

Groundwater-Table Responses to Wave Run-up: An Experimental Study From Western Australia

Bruce J. Hegge[†] and Gerhard Masselink[‡]

[†]Department of Geography
University of Western Australia
Nedlands, Western Australia
Australia 6009

[‡]Department of Physical
Geography
University of Utrecht
3508 TC Utrecht,
The Netherlands



ABSTRACT

HEGGE, B.J. and MASSELINK, G.M., 1991. Groundwater-table responses to wave run-up: an experimental study from Western Australia. *Journal of Coastal Research*, 7(3), 623-634. Fort Lauderdale (Florida). ISSN 0749-0208.

Groundwater-table responses to wave run-up were observed on a natural sandy beach at South City Beach, Western Australia. The run-up spectrum was dominated by a broad band of swell energy. In contrast the groundwater spectrum was dominated by low-frequency energy. Thus the beachface and sediment matrix effectively filter input swash oscillations as they are transmitted through to the groundwater-table. The filtering appears to be that of a band-pass filter in which oscillations with a frequency of 0.013 Hz (77 s) are less attenuated than either longer or shorter period fluctuations. Despite intense filtering, groundwater-table oscillations at incident swell frequencies were still detected. These oscillations were closely related to swash motions on the beachface.

Low-amplitude run-up did not induce a detectable response in the groundwater-table, and the groundwater-level continued to decline. Swashes with moderate run-up resulted in the transmission of a pressure force, via the saturated sands, which induced a temporary stabilizing of the falling groundwater-level. Swashes that extended beyond the mean groundwater-table level caused the groundwater-table to rise. The water-table rise and rate of rise were directly related to the amplitude of swash run-up. The groundwater-table rise was caused by swash water infiltration and in part by the reversed Wieringermeer effect. A groundwater-table response asymmetry was detected whereby the groundwater-level rises more rapidly than it falls.

ADDITIONAL INDEX WORDS: Beachface, groundwater, run-up, swash, beach water-table.

INTRODUCTION

On a sandy beach the water-table is an active boundary which responds to back-beach groundwater fluctuations, nearshore water-level oscillations and swash motion on the beachface (GRANT, 1946, 1948; EMERY AND FOSTER, 1948). These interactions are important in two respects. First, the elevation of the beach groundwater-table is an important factor governing beachface dynamics, and hence coastline stability. Second, the groundwater-level largely governs interstitial oxygenation processes and therefore controls biological gradients in the beach ecosystem (MCLACHLAN, 1980).

Previous studies of the dynamics of the beach groundwater-table have focussed upon long-period oscillations. These include groundwater-level changes induced by seasonal variations

(CLARKE AND ELIOT, 1983), barometric pressures (HARRISON *et al.*, 1971; DOMINICK *et al.*, 1971; ELIOT AND CLARKE, 1986), tides (DUNCAN, 1964; ERICKSEN, 1970; HARRISON *et al.*, 1971; NIELSEN *et al.*, 1988), shelf waves (LANYON *et al.*, 1982) and infragravity waves (WADDELL, 1973; LEWANDOWSKI and ZEIDLER, 1978). Despite the extensive literature on these long-period groundwater changes, high-frequency groundwater oscillations as a response to swash activity has received minor attention. Only two projects, those by WADDELL (1973, 1980) and BRADSHAW (1974), have monitored groundwater-level oscillations at incident swash frequencies.

WADDELL (1973, 1980) noted that high-frequency oscillations of the groundwater-table, with periods ranging from 8 to 11 s, could be identified in a well located 5 m landward of the base of the beach, just beyond the uprush limit. He ascribed the oscillations to a pressure force transmitted through the saturated sand by

waves breaking at the base of the beachface. This pressure force caused an instantaneous rise of the groundwater-level.

BRADSHAW (1974) positioned groundwater wells on the saturated beachface. He suggested that incident groundwater fluctuations were induced by a pressure force transmitted through the saturated portion, and infiltration into the unsaturated part of the beachface.

Recent work by NIELSEN *et al.* (1988) and TURNER (1989) has highlighted the importance of the reversed Wieringermeer effect in beach groundwater-table studies. This effect has been investigated by GILLHAM (1984) and refers to the disproportionately large and rapid water-table rises induced by the addition of a thin film of water when the capillary fringe extends to the surface. The capillary fringe is a zone of fully saturated sands that extends above the water-table. The superelevated groundwater is maintained by capillary forces and thus the pore water pressure is less than atmospheric. Field measurements by TURNER (1989) appear to confirm the existence of the capillary fringe in sandy beaches.

Although these projects made a significant contribution to our understanding of swash and groundwater interactions, the effect of individual swashes on the groundwater-table has not been examined in detail.

ENVIRONMENTAL SETTING

Fieldwork was conducted on 1 November 1989 at South City Beach, an open coast beach in the Perth Metropolitan Region, Western Australia (Figure 1). This coast experiences a mixed, but predominantly diurnal, tidal regime, with a Lowest to Highest Astronomical Tidal range of 1.1 m (ANON., 1989). Spring tide conditions were experienced on the day of the experiment with a tidal range of 0.6 m. Data collection commenced some 35 minutes after high tide. No rainfall was recorded in the week preceding this experimental run.

A groyne was located approximately 120 m north of the experimental profile. To the south the beach is uninterrupted for 5 km. At the time of the survey, low-relief cusps, with wavelengths in the order of 30 to 40 m, were apparent on the upper beachface. The beachface had a slope of approximately 7 degrees (Figure 2). The quartz/carbonate sediment obtained from

the surface of the mid-beachface had a mean and median grain size of 0.35 mm and its grain size distribution was moderately well sorted, following the classification of FOLK (1974). Detailed observations of the beachface stratigraphy or textural variation with depth were not conducted.

Total porosity, calculated by using methods outlined by DANIELSON and SUTHERLAND (1986), was 38%. Sediment infiltration rate was measured *in situ* using a constant head technique similar to that described by BOUWER (1986). The resulting saturated, steady state, hydraulic conductivity was calculated for sea water using the method described by TURNER *et al.* (1984) and resulted in a value of 0.077 cm/s.

During the experiment, waves were normally incident and predominantly swell with periods ranging from 10 to 20 s. Breaker heights in the order of 1 m prevailed for the duration of monitoring. Breaker shape was predominantly plunging/collapsing in accordance with the classification of GALVIN (1972). The surf zone was approximately 25 m in width. The excursion length of the uprush, measured from the mean sea-level intercept to the uprush limit, had a mean and maximum of 7.5 m and 11 m respectively. The value of the surf scaling parameter (GUZA AND INMAN, 1975) during this experiment was 0.7, indicative of morphodynamic conditions associated with wave reflection (WRIGHT AND SHORT, 1984).

METHODOLOGY

Field equipment was deployed to monitor swash motion on the beachface and the beach groundwater-level. The data were collected with respect to a single shore-normal profile located on a cusp salient. In order to determine groundwater responses to individual swashes, it was necessary to obtain data on run-up and groundwater-level simultaneously. Digital loggers were employed to record the data with a sampling interval of 0.25 s. The beach profile and field equipment was surveyed using standard levelling techniques. All elevations were referenced to mean sea-level, which was determined from a time average of a nearshore stilling well record.

A dual resistance wire, similar to that used by HOLMAN AND GUZA (1984), was positioned

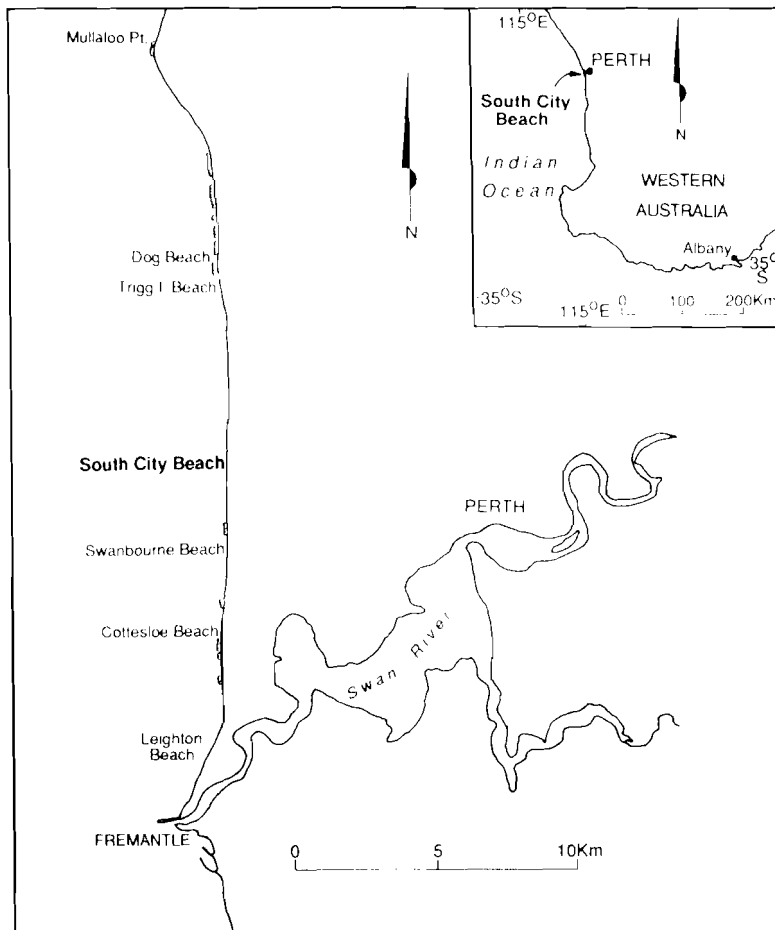


Figure 1. Regional setting and location of South City Beach in the Perth Metropolitan area.

across the beachface in order to measure the location of the leading edge of the swash. The wire was 15 m in length and positioned at an elevation of 2 cm above the bed. This elevation was maintained by frequent adjustments throughout the experiment, since HOLMAN AND GUZA (1984) showed that the precision of the run-up sensor is highly dependent upon the elevation of the wire above the beachface. The run-up wire was calibrated *in situ* before and after the experiment and resulted in a variance error of approximately 1%.

A groundwater piezometer was positioned at the berm crest, some 15 m landward of the mean sea-level intercept. The elevation of the beachface groundwater-table in this piezometer was

monitored by using a capacitance water-level probe, with an accuracy of $\pm 1\%$. Numerous perforations in the base of the piezometer allowed free flow of groundwater and enabled an almost instantaneous response. These perforations were covered by a fine mesh to prevent sand intrusion.

OBSERVATIONS AND ANALYSIS

During the 46 mins of data collection 233 separate swashes were recorded. The average run-up of the swashes was 890 mm (Table 1). The mean elevation of the beach groundwater was 880 mm.

Inspection of the groundwater record indi-

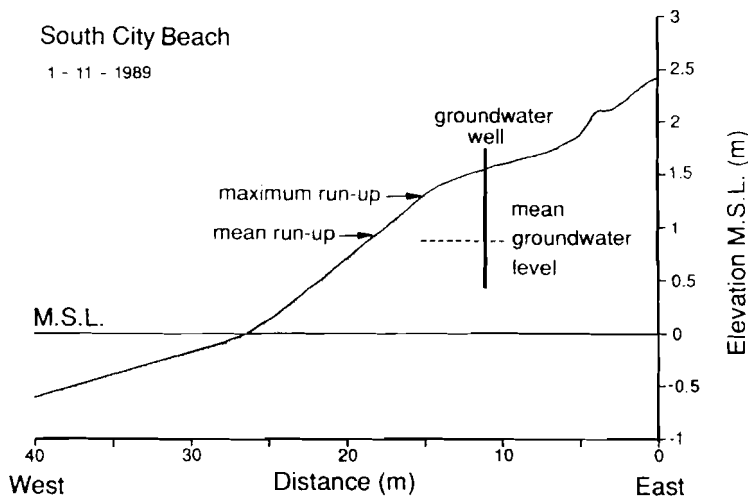


Figure 2. Beach profile showing the position of the groundwater well on the beach and the mean groundwater-table elevation.

Table 1. Descriptive statistics for run-up and groundwater-level.

Variable	mean	s.d.	min.	max.	n
Run-up (mm)	890	190	490	1330	223
Groundwater-level (mm)	880	10	850	920	11000

cated that it was possible to detect groundwater responses to individual swashes (Figure 3). An individual swash uprush induces one of three types of groundwater-level response. A swash may:

- (1) produce no response of the groundwater-table;
- (2) interrupt the water-table decline so that the groundwater-level remains temporarily stable; or
- (3) cause the groundwater-level to rise.

It was expected that the elevation of the uprush limit, run-up, would be a significant factor determining the type of groundwater response.

An event-by-event analysis was conducted in order to examine the type of groundwater response induced by each swash. In the analysis, water-table responses were matched to the run-up that induced the response. Only 16% (38) of swashes had no detectable influence on

the groundwater-level. The mean run-up of these swashes was 680 mm (Table 2). A detectable groundwater response occurred as the run-up increased in amplitude. Thirty-three percent (74) of swashes resulted in a stabilizing of the groundwater-table and had a mean run-up of 810 mm. An actual rise in the groundwater-table was induced by 52% (121) of the swashes. These swashes had a mean run-up of 1020 mm.

Of the 121 swashes which resulted in a groundwater rise, the mean rise was 7.4 mm (Table 3). The average rate of rise was 1.3 mm/s, and a maximum of 5.2 mm/s was recorded. The event-by-event analysis demonstrated that the peak in the groundwater-table lagged an average of 4 s behind the time of maximum swash excursion. The groundwater-level declined 120 times during this experiment, with a mean fall rate of 0.2 mm/s and a maximum fall rate of 0.5 mm/s.

Groundwater Rise and Rates of Groundwater Change

The 121 swashes which resulted in a groundwater rise were examined further to determine whether the run-up had a significant influence upon either the magnitude or rate of groundwater-level rise. An event-by-event approach

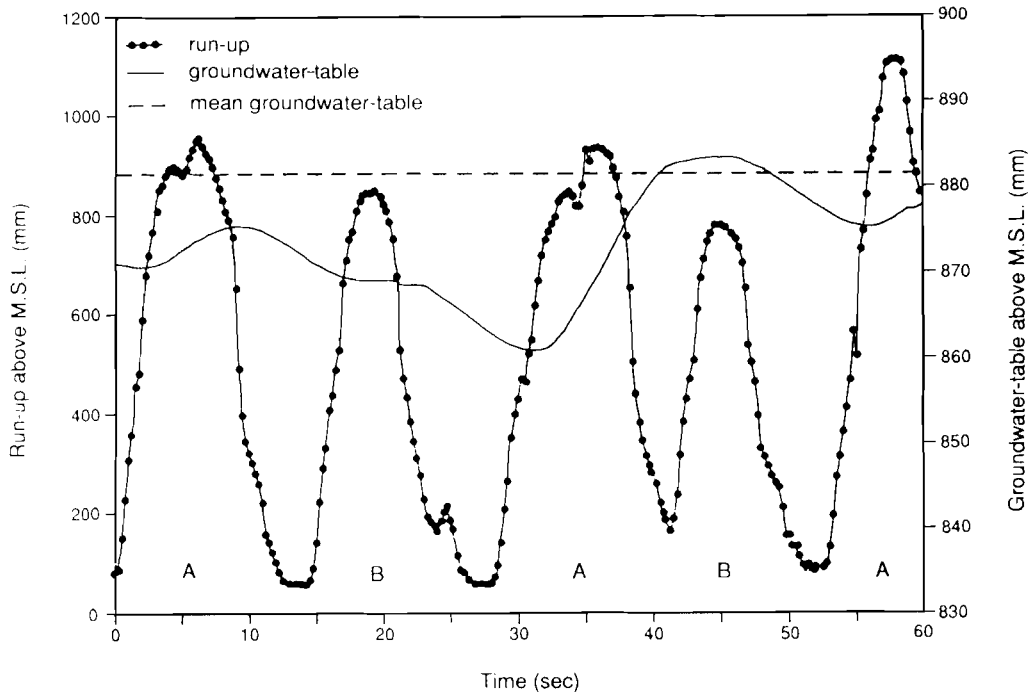


Figure 3. Example of the run-up and groundwater-level records. Two types of groundwater response to wave run-up can be identified in this diagram: (A) a rise in groundwater-level, (B) a stabilized groundwater-level. Note the groundwater response asymmetry, with rapid rise rates and slow descents.

Table 2. Description of run-up characteristics for the three types of groundwater responses.

Groundwater response	Run-up characteristics			
	mean (mm)	s.d. (mm)	n	%
No response	680	0.11	38	16
Stable watertable	810	0.11	74	32
Rise in watertable	1020	0.15	121	52
Total	890	190	233	100

was adopted whereby run-up was separately regressed against the corresponding amount of

Table 3. Descriptive statistics for groundwater rise, groundwater rise rate and groundwater fall rate.

Variable	mean	s.d.	min.	max.	n
Groundwater rise (mm)	7.4	7.3	0.2	46.6	121
Groundwater rise rate (mm/s)	1.3	0.7	0.2	5.2	121
Groundwater fall rate (mm/s)	0.2	0.1	0.0	0.5	120

groundwater rise and the rise rate (Figures 4 and 5). Both regression slopes were positive and significant at the 5% significant level ($p < 0.05$). They explained 51% and 49% of the variance respectively.

The influence of the antecedent groundwater condition on the magnitude and rate of groundwater rise was also examined. The preceding elevation of the groundwater-table was negatively related to the magnitude of groundwater rise. However, this association was found to be marginally significant ($p < 0.05$), with a coefficient of determination (R^2) of 0.05. The preceding groundwater-level had no significant ($p < 0.05$) influence on the groundwater rise rate. It was found that the preceding groundwater elevation was positively related to the fall rate of the groundwater-table. The coefficient of determination (R^2) was rather low (0.20), but significant ($p < 0.05$).

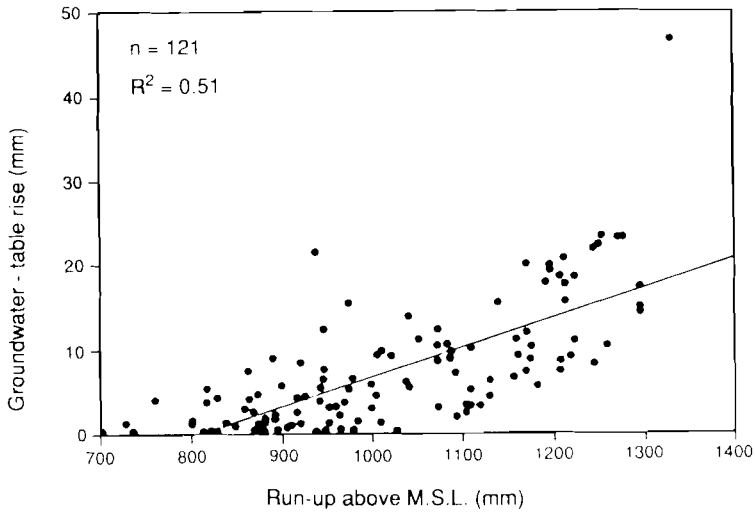


Figure 4. Relationship between run-up and groundwater-level rise.

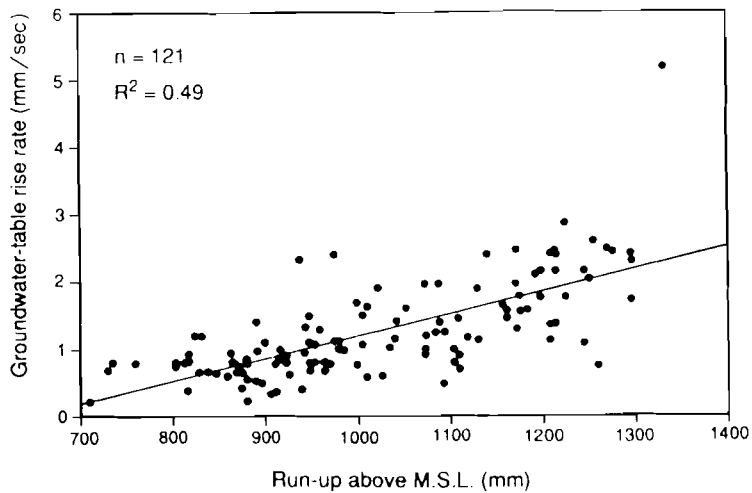


Figure 5. Relationship between run-up and groundwater-level rise rate.

SWASH—GROUNDWATER-TABLE INTERACTION

Previous surveys of wave propagation across

the groundwater-table (*e.g.* EMERY AND FOSTER, 1948; WADDELL, 1973, 1980; LEWANDOWSKI AND ZEIDLER, 1978) have stressed the filtering capacity of the beach matrix. This filtering

effect is apparent as a change in wave amplitude occurring with distance landward from the beachface. It can be discerned from spectral analysis of the time series records of run-up and groundwater-level. In this context a fast Fourier transform (COOLEY *et al.*, 1976) was performed on the run-up and groundwater records in order to determine the dominant frequencies operating on the beachface. The run-up spectrum (Figure 6) contains a broad band of swell energy from 0.05 Hz to 0.10 Hz. Two distinct swell peaks are apparent at 0.067 Hz (15 s) and 0.079 Hz (13 s). A clear spectral peak with a frequency of 0.021 Hz (48 s) is present at the low-frequency end of the spectrum. The origin of this wave is unknown. Several other distinct peaks are present in the low frequency end of the run-up spectra.

The groundwater spectrum contains less overall energy than the run-up spectrum and is dominated by low-frequency energy (Figure 7). Three distinct peaks are apparent at frequencies of 0.0055 Hz, 0.0127 Hz and 0.019 Hz, corresponding to periods of 182 s, 79 s and 53 s respectively. These peaks correspond closely to the first three peaks at the low-frequency end of

the run-up spectrum. It is noteworthy that the groundwater spectrum also contains a small amount of energy at the two swell frequencies.

In order to further examine the relationship between run-up and groundwater, in the frequency domain, the coherence and gain functions were calculated. The coherence function was calculated to establish the degree of association between the run-up and groundwater series. The coherence at each frequency can be interpreted as a correlation coefficient and thus expresses the degree of linear relationship between the two time series at each frequency (Koopmans, 1974). A coherence of one corresponds to the maximum degree of correlation possible, similarly a zero coherence indicates a complete lack of correlation.

EMERY AND GALE (1951) were among the first to recognize that the beachface acts as a filter that allows only the larger or longer period swashes to pass. In order to directly determine the filtering effect of the beachface, a gain function was calculated. The gain function expresses the linear amplitude modification of common components of one time series to form a second (BRILLINGER, 1975). Thus, the gain

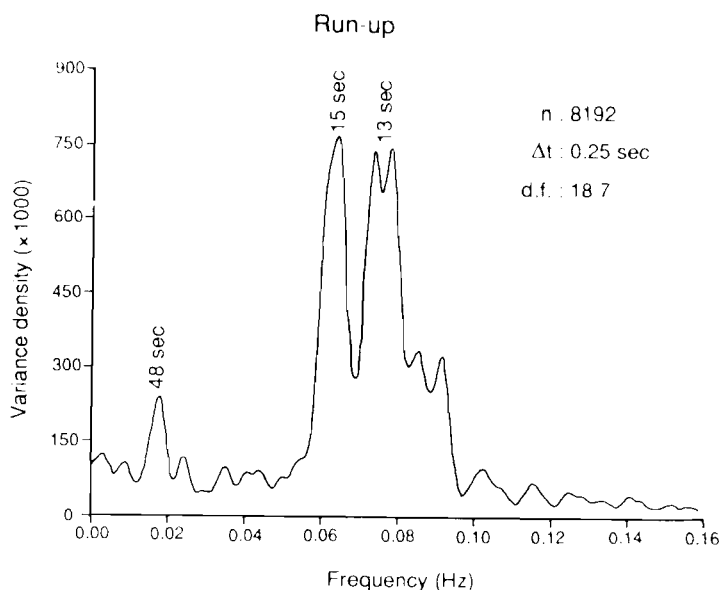


Figure 6. Energy spectrum of run-up. Note the broad band of swell energy, from 0.05 to 0.10 Hz, and the low-frequency peak at 0.021 Hz.

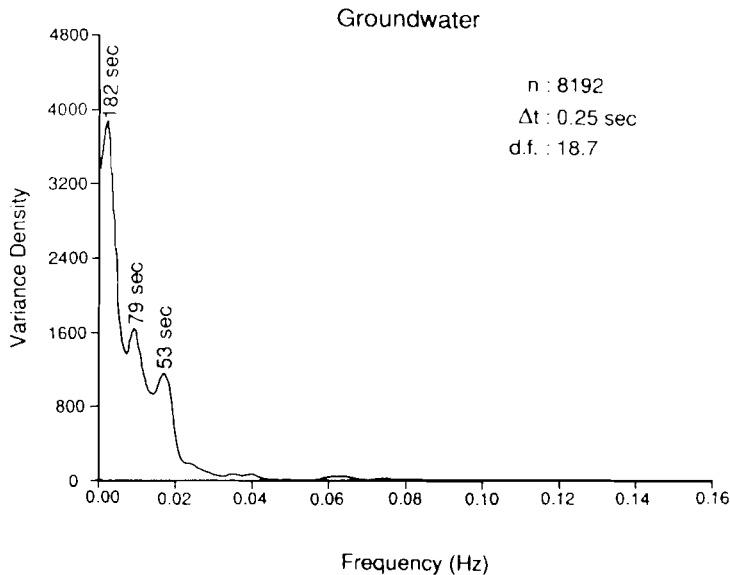
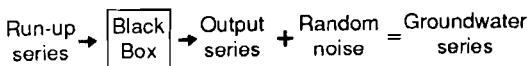


Figure 7. Energy spectrum of groundwater. The spectrum is dominated by low-frequency energy, though some energy is present across the incident swell band.

function displays the proportion of each frequency of the input series that is transferred to the output series.

The coherence and transfer functions are closely linked. This linkage may be demonstrated from the conceptual sequence illustrated below.



The coherence function expresses the association between the input run-up time series and the measured groundwater time series. Thus, the coherence function reflects the degree of noise that is added following the "black box" transformation. The gain function, on the other hand, reflects the amplitude modification from the input run-up series to the output series.

High coherence between the run-up and groundwater records was detected at the low-frequency (48 s) peak and across the broad swell band (Figure 8). This supports the observation that frequencies detected in the groundwater

record at both low- and high-frequencies are largely determined by oscillations of similar frequency occurring on the beachface.

The gain function from run-up to groundwater demonstrated that attenuation of long-period waves is smallest (Figure 9). A distinct peak in the gain function is apparent at a frequency of 0.013 Hz (77 s), which closely corresponds to the 0.0127 Hz (79 s) peak in the groundwater spectrum. A rapid increase in the degree of attenuation is apparent from 0.013 Hz to 0.04 Hz. Frequencies higher than 0.04 Hz are strongly attenuated.

DISCUSSION

The beachface acts to reduce the amplitude and frequency of the input swash energy. Comparison of the run-up and groundwater spectrum shows a considerable reduction in overall energy and also a shift in dominant energy towards lower frequencies. Examination of the gain function indicates that waves with a period of 77 s are selectively transferred from the swash into the groundwater-table at South City Beach. The filtering appears to be that of

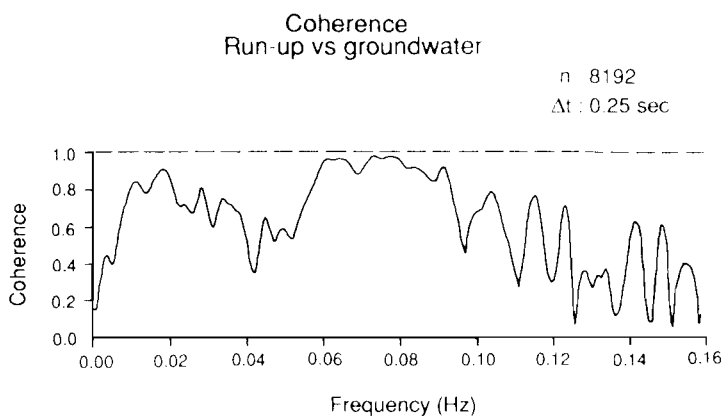


Figure 8. Coherence between run-up and groundwater. Note the high coherence across the broad swell band and at the low-frequency peak at 0.021 Hz.

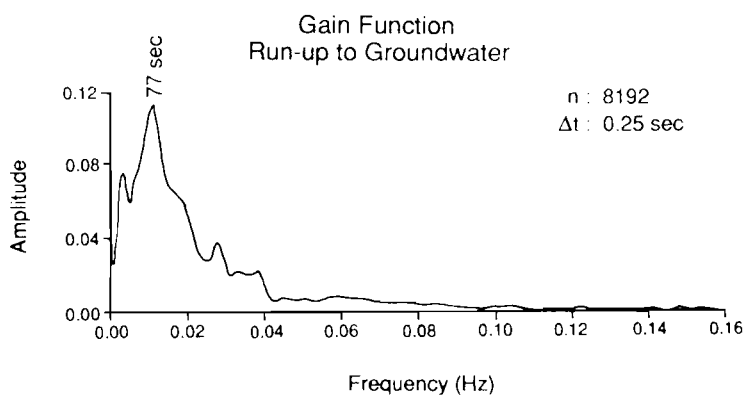


Figure 9. Amplitude of gain function from run-up to groundwater. Attenuation of energy is least from 0.005 to 0.015 Hz, frequencies higher than 0.04 are strongly attenuated.

a band-pass filter which selectively transmits a particular frequency range and filters both higher and lower frequencies.

Gain functions from waves to groundwater were also presented by WADDELL (1973) and LEWANDOWSKI AND ZEIDLER (1978). Visual examination of the functions presented by these researchers reveals a frequency band which was not strongly attenuated. However, it is not yet known what determines the occurrence or fre-

quency of the pass band on a particular beach. It is considered by the present authors that the cut-off frequencies of the filter will be a function of tidal state, hydraulic conductivity, beachface slope and the position of the groundwater piezometer relative to the shoreline. Further field experiments on different beaches and under different tide and wave conditions will be necessary to test this.

Despite the acute filtering of swell energy,

swell frequencies were still detectable in the groundwater-table oscillations. High coherence between the run-up and groundwater series across the incident swell band demonstrated that the groundwater-level oscillations are induced by swash motions on the beachface. Close inspection of the run-up and groundwater-level time series showed that the amplitude of the swash run-up influenced the type of groundwater-level response. These responses were examined further by event-by-event analysis.

Prior to the arrival of a swash at the base of the beach the groundwater-table was generally in a state of decline. If the run-up of the subsequent swash was of low-amplitude, and the swash did not substantially exceed the mean groundwater-level, then the groundwater-table continued to decline and no detectable groundwater-level response was identified.

The groundwater-table decline is a gravity driven discharge, the rate of which is governed by the hydraulic head. Fall rates consequently have a low deviation and are positively related to the antecedent groundwater-level. The groundwater discharge may be either landward or seaward, the net direction will depend on the hydraulic gradient, which will alter throughout the tide cycle. Despite the significance of the hydraulic head it is expected that the hydraulic conductivity of the beach matrix will be of greater importance in governing the rate of groundwater-table discharge.

As the amplitude of an individual swash increases the falling groundwater-level is first stabilized as a result of pressure forces transmitted through the saturated sands and then further raised by direct swash input. The pressure effect was first identified by WADDELL (1973). At South City Beach, the majority of swashes causing a temporary groundwater-level stability were below the mean groundwater-level and hence did not extend beyond the saturated beachface sands. Thus, their influence on the groundwater-table is via a mass pressure flux through the saturated sands.

Eighty percent of swashes that extended beyond the mean groundwater-level induced a rise in the groundwater-level. The groundwater-table rise would be a response to the swash infiltration with the additional influence of the reverse Wieringermeer effect. It is not possible

to examine these mechanisms separately with the present data. Swashes with a large run-up had a correspondingly large input area and hence caused the magnitude and rate of groundwater-level rises to increase. Nevertheless, groundwater-table responses are the result of a combination of pressure forces and water input.

A typical groundwater-level rise response is characterized by the following sequence of events. Prior to the arrival of the swash at the base of the beach the groundwater-level is declining. As the swash advances up the beachface the groundwater-level is temporarily stabilized. The groundwater-table begins to rise as the swash extends beyond the outcrop of the groundwater-table on the beachface. Generally the groundwater-table ceases to rise some 4 to 5 seconds after the swash mass reached its maximum landward excursion. This lag may be attributed to the effects of frictional retardation on the input swash water.

These results are in contrast to the findings of WADDELL (1973). He noted that a wave arriving at the base of the beachface induced an instantaneous groundwater-level rise as a result of the transmission of pressure forces through the saturated sands. WADDELL (1973) also observed that the maximum groundwater-level lagged less than half a second behind the maximum swash depth at the base of the beachface. WADDELL (1973) thereby emphasized the importance of pressure forces transmitted through the saturated sand which induced high-frequency groundwater-level rise responses. The pressure effect identified by WADDELL (1973) appears to be of only secondary importance or confined to the lower reaches of the beachface, in the present investigation.

Several factors may account for the disparity between the findings of WADDELL (1973) and the present investigation. During the study of WADDELL (1973), waves broke on the base of the beachface and resulted in the transmission of large pressure forces through the groundwater. However, in the present project, waves broke some 15 m off-shore and arrived at the beachface as bores. WADDELL (1973) monitored the groundwater-level 5 m landward of the base of the beach, whereas during this experiment, the groundwater-level was monitored 15 m from the base of the beach.

It is also expected that the location of the groundwater-table outcrop on the beachface

will be significant in determining the relative importance of pressure versus swash input in causing a groundwater-table response. The groundwater-table outcrop is a dynamic boundary which fluctuates at many frequencies, including tidal and incident periods. It is anticipated that pressure forces will dominate seaward of the groundwater-table outcrop and infiltration will be more important landward of the groundwater-table outcrop. The reverse Wieringermeer effect may be significant just above the groundwater-table outcrop.

High-frequency groundwater-level responses have a distinct response asymmetry, whereby the rate of groundwater decline is less than the rate of rise. Thus, input to the groundwater occurs more rapidly than output. Such an asymmetry may be attributed to the fact that the beachface has a finite angle (NIELSEN *et al.*, 1988) and that the force of the waves pushing water into the beach by both pressure affects and infiltration is large compared to the hydraulic head driving the discharge. The balance between net groundwater recharge or discharge is the result of the interaction between the hydraulic gradient, the hydraulic conductivity of the beach matrix, beach slope and the timing of the swash.

The antecedent groundwater-level had a negative influence on the magnitude of groundwater rise and did not significantly influence the rate of groundwater rise. This is probably an artifact of the groundwater response asymmetry combined with wave groupiness. A series of high waves will induce a rapid rise of the groundwater-table. The slow rate of groundwater-level decline will ensure that the groundwater-table will remain elevated for some period. As a result of groupiness the following waves may be successively reduced in size and hence their effect on the elevated groundwater-table will be reduced.

CONCLUSIONS

After high tide the groundwater-level was generally in a state of decline until the arrival of a swash. If the run-up amplitude of the swash was sufficiently small then the groundwater-level continued to decline and no detectable groundwater-level response was identified. If the run-up increased in amplitude it caused a pressure flux through the saturated sands and

led to a temporary stabilizing of the groundwater-level. Large swashes that extended beyond the mean groundwater-level occasioned an initial stabilizing of the groundwater-level. However, swashes that extended above the mean groundwater-level induced a groundwater-table rise. This rise may be attributed to swash infiltration and in part the reverse Wieringermeer effect. It is expected that lower on the beachface pressure forces become increasingly important in inducing groundwater-table fluctuations.

High-frequency groundwater-table oscillations are characterized by a response asymmetry whereby the rate of rise is considerably greater than the rate of fall. Thus interstitial recharging occurs more efficiently than the draining process. This is comparable to the observations by NIELSEN *et al.* (1988) of asymmetric groundwater-level variations at tidal frequencies.

At South City Beach the beachface acted as a band-pass filter selectively allowing the transfer of energy in a particular frequency window. Higher frequency oscillations are substantially filtered. Despite this, energy was detectable in the groundwater record across the incident swell band. These groundwater-level oscillations were closely related to swash motions on the beachface.

ACKNOWLEDGEMENTS

The authors thank the Perth City Council for access to South City Beach. We also gratefully acknowledge field assistance from Dr. I. Eliot, P. Farrell, Dr. B. Knott, R. Swan and W. Wilson. We thank Dr. J. Henstridge who provided fruitful discussions on the time series analysis, which was conducted using the TSA program. The cartography was completed by G. Foster, Department of Geography, University of Western Australia. This study was partly supported by a CTEC grant awarded to Drs. I. Eliot, J. Hsu and B. Knott for 1987/1988. Additional funds were generously provided by the Department of Geography, University of Western Australia.

LITERATURE CITED

- ANONYMOUS, 1989. *Australian National Tide Tables*. Australian Government Printing Office, Canberra, A.C.T., 245p.

- BOUWER, H., 1986. Intake rate: cylinder infiltrometer. In: KLUTE, A., (ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods (2nd Edn.)*. Madison, Wisconsin: American Society of Agronomy, pp. 825-844.
- BRADSHAW, M.P., 1974. High frequency water table fluctuations and mass movement on sandy beaches. Honours Thesis, Department of Geography, Australian National University, 122p.
- BRILLINGER, D.R., 1975. *Time Series: Data Analysis and Theory*. New York: Holt, Rinehart & Winston, 500p.
- CLARKE, D.J. and ELIOT, I.G., 1983. Mean sea level and beach width variation at Scarborough, Western Australia. *Marine Geology*, 51, 251-267.
- COOLEY, J.W.; LEWIS, P.A.W., and WELSH, P.D., 1976. The fast Fourier transform and its application to time series analysis. In: ENSLEIN, K.; RALSTON, A., and WILF, H., (eds.), *Statistical Methods for Digital Computers*. New York: Wiley.
- DANIELSON, R.E. and SUTHERLAND, P.L., 1986. Porosity. In: KLUTE, A., (ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods (2nd Edn.)*. Madison, Wisconsin: American Society of Agronomy, pp. 443-461.
- DOMINICK, T.F.; WILKINS, B., and ROBERTS, H., 1971. Mathematical model for beach groundwater fluctuations. *Water Resource Research*, 7, 1626-1635.
- DUNCAN, J.R., JR., 1964. The effects of watertable and tide cycle on swash-backwash sediment distribution and beach profile development. *Marine Geology*, 2, 186-197.
- ELIOT, I.G. and CLARKE, D.J., 1986. Minor storm impact on the beachface of a sheltered sandy beach. *Marine Geology*, 73, 61-83.
- EMERY, K.O. and FOSTER, J.F., 1948. Water tables in marine beaches. *Journal of Marine Research*, 7, 644-654.
- EMERY, K.O. and GALE, J.F., 1951. Swash and swash mark. *American Geophysical Union, Transactions*, 32, 31-36.
- ERICKSEN, N.J., 1970. Measurement of tide induced change to water table profiles in coarse and fine sand beaches along Pegasus Bay, Canterbury. *Earth Science Journal*, 4, 24-31.
- FOLK, R.L., 1974. *Petrology of Sedimentary Rocks*. Austin, Texas: Hemphills, 182p.
- GALVIN, C.J., 1972. Waves breaking in shallow water. In: MEYER, R.E., (ed.), *Waves on Beaches*. London: Academic, pp. 413-455.
- GILLHAM, R.W., 1984. The capillary fringe and its effect on water-table response. *Journal of Hydrology*, 67, 307-324.
- GRANT, U.S., 1946. Effects of groundwater table on beach erosion. *Geological Society American Bulletin*, 57, 1252. (Abstract.)
- GRANT, U.S., 1948. Influence of the water table on beach aggradation and degradation. *Journal of Marine Research*, 7, 655-660.
- GUZA, R.T. and INMAN, D.L., 1975. Edge waves and beach cusps. *Journal of Geophysical Research*, 80, 2997-3012.
- HARRISON, W.; FANG, C.S., and WANG, S.N., 1971. Groundwater flow in a sandy tidal beach: 1. One-dimensional finite element analysis. *Water Resources Research*, 7, 1313-1322.
- HOLMAN, R.A. and GUZA, R.T., 1984. Measuring run-up on a natural beach. *Coastal Engineering*, 8, 129-140.
- KOOPMANS, L.H., 1974. *The Spectral Analysis of Time Series*. New York: Academic, 366p.
- LANYON, J.A.; ELIOT, I.G., and CLARKE, D.J., 1982. Observations of shelf waves and bay seiches from tidal and beach groundwater-level records. *Marine Geology*, 49, 23-42.
- LEWANDOWSKI, A. and ZEIDLER, R.B., 1978. Beach ground-water oscillations. *Proceedings of the 16th Conference on Coastal Engineering*, pp. 2051-2065.
- McLACHLAN, A., 1989. Intertidal zonation of macrofauna and stratification of meiofauna on high energy sandy beaches in the Eastern Cape, South Africa. *Transactions of the Royal Society of South Africa*, 44, 213-223.
- NIELSEN, P.; DAVIS, G.A.; WINTERBOURNE, J.M., and ELIAS, G., 1988. Wave setup and the water table in sandy beaches. New South Wales Public Works Department, Coastal Branch, *Technical Memorandum T.M. 88/1*, 132p.
- TURNER, A.K.; WILLATT, S.T.; WILSON, J.H., and JOBLING, G.A., 1984. *Soil Water Management*. Canberra, A.C.T.: International Development Program of Australian Universities and Colleges.
- TURNER, I.L.L., 1989. The total water content of sandy beaches. Honours Thesis, Coastal Studies Unit, University of Sydney, 115p.
- WADDELL, E., 1973. Dynamics of swash and implications to beach response. Technical Report 139, Coastal Studies Institute, Louisiana State University, Baton Rouge, 49p.
- WADDELL, E., 1980. Wave forcing of beach groundwater. *Proceedings of the 17th Conference on Coastal Engineering* (Sydney, Australia), pp. 1436-1452.
- WRIGHT, L.D. and SHORT, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology*, 56, 93-118.