemplify the practical significance of groundwater over-height in the coastal zone, results are presented from a three month monitoring of the fluctuating groundwater profile within a narrow coastal aquifer (north coast New South Wales, Australia). The mean watertable on the upper beach face stood at over 1.2 m above mean sea level, rising to 2.0 m during a period of coincident spring tides, storm waves and rainfall. This elevation was sufficient to temporarily reverse net seaward groundwater discharge. Fourier analysis and cross-correlation assist to distinguish the role of tides in maintaining groundwater super-elevation, from the role of storm waves in further raising the coastal watertable for periods of 2 to 3 days. The results of a simple numerical simulation demonstrate that estimated rates of groundwater discharge at the study site were halved when the effects of tides and waves were incorporated in the definition of the ocean boundary.

ADDITIONAL INDEX WORDS: *Coastal watertable, beach face, runup infiltration, groundwater seepage, unconfined aquifer, coastal discharge, numerical simulation.*

INTRODUCTION

In the last five years a resurgence of interest in the coastal literature has highlighted that ocean processes can have a significant influence on unconfined coastal aquifers, resulting in a net super-elevation of the watertable at the land-ocean boundary to groundwater discharge. This theoretical and experimental notion appears to be less well recognized in the field of groundwater investigation, where it is common to assume that the coastal boundary is equivalent to mean sea level. This discrepancy may have important implications to a range of research and practical applications, including shoreline stability, the design of structures adjacent to the coast, water quality in closed coastal lakes and lagoons, coastal ecological studies, the operation of dune sewage disposal, and domestic water supply. A wider discussion of these applications is detailed in TURNER (1995a).

The objectives of this paper are twofold: in Part I the analytical and experimental results of a number of researchers are brought together to provide an overview of the current understanding of wave/tide-groundwater interactions; and in Part II the results of a field investigation are presented to provide a practical demonstration of the significance of tides and waves to groundwater research, planning and design in the coastal zone.

PART I: REVIEW

The watertable within a beach follows the diurnal rise and fall of the swash zone across the beach face. The elevation and extent of this region of runup infiltration and groundwater seepage is a function of several factors, principally beach morphology, tidal stage, and prevailing wave conditions. As the beach face represents the coastal boundary to groundwater discharge, investigation of watertable elevation and fluctuations immediately landward of this region is fundamental to a clear understanding of groundwater processes in the coastal zone.

The 'Textbook' Solution to Tidal Fluctuations

The governing equation for one-dimensional unsteady groundwater flow in an unconfined, homogeneous and isotropic aquifer of hydraulic conductivity K and specific yield (or drainable porosity) S_x is derived from Darcy's Law:

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$$v_x = -K\frac{\partial h}{\partial x} \qquad (1)$$

and the continuity equation

$$\frac{\partial h}{\partial t} = \frac{1}{S_x}\frac{\partial}{\partial x}(hv_x) \qquad (2)$$

where v_x is specific discharge (or Darcy velocity) and h the elevation of the free water surface (watertable) above some lower-bounding aquitard. Substituting Eqn. 1 into Eqn. 2:

$$\frac{\partial h}{\partial t} = \frac{K}{S_x w}\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) \qquad (3)$$

the familiar Boussinesq equation is defined to describe transient horizontal flow. Under the assumption that hydrostatic conditions prevail (i.e. horizontal flow dominates over vertical), this 1-D governing equation is sufficient to describe shore-normal groundwater flow (NIELSEN, 1990). In general, when the magnitude of watertable fluctuations is small compared with the depth d of the aquifer, Eqn. 3 may be linearized to give

$$\frac{\partial h}{\partial t} = \frac{Kd}{S_x}\frac{\partial^2 h}{\partial x^2} \qquad (4)$$

By substitution of aquifer transmissivity T (= hydraulic conductivity × saturated depth) and equating specific yield to unconfined storativity, Equation 4 reduces to a form more familiar in hydrological texts

$$\frac{\partial^2 h}{\partial x^2} = \frac{S_x}{T}\frac{\partial h}{\partial t} \qquad (5)$$

An idealized coastal geometry can be considered to be vertical beach face overlaying a horizontal impermeable layer. Numerous researchers have investigated the watertable fluctuations that result when this vertical coastal boundary is subject to periodic rise and fall of the ocean water-level (*e.g.* FERRIS, 1951; WERNER and NOREN, 1951; GREGG, 1966). For simplicity, the head at the ocean boundary is defined by a simple sinusoidal oscillation

$$h = h_0 \sin \omega t \qquad (6)$$

where h_0 is the tidal amplitude and ω is the angular velocity of the tide. If it is further assumed that $h = 0$ at $x = \infty$, by applying these boundary conditions a solution to Equation 5 is derived

$$h(x,t) = h_0 e^{-x\sqrt{\pi S_x/t_0 T}} \sin\left(\frac{2\pi}{t_0} - x\sqrt{\pi S_x/t_0 T}\right) \qquad (7)$$

This is the standard solution to tide-induced groundwater fluctuations found in popular hydrological texts (e.g. TODD, 1980 p. 242–246; FETTER, 1988 p. 156–157). The amplitude of groundwater fluctuations at a distance x from the shoreline is simply

$$h_x = h_0 e^{x\sqrt{\pi S_x/t_0 T}} \qquad (8)$$

and the time lag of these fluctuations relative to the ocean tide found by

$$t_L = x\sqrt{t_0 S_x/4\pi T} \qquad (9)$$

The tidal wave propagates landward through the coastal aquifer with a velocity

$$v_\omega = \frac{x}{t_L} = \sqrt{4\pi T/t_0 S_x} \qquad (10)$$

and wavelength

$$L_\omega = v_w t_0 = \sqrt{4\pi t_0 T/S_x} \qquad (11)$$

By substitution of L_ω for landward distance in Equation 8, the simplified solution (Equation 7) to tidal groundwater oscillations can be seen to describe a sinusoidal wave that decreases in amplitude landward by a factor $e^{-2\pi}$ per wavelength. The ratio of groundwater to tidal amplitude is known as the *tidal efficiency* of the aquifer (JACOB, 1940). Most importantly, *by this standard textbook solution the mean elevation at the land-ocean boundary is equal to mean sea level.*

Shortcomings

There are three principal shortcomings to the tidal groundwater solution presented above. The first is that waves are not included. Infiltration from wave setup and runup at the beach face will raise the effective ocean water-level above the elevation of the ocean tide. These processes are discussed later. The second and third inadequacies of this standard solution are of equal importance, for it fails to describe two important and experimentally well demonstrated characteristics of watertable fluctuations at the coast. Since the pioneering work of EMERY and FOSTER (1948) and the experimental work of a number of subsequent investigators (*e.g.* ERICKSON, 1970; HARRISON *et al.*, 1971; LANYON *et al.*, 1982; NIELSEN *et al.*, 1988), it is now well recognized that:

(1) coastal watertable fluctuations exhibit a marked *skewness* with time, and
(2) mean watertable elevation may stand significantly *above* mean sea level.

It is an over-simplification to consider beach watertable fluctuations as exponentially-decaying sinusoidal waves propagating landward around the elevation of mean sea level.

Vertical Beach Face Solution

PHILIP (1973) may be the first researcher to have investigated an analytical solution to the non-linearity of tidal watertable fluctuations. As a practical application of the more general problem of non-linear diffusion, the super-elevation of the mean groundwater-level landward of the beach face is shown to arise due to the non-linearity of Equation 3. This deviation becomes increasingly significant as the amplitude of tidal fluctuations h_0 approaches the depth d of the aquifer. Philip again assumed a vertical interface between the sea and land, and derived an expression for the asymptotic inland over-height h_∞, which as re-expressed by NIELSEN (1990) is approximately

$$h_\infty = \frac{h_0^2}{4d} \qquad (12)$$

For the extreme case of a tidal amplitude equal to the depth of a shallow coastal aquifer (i.e. $h_0 \approx d$), even in the absence of net through flow, the inland watertable will stand approximately 25% higher than mean sea level.

The simple physical explanation for this over-height phenomenon in shallow coastal aquifers is that the effective aquifer transmissivity (*i.e.* hydraulic conductivity × saturated depth) is greatest at high tide, so water from the ocean can flow landward more readily at high tide than it flows seaward at low tide. Analogous to wave setup at the shoreline balancing the excess landward flux of momentum in the nearshore, the over-height of groundwater at the beach face balances the tendency for enhanced landward flow. SMILES and STOKES (1976) confirmed experimentally the findings of PHILIP (1973) in a Hele-Shaw cell. KNIGHT (1981) further extended the analytical solution of Philip by demonstrating that it is valid for both two dimensional as well as one dimensional flow.

Sloping Beach Face Solution

The existence of an asymptotic inland over-height in the coastal watertable is a useful result, but it still does not provide insight into the dynamic behavior of coastal groundwater. It must also be emphasized that this mechanism is only significant in shallow aquifers. Importantly, this approach neglects probably the most critical physical process influencing groundwater elevation at the coast. The land-sea interface is (of course) a non-vertical beach face, and this sloping boundary dominates watertable response to ocean forcing.

The physical explanation for the significance of a sloping coastal boundary is straightforward to comprehend. Water can infiltrate vertically into the beach face during the flooding tide, but must seep essentially horizontally through the beach during the ebbing tide. In simple terms, a beach will 'fill' more easily that it can 'drain'. It is clear that a sloping beach face favors ocean inflow, implying a tendency for net super-elevation of the coastal watertable and an accompanying skewness of the time variation for tidal watertable fluctuations.

The analytical description of such groundwater behavior is unfortunately complex. The non-linear filter effect of a sloping beach face is an unusual boundary condition. Attempts at undertaking such analysis have only begun to appear in the literature within the last five years. NIELSEN (1990) adopted a perturbation approach in order to incorporate some of effects of a sloping beach face. The starting point is to assume that the solution to the 'sloping beach problem' can be written in the form

$$h(x,t) = h_0(x,t + \epsilon\, h_1(x,t) + \epsilon^2\, h_2\,(x,t) + \ldots\ldots \qquad (13)$$

where $h(x,t)$ is the time dependent elevation of the watertable at a point x landward of the shoreline, h_0 is the "vertical beach solution" (Equation 7), and the non-dimensional perturbation parameter ϵ is given by

$$\epsilon = k\mathrm{A} \cot \beta \qquad (14)$$

i.e. the wave number k times the horizontal semi-excursion of the tide across the beach face ($A \cot \beta$). A solution correct to the first order in ϵ was derived

$$h(x,t) = MSL + A\cos(\omega t - kx)e^{\sqrt{2}kx} + \epsilon A\left[\frac{1}{2} + \frac{\sqrt{2}}{2}\cos\left(2\omega t + \frac{\pi}{4} - \sqrt{2}kx\right)e^{-\sqrt{2}kx}\right] \qquad (15)$$

which shows that the first order effect of a sloping beach is to lift the mean watertable within a beach a distance $0.5\epsilon A$ above mean sea level, and produce a skewing of the time variation via the ($\cos 2\omega t$) term.

A comparison by NIELSEN (1990) of recorded water table fluctuations with both the vertical beach face solution (Equation 7) and the first order sloping beach face solution (Equation 15), found that some improvement is achieved. However, neither the predicted over-height nor the steepening of the rate of watertable rise are strong enough. A second order solution was found to provide only minor improvement.

Seepage Face Development

A fundamental assumption necessary to the derivation of the sloping beach face solution (Equation 15) is that the watertable tracks the movement of the tide across the beach face. Hence the elevation of the watertable immediately landward of the beach face is assumed to match the elevation of the ocean tide. In reality, across a low gradient beach face the watertable typically decouples during tidal ebb, resulting in the formation of a seepage face that continues to increase in vertical extent through the falling tide. An outcropping of groundwater at the beach face results when the rate of tidal fall exceeds some maximum rate of exit point fall. Once it has occurred the continued motion of the free surface, prior to exit point over-topping on the flooding tide, remains independent of ocean water-levels.

A recent field study of beach seepage face development is reported by TURNER (1993a, 1993b, 1994). The maximum rate of vertical exit point fall ($V_{\max}$) across a beach face can be approximated by

$$V_{\max} = -\frac{K}{n}\sin^2\beta \qquad (16)$$

where K and n are hydraulic conductivity and porosity of the beach face and β is beach face slope. By neglecting the effects of waves and assuming that the tide may be approximated by a simple sinusoid, TURNER (1994, 1995b) derived a seepage face parameter Σ to indicate the range of tide, morphological and sediment characteristics for which seepage face development is anticipated. From these results it is evident that watertable-tide decoupling will occur on all but the steepest of tidal beaches composed of very coarse sediment. In support of this field research, ASEERVATHAM *et al.* (1993) report on a series of Hele-Shaw cell experiments to test NEILSEN'S (1990) sloping beach face model, and similarly conclude that seepage face development limits the usefulness of the 1D analytical approach. It is notable that the lowest slope included in these laboratory experiments was 40°, clearly far in excess of typical beach face slopes, but still sufficient to produce significant deviation between observed and predicted near-coast watertable elevation and dynamics.

Wave Effects

The role of waves in further modifying groundwater elevation in the coastal zone is two-fold: setup at the shoreline results in a raising of the mean water surface at the shoreline; and runup of waves across the beach face further elevates the potential zone of seawater inflow. BOWEN *et al.* (1968) provided a simple model of setup B_s at the shoreline as a linear function of wave height

$$B_s = B_{min} + \frac{3}{8}\gamma H_b \qquad (17)$$

where H_b is breaker wave height, γ is the ratio of wave height to water depth and B_{min} is the maximum setdown immediately prior to wave breaking. With waves typically breaking in water depths approximately 1.2 times their height, setup at the shoreline by this formulation is anticipated to be approximately 25% of the height of wave breaking. This model provides an appealing means of predicting setup at the shoreline as a linear function of water depth. However, experimental studies including BOWEN *et al.* (1968) and VAN DORN (1976) suggest that the mean water surface close to the shoreline steepens still further. An extensive field investigation of setup along the NSW coast reported in HANSLOW and NIELSEN (1993) provides an alternative empirical relationship

$$B_s = 0.048(H_{orms}L_o) \qquad (18)$$

Here setup at the shoreline is given as a function of deep-water root mean square (rms) wave height H_{orms} and wave length L_o. As a rule-of-thumb, the authors conclude that shoreline setup on natural beaches will raise the mean water-level at the beach face approximately 40 % of the rms offshore wave height above the elevation of the ocean tide.

Runup of waves on the beach face is super-imposed on the already elevated mean water-level induced by wave setup. The maximum height of wave runup is a function of beach slope, slope roughness, slope permeability and wave steepness. These parameters are in turn dependent on such parameters as sediment grain size, local wave climate and nearshore bathymetry. Little work in quantifying rates of runup infiltration at the beach face has been attempted. NIELSEN *et al.* (1988) proposed an analytical approach to incorporate wave effects within a modified solution to coastal watertable fluctuations. The diffusion equation (Equation 3) becomes inappropriate between the still water-level X_S at the shoreline and the maximum runup limit X_R, and instead may be replace by

$$\frac{\partial h}{\partial t} = \frac{K}{n}\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + U_I \qquad \text{for } X_S < x < X_R \qquad (19)$$

where U_I represents some time-dependent rate of infiltration. For the simplified case of no tides the problem reduces to one of quasi steady-state conditions, and Equation 19 becomes

$$\frac{\partial^2 h}{\partial x^2} = -\frac{n}{Kd}U_I(x) \qquad (20)$$

An interesting result of this simple steady-state analysis is that if the (unknown) form of the infiltration velocity is assumed proportional to *K*, then solutions to Equation 20 (see NIELSEN *et al.*, 1988; KANG and NIELSEN, 1994) suggest that the inland over-height is independent of beach hydraulic conductivity. Recent wave flume experiments incorporating both fine and coarse sand appear to confirm this result (ASEERVATHAM *et al.*, 1993; KANG and NIELSEN, 1994; KANG *et al.*, 1994). Through regression analysis it was determined that, for the range of wave and beach slopes examined, watertable over-height in the absence of tides may be approximated by

$$h_\infty = 0.62 \tan\beta(H_oL_o)^{0.5} = 0.62\xi \qquad (21)$$

where ξ is the surf similarity parameter (BATTJES, 1971).

The inclusion of wave effects within the non steady-state description of tidal watertable rise and fall is yet to be attempted. Sufficient knowledge of infiltration characteristics within the runup zone is not available. In light of the additional complications inherent due to watertable-tide decoupling it appears unlikely that an analytical solution to wave/tide watertable response is close at hand. At present, site specific monitoring is the only practical means of quantifying groundwater over-height at the coast.

PART II: FIELD INVESTIGATION

Field Site and Methodology

To demonstrate the practical significance of tides and waves to groundwater elevation at the coast, a shore-normal transect of seven in-ground water-level recorders were installed within screened piezometers near Lennox Head, on the far north coast of New South Wales, Australia (Figure 1). The study aquifer is approximately 150 m wide and 30 m deep, representing a prograded Pleistocene sand barrier capped on its seaward side by a receding Holocene foredune system (ROY, 1982; DRURY, 1982). The inferred characteristics of the study aquifer are summarized in Figure 2.

The piezometer transect is bound on its western (landward) side by the coastal Lake Ainsworth, and on its eastern (seaward) side by the Pacific Ocean. The presence of the Lake provided a convenient control on the regional groundwater elevation. The occurrence of the heavy minerals rutile, zircon and ilmenite in economic quantities has resulted in extensive sand mining of the beach and frontal dunes prior to 1974 (NSW PUBLIC WORKS, 1983). This activity may account for the lack of indurated material encountered during aquifer investigations. Piezometer installation was achieved by vibrocoring and rotary drilling, permitting the recovery of core and sand samples for sieve grain size analysis. Hydraulic conductivity of the Pleistocene and Holocene units was inferred from the grain size technique of Hazen (refer FREEZE and CHERRY, 1979); and *in situ* from repeated compressed air slug tests analyzed by the methodology of HVORSLEV (1951). A more detailed discussion of the above equipment installation and aquifer investigations is detailed in TURNER (1995a).

The seaward-most piezometer (site A) was located on the upper beach face approximately 5 m seaward of the incipient foredune. This represents the approximate runup limit during spring high tides. The next four piezometers (sites B, C, D, G) were spaced at approximate 10 m intervals landward of this point. Sites E and F were located in the landward half of the aquifer (refer Figure 1). Piezometers were constructed

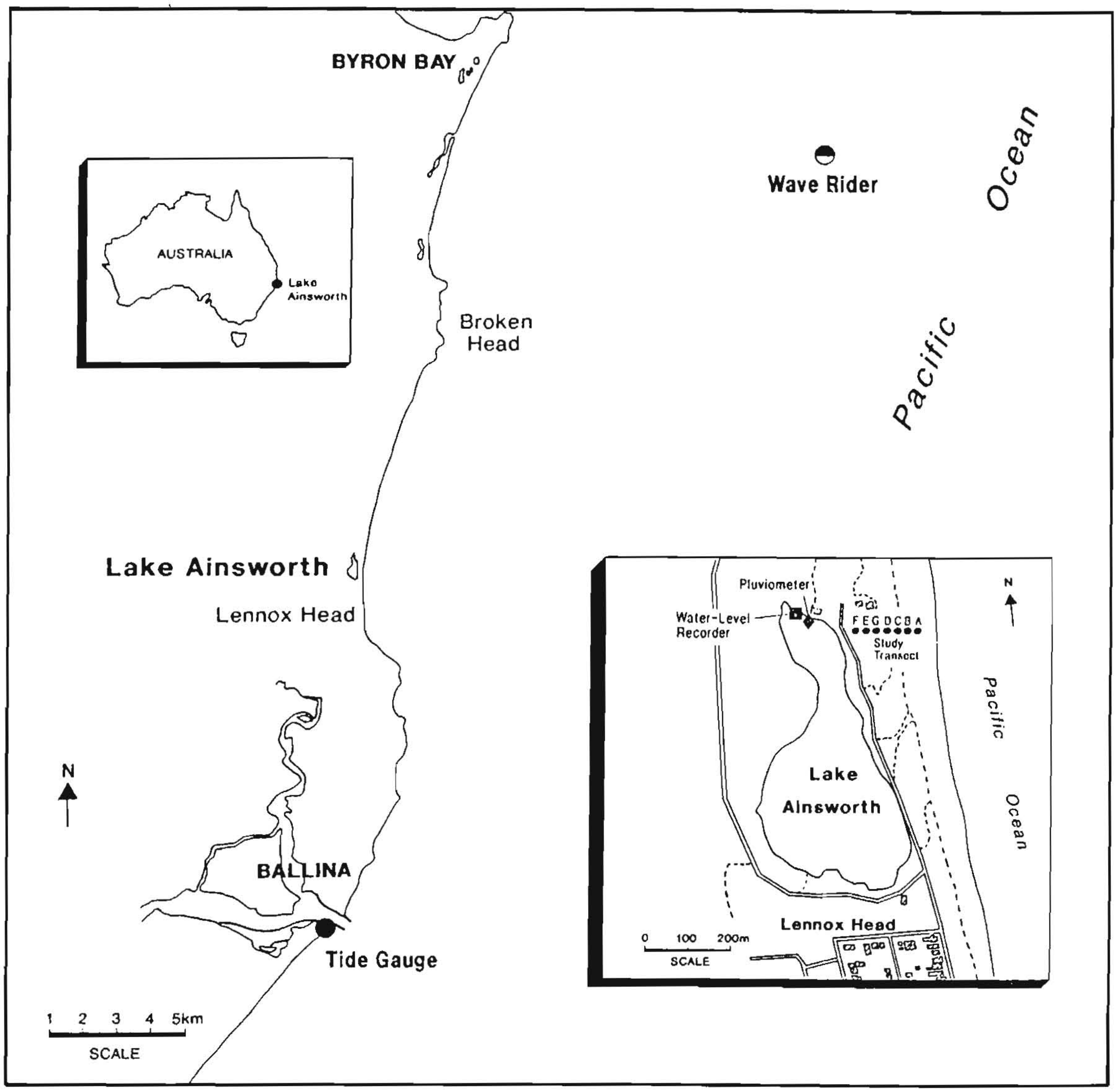

Figure 1. Location map of field site: near Lennox Head, on the far north coast of New South Wales, Australia.

of 50 mm PVC screwed and socketed pipe. The intake zone consisted of a 1.0 m section, machine slotted to 0.04 mm at a spacing of 10 mm. A geotextile sheath excluded the entry of fine sand. Pairs of screened piezometers were installed at sites B, C and F to assess the variation of hydraulic conductivity with depth.

At each site a stand-alone vented pressure sensor was installed to log at 15 minute intervals. A telemetered network of existing instrumentation maintained by NSW Public Works provided the additional data necessary to this study. Hourly significant wave heights were obtained from a waverider buoy located in approximately 80 m of water 20 km north-east of Lennox Head. A water-level recorder and pluviometer installed in Lake Ainsworth provided 15 minute lake-level and local rainfall intensities and duration. A tide gauge located 10 km to the south provided 15 minute ocean tide levels.

Results

Water-levels recorded at sites A to E for a three month monitoring period from October to December, 1994 are compiled in Figure 3 (site F is not shown—a fault in the instrument caused it to be highly temperature sensitive, resulting in a spurious diurnal signal). During this three month deployment the level of Lake Ainsworth fell approximately 450 mm from 2.15 to 1.70 m AHD (Australian Height Datum), before rising sharply in early December to its prior level. As

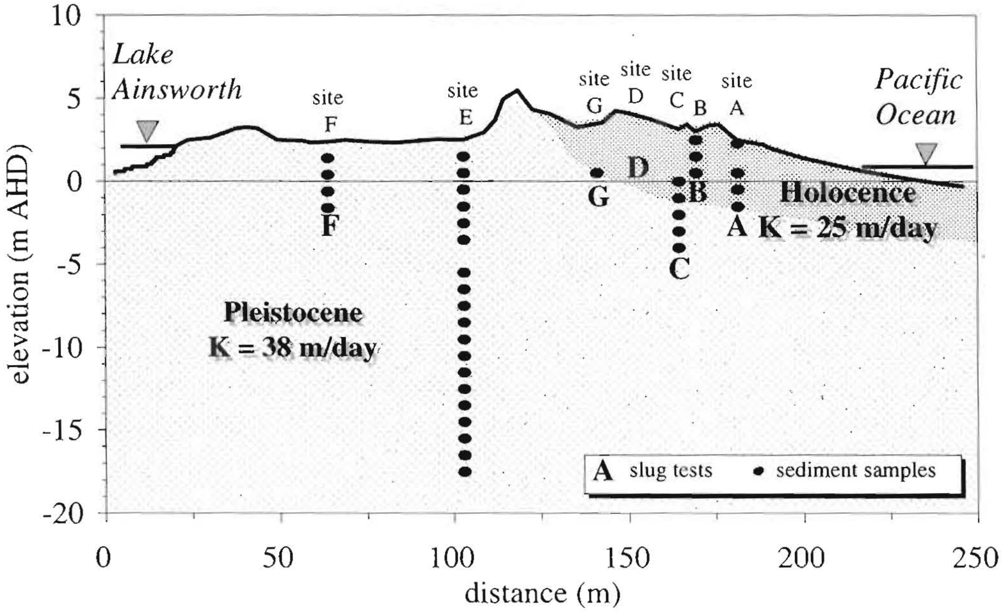

Figure 2. Summary of aquifer characteristics.

noted previously, the water-level in the Lake corresponds to the fall and rise of regional groundwater. In contrast, the elevation of the watertable at the upper beach face (site A) shows much greater variability (up to 1.0 m), fluctuating in the range 1.0 to 2.0 m AHD.

There are three notable features to these time series of near-coast groundwater elevation: the watertable at the land-ocean boundary is consistently elevated above mean sea level (≈ 0 m AHD); higher frequency (daily) oscillations of the order of 10 cm at the seaward-most well attenuate rapidly in the landward direction; and lower frequency, but larger magnitude (0.2–1.0 m) events further elevate groundwater for periods of several days.

Qualitative insight into the role of waves and tides in producing these latter two features of recorded watertable elevation can be inferred from Figures 4 to 6. In these Figures the elevation of the watertable at the seaward-most site A is plotted, along with the corresponding time series of ocean tide level, offshore significant wave height and rainfall (note change of watertable and rainfall axis-scaling in Figure 6). It is evident that higher frequency oscillations of the watertable correspond to the daily rise and fall of the tides, with the larger of these oscillations tending to correspond to periods of spring tides (*e.g.* around the 20th November, Figure 5). Peaks in the super-elevation of the watertable in October (21st–25th), November (7th–11th) and December (3rd–7th) are associated with larger wave events (of the order of 3.0 m significant wave height) super-imposed on spring tides. The highest watertable peak recorded in early December resulted from the coincidence of large waves (and hence significant setup and runup infiltration at the beach face), high ocean levels due to king spring tides, and significant rainfall (200+ mm in 48 hours). During this event the hydraulic gradient within the aquifer reversed for a period of approximately 2 days, indicating the stagnation and probable net landward flow of groundwater at this time.

Mean, Maximum and Minimum Watertable Elevation

The mean, maximum and minimum watertable elevations recorded at each site during the three month deployment are summarized in Table 1. The lake level is included for comparison. On the upper-beach face, in the vicinity of the runup limit of larger waves (site A), the mean elevation of the recorded watertable stood at over 1.2 m AHD. This single observation highlights the importance of including for the effects of waves and tides in coastal groundwater investigation. With the mean elevation of the Lake at approximately 2.0 m

Table 1. *Mean, maximum and minimum watertable elevation. Sites A to F, October–December, 1994 (Lake Ainsworth is included).*

Piezometer ID	Distance from Upper Beach Face (m)	Mean Elevation (m AHD)	Max. Elevation (m AHD)	Min. Elevation (m AHD)
Site A	0	1.22	2.00	0.94
Site B	12.5	1.33	2.05	1.06
Site C	21.4	1.42	2.12	1.14
Site D	31.9	1.45	2.16	1.20
Site G	41.4	1.52	2.21	1.24
Site E	79.2	1.63	2.12	1.34
Site F	118.6	1.84	2.25	1.54
Lake	161.4	1.99	2.12	1.71

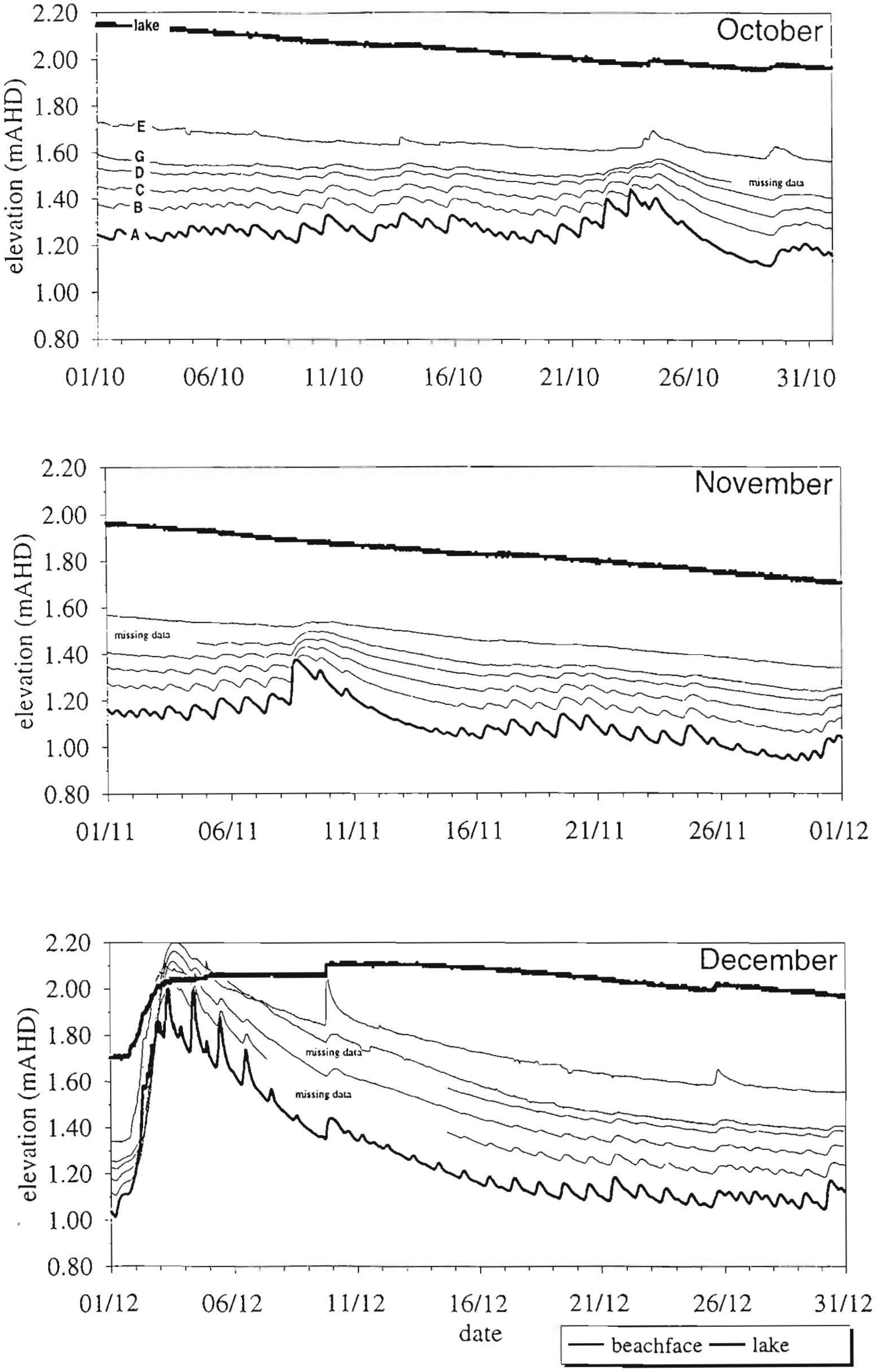

Figure 3. Logged water-levels: October to December, 1994.

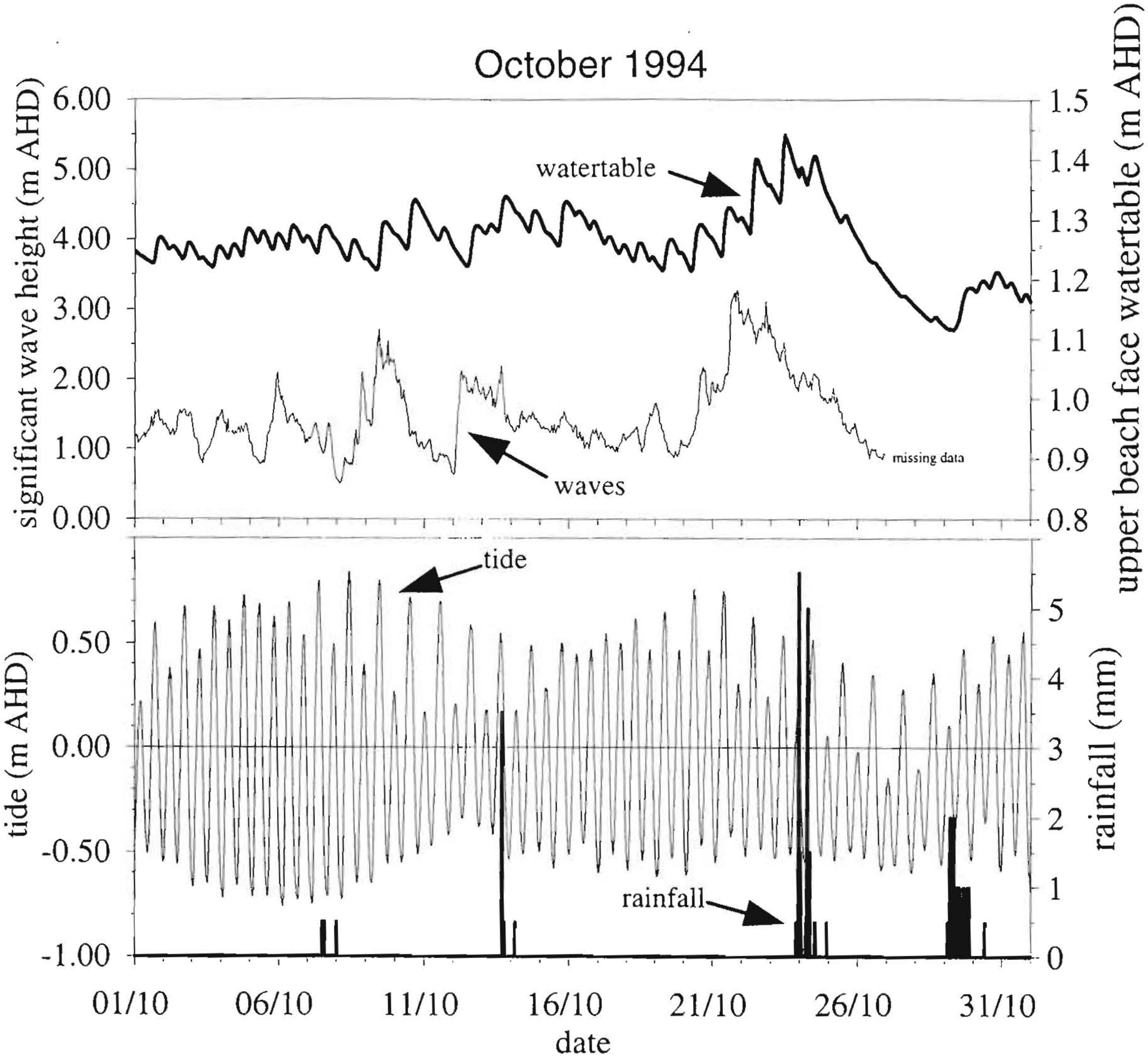

Figure 4. Upper beach face watertable, ocean tide level, offshore significant wave height and rainfall—October, 1994.

AHD, the prevailing assumption that mean sea level (0 m AHD) is the ocean boundary to coastal groundwater flow, would result in a more than doubling of the actual mean hydraulic gradient driving groundwater discharge. The tide, wave (and rainfall) driven fluctuations are of sufficient magnitude and duration to result in significant variability to rates of through-barrier flow.

Tidal Watertable Fluctuations

The landward propagation and attenuation of diurnal watertable oscillations is evident in Figure 3, and their association with ocean tides apparent from a visual examination of Figures 4, 5 and 6. Spectral analysis provides a convenient technique to further demonstrate the role of tides in driving coastal groundwater fluctuations, and the action of the beach face as a low pass filter to oscillations at the ocean boundary. In Figure 7 the time series of the tide and logged water-levels at sites A to D for the month of October have been transformed to the frequency domain. The time series were de-meaned prior to fast Fourier transformation, and smoothed using a Parzen window.

The rapid landward attenuation of the principal lunar (12.42 hrs) and principal solar (12.00 hrs) tidal constituents is apparent. Despite this diurnal frequency dominating tidal fluctuations, at site B (approximately 10 m landward of the beach face) corresponding watertable oscillations are virtually undetected. The merging of these two constituents in to one spectral peak in the tide and site A spectra is indicative of their frequencies being too close to distinguish. Spectral peaks corresponding to the principal diurnal lunar (25.82 hrs)

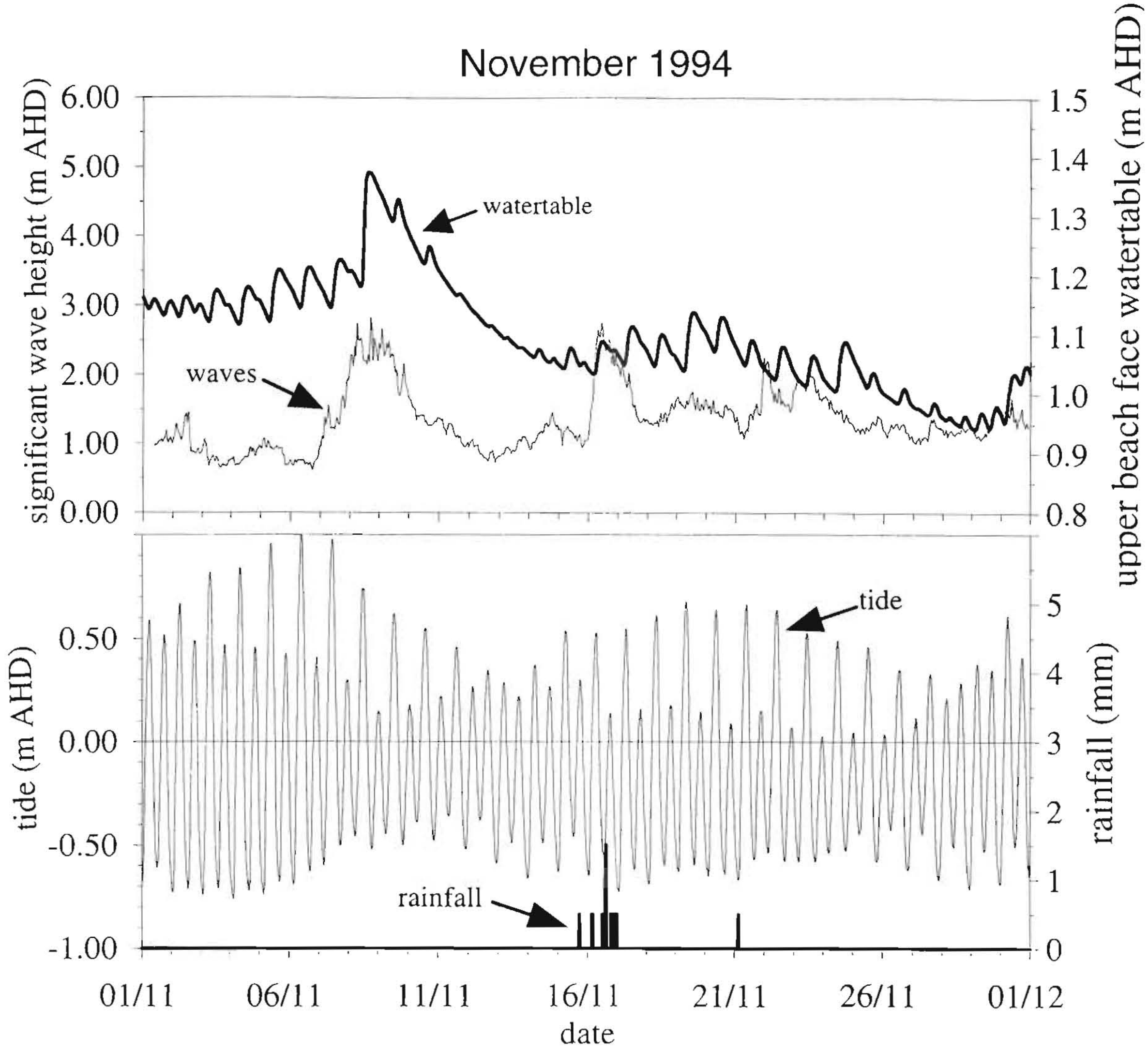

Figure 5. Upper beach face watertable, ocean tide level, offshore significant wave height and rainfall—November, 1994.

and principal diurnal solar (24.07 hrs) constituents are of greater relative importance, but again their attenuation is rapid. By site D (30 m landward of the beach face) diurnal watertable oscillations have almost disappeared. As has been noted by previous researchers (*e.g.* LANYON *et al.*, 1982; WADDELL, 1976; HEGGE and MASSELINK, 1991) it is apparent that the beach face acts as a low pass filter. The lower the frequency of periodic fluctuations at the beach face, the further inland these oscillations will propagate within an unconfined aquifer.

The landward attenuation of the tides may appear to suggest their relative insignificance to groundwater in the coastal zone. However this is a misinterpretation. For it is not the magnitude of tide-induced fluctuations that is significant, but rather their *asymmetry* in producing a super-elevation of the watertable. As illustrated in Figure 8, this results in a characteristic skewing of tidal watertable fluctuations. The watertable rises on the flooding tide at a greater rate than it falls during tidal ebb. The incomplete drainage of the beach face repeated over many tidal periods results in a net raising of the groundwater elevation above mean sea level, even in the absence of wave setup and runup. The lower the beach face slope and/or finer the sand of which it is composed, the higher coastal groundwater is anticipated to stand above mean sea level.

Wave-Associated Watertable Fluctuations

The role of waves in driving the larger groundwater fluctuations observed at Lennox Head has already been identi-

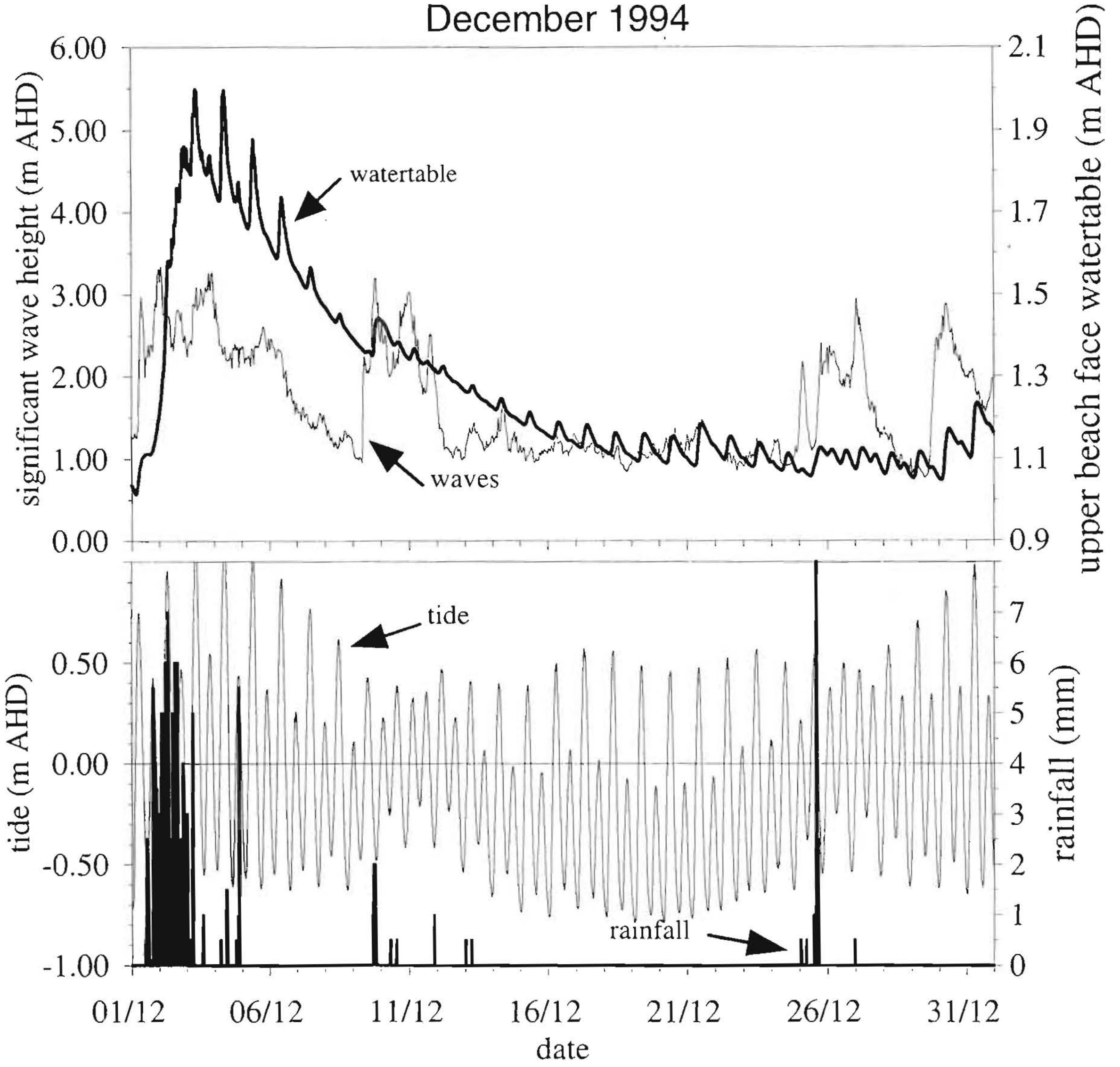

Figure 6. Upper beach face watertable, ocean tide level, offshore significant wave height and rainfall—December, 1994.

fied in a qualitative manner in Figures 3, 4 and 5. Cross-correlation provides a meaningful tool with which to quantify the strength of the association between wave height variation and recorded watertable fluctuations. In Figure 9 the results are shown of cross-correlation between offshore significant wave height and the recorded time series of groundwater elevation at sites A, B, C, and D. The month of November was selected for this analysis as negligible rainfall recorded during the 30 day period (refer Figure 4) removes the confounding influence of recharge by precipitation. Cross-correlations between recorded wave height and monitored watertable elevation are indicated for successive 15-minute time lags from 0 to 300 (*i.e.* 0 to 75 hours).

At all sites, strong correlation between wave height and watertable elevation is apparent, statistically significant at the 95% level. The time lag at which the peak correlations are calculated increase in the landward direction, demonstrating the relatively slow response rate of the coastal aquifer to varying setup and runup at the beach face. On the upper beach face (site A) the response of the watertable lagged changing wave height by close to 24 hours, and by site D this nearly doubles (41.5 hrs). The explanation for this marked delay in aquifer response to wave effects has not been previously addressed in the literature, but is probably accounted for by tidal regulation. Enhanced setup and runup will result in significant infiltration only when the mean water-level is elevated above the outcrop of the watertable on the beach face. As this is limited to around the daily highest

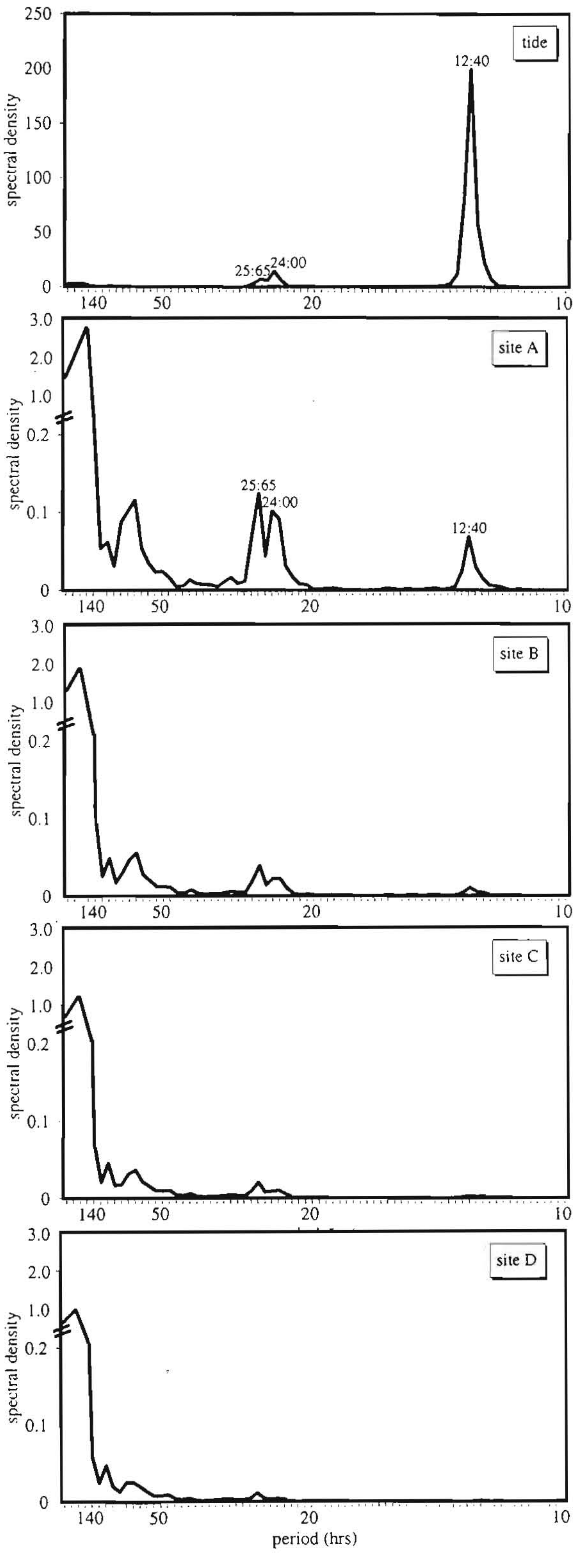

Figure 7. Spectral analysis of groundwater oscillations, sites A to D.

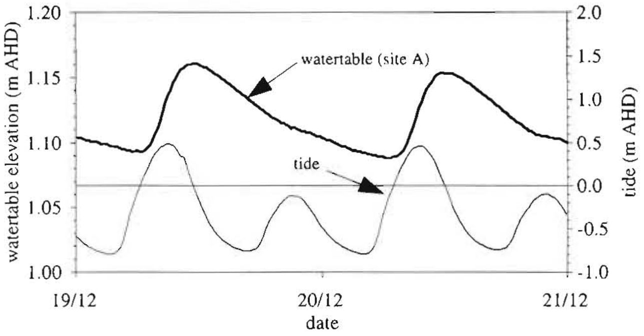

Figure 8. Asymmetric beach face watertable fluctuations.

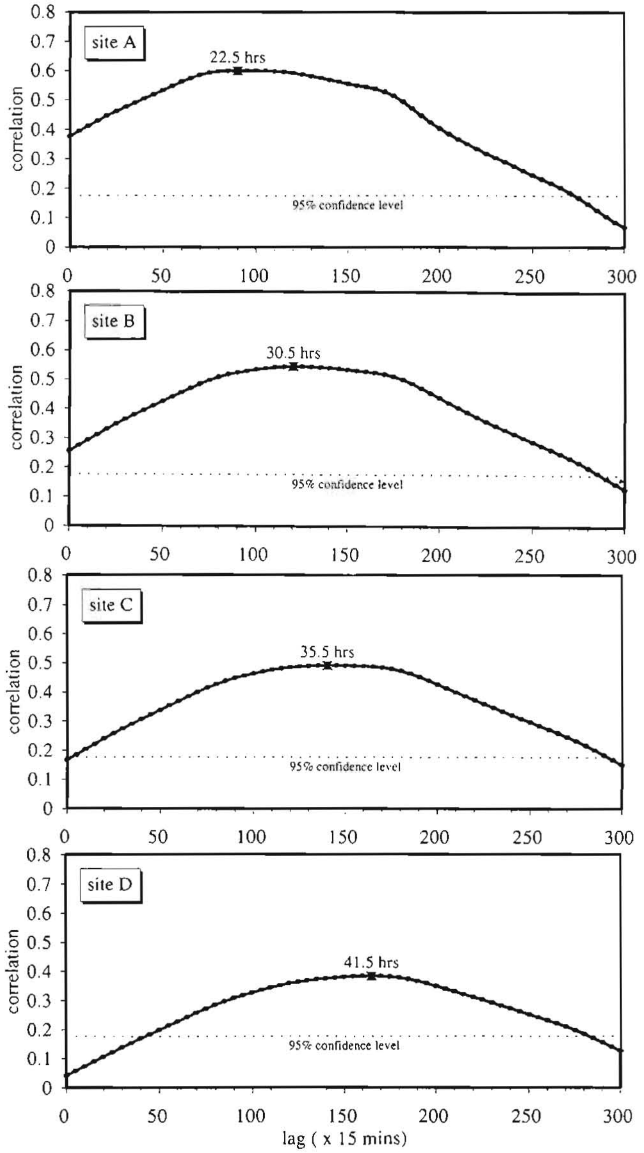

Figure 9. Cross-correlation between offshore significant wave height and beach face watertable elevation. Horizontal dotted line is 95% confidence level.

tide on fine sand and low gradient beaches, the tide in effect regulates the potential for groundwater inflow at the beach face.

Numerical Simulation

The three month field monitoring at Lennox Head confirms the theoretical notion that waves and tides are significant variables that should be considered within groundwater-related coastal research or management. To highlight the particular significance of the mean watertable standing above mean sea level, a simple numerical simulation was developed to enable rates of groundwater discharge to be contrasted in the presence/absence of beach face super-elevation.

It is tempting to foresee a numerical scheme that incorporates a sloping beach face, subject to the periodic rise and fall of the tide, superimposed by runup and backwash in the swash zone. Unfortunately, such a numerical model is most likely beyond the present state of the art. In particular, insufficient insight is available as to the rate and distribution of runup infiltration at the beach face. Further complications include the time-varying distribution of unsaturated flow, and the dynamics of the capillary fringe above an oscillating watertable. As a practical alternative, the simplified approach adopted here is to neglect the complexities of the beach face, and instead incorporate the monitored time-varying head at the aquifer-ocean boundary, within an 'off the shelf' groundwater package. The model used here is the U.S. Geological Survey's MODFLOW (McDONALD and HARBAUGH, 1984), the code most widely used by groundwater professionals. The pre- and post-processor PROCESSING MODFLOW (CHIANG and KINZELBACH, 1991) was used to calculate flow budgets. To keep the analysis as simple as possible, the model was effectively run in two dimensions (depth and shore-normal distance), to simulate groundwater discharge to the coast per unit width of shoreline.

Model Implementation

A two layer aquifer was defined, incorporating a 30 m deep Pleistocene unit, the top 5 m on the seaward side replaced by a Holocene unit (refer Figure 2). Model grid spacing in the x-direction (shore-normal) was set at 2 m, extending from the shore of Lake Ainsworth to the location of site A on the upper beach face. Three simulations are detailed. In all cases the landward (Lake Ainsworth) boundary was defined as a specified and variable head, matching the declining lake-level logged during the two week period from the 1st to 14th of November, 1994 (refer Figure 3). As no rainfall was recorded during this time (Figure 5) the need to incorporate recharge by precipitation is removed. The ocean boundary condition was defined in a different manner in each simulation:

(1) *simulation 1*—The logged water-level at site A was used to define a specified and variable head ocean boundary, corresponding to the super-elevated watertable recorded during the first two weeks of November.
(2) *simulation 2*—The ocean boundary was fixed at 0 m AHD at the position of site A equivalent to the upper beach face.
(3) *simulation 3*—The model grid was extended 40 m (20 grid cells) further seaward to match the intersection of mean sea level with the beach face. The ocean boundary was fixed at 0 m AHD at this position corresponding to the mid beach face.

The second and third simulations are both included as there remains some uncertainty as to where the seaward boundary to an unconfined coastal aquifer should be defined. It is anticipated that the upper beach face is more commonly selected, as this region is simpler to distinguish from maps and aerial photography. However, the intersection of mean sea level with the beach face is probably a more realistic choice.

The model was first run in a steady-state mode, to solve for initial heads within the aquifer. Transient simulations were then run for a simulated period of 14 days, incorporating 336 stress periods of 1 hour duration, 4 time steps (15 minutes) per stress period. Model calibration and verification was achieved by matching simulated heads with recorded water-levels at sites B, C, D, G, E and F.

Simulation Results

Figure 10 contrasts daily discharge (per meter shoreline) through the cross-sectional area of the model aquifer, measured mid way between the lake and ocean. The difference between calculated rates of groundwater discharge is striking. For the monitored ocean boundary (*simulation 1*), the mean daily rate of through-barrier flow is 5.0 m^3 per meter shoreline, contrasting with a more than doubled mean discharge rate of 11.6 m^3/m when the ocean boundary is fixed at 0 m AHD on the upper beach face (*simulation 2*). A modest reduction to 8.9 m^3/m in this mean rate of daily discharge is apparent when the ocean boundary is more realistically located on the mid beach face (*simulation 3*). It is also significant to note in *simulation 1* that, relative to mean daily through-flow, a 20% reduction in discharge is evident during the raised watertable event corresponding to the 8th November storm. Increased runup infiltration at the beach face resulted in enhanced super-elevation of the watertable, and hence a further reduction in hydraulic gradient driving groundwater flow to the coast. For a period of several days the daily rate of groundwater through-flow dipped appreciably below the calculated mean.

The importance of recognizing the role of tides and waves in super-elevating groundwater at the coast is succinctly demonstrated in Figure 11. Cumulative 14-day discharge for the three simulations is shown, and clearly illustrates that significant over-estimation of groundwater discharge can result when beach face super-elevation is neglected. Contrasting with the favored estimate of 70 m^3/m shoreline over the 14-day period, depending on where at the beach face the ocean boundary is deemed fixed at 0 m AHD, rates of simulated discharge vary between 125 m^3 and 163 m^3 per m shoreline. Integrated over much longer time periods, it is apparent that large discrepancies may arise between calculated and estimate discharge if the ocean boundary is inappropriately defined.

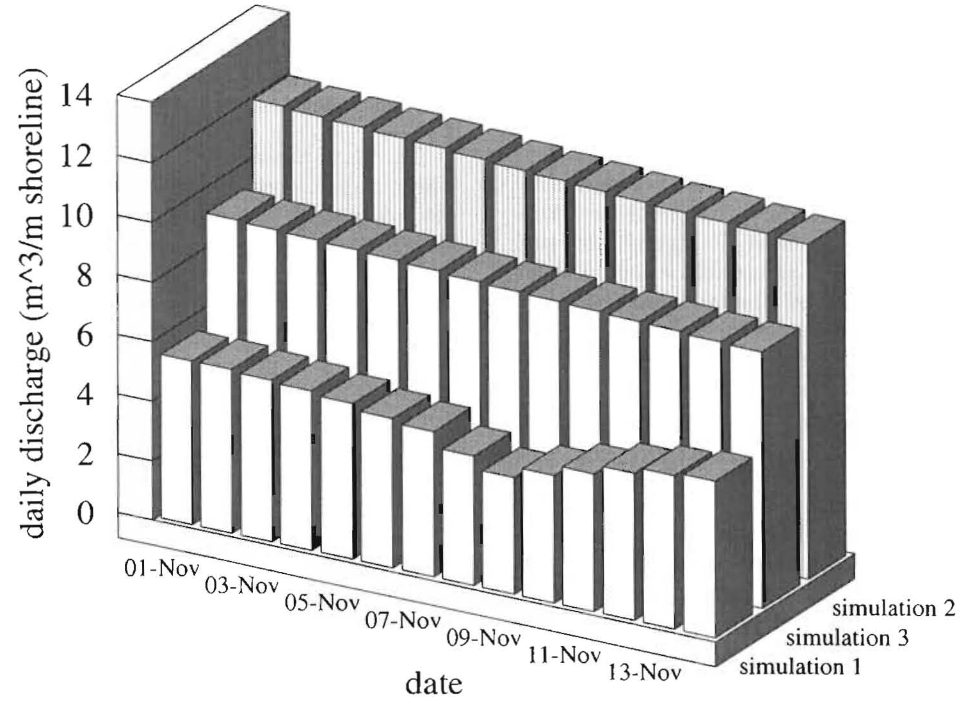

Figure 10. Comparison of daily discharge per m shoreline.

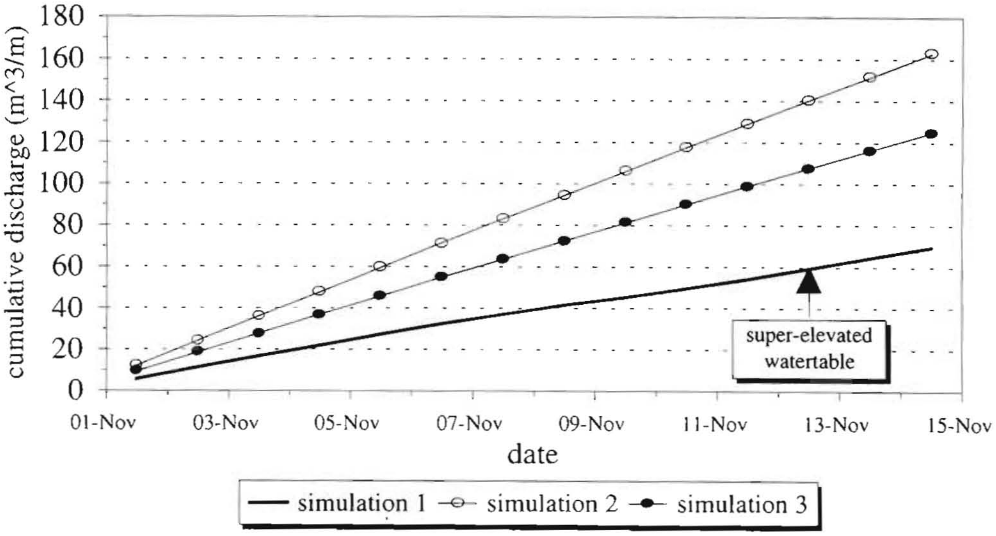

Figure 11. Comparison of cumulative discharge per m shoreline.

CONCLUSIONS

The action of tides and waves across a sloping beach face results in the super-elevation of groundwater at the coast. This is counter to a prevailing assumption that the ocean boundary to groundwater discharge is equivalent to mean sea level.

The periodic rise and fall of the tide produces an asymmetric variation in watertable elevation at the beach face. Due to the ability of a beach to 'fill' (vertical infiltration) more easily than it can 'drain' (horizontal seepage), watertable-ocean decoupling and seepage face development are common during the ebbing tide. Prior to over-topping by the flooding tide, the continued motion of the watertable exit point is independent of ocean water-levels. The action of wave setup and runup at the beach face results in further infiltration (and hence super-elevation) above the still ocean level.

The field results obtained in this study indicate that the magnitude of groundwater super-elevation can be significant. The mean beach face elevation of groundwater at the study site stood at approximately 1.2 m above mean sea level. This over-height was observed to vary by over 1.0 m, rising to a maximum of 2.0 m above mean sea level in response to coincident spring tides, storm waves and rainfall. It is anticipated that the height of groundwater super-elevation will increase with rising tide range, greater exposure to the prevailing wave climate, and finer sediment grain size.

The numerical simulation of coastal discharge in the presence/absence of a super-elevated ocean boundary demonstrates the practical importance of recognizing tide and wave effects when undertaking groundwater studies in the coastal zone. Calculated rates of discharge at the field site doubled when these processes were neglected.

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