CHAPTER 66

RUNUP, SETUP AND THE COASTAL WATERTABLE

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Abstract

The three related phenomena of wave runup, wave setup and the dynamics of the coastal watertable are considered and their inter-relations are investigated via a comprehensive field study. The measured runup distributions confirm the expectation that the Rayleigh distribution is a reasonable model and that the vertical scale of the distributions is proportional to $\sqrt{(H_{orms} L_o)}$ as in Hunt's (1959) formula but that the proportionality to the beach slope, also prescribed by this formula, only applies for fairly steep beaches. The measured setup profiles are quite different from the ones predicted on the basis of $H=\gamma h$ and linear wave theory in the surf zone. The measured profiles are flatter in the outer surf zone and steeper close to the beach. The shoreline setup is generally about $0.4\ H_{orms}$, which is somewhat higher than the previously suggested values. This is because the previous values of the shoreline setup were rarely measured but generally extrapolated with insufficient recognition of the steepening of the profile near the shoreline. The watertable data show that the inclined beach face acts as a strongly non-linear filter which makes the watertable variation at a point inside the beach far from sinusoidal (when the tide is approximately sinusoidal) and elevates the average position of the watertable considerably compared to the mean sea level.

1. Introduction

The concepts of wave runup, setup and the coastal watertable have been described previously in the literature but articles dealing with the three together are virtually absent. One notable exception to this rule is Longuet-Higgins (1983).

Articles about wave setup tend to be "geographically" restricted to the area seaward of the swash zone, i.e. where the sand surface is always under water, while papers about the watertable have been restricted to the area landward of the runup limit. Thus the setup profiles and the watertables of the litterature rarely meet, see Figure 1. Consequently, since the runup literature, which rules the swash zone, has

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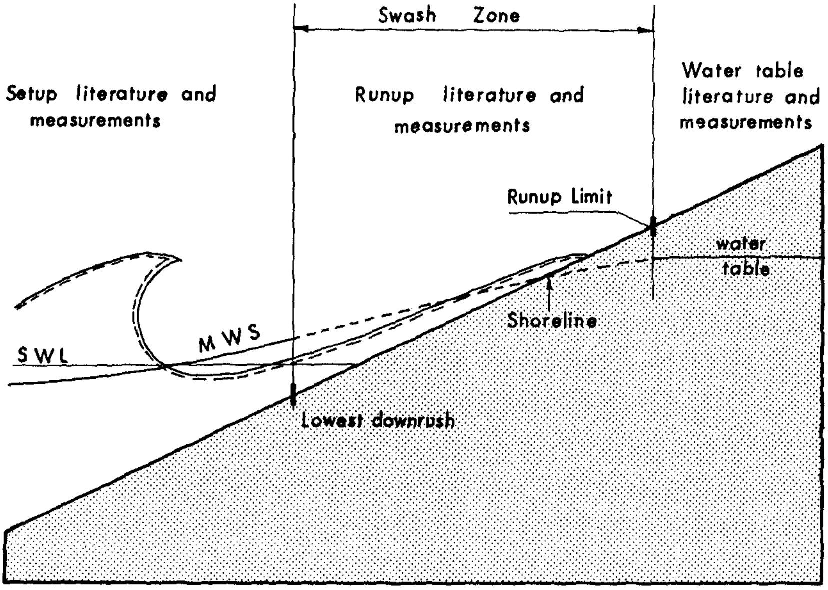


Figure 1: The literature on setup, runup and the coastal watertable is geographically separated into three non-overlapping areas: the setup literature considers the surf zone seaward of the point of lowest dowmrush, the runup literature considers the swash zone and the watertable literature considers only the area landward of the runup limit.

has been generally uninterested in the MWS, the latter can only be drawn as a broken line through the swash zone. This is particularly unfortunate because a most important part of the MWS namely the shoreline always falls within the swash zone where the MWS is but vaguely described.

The present study presents an attempt to give an integrated description af the three phenomena with the aid of new field data sets which include runup-, setup- and watertable measurements taken simultaneously.

2. Field equipment

The system of manometer tubes which was applied to get the setup measurements has been described and discussed in detail by Nielsen (1988) and Nielsen et al (1988), it consists of hard though flexible nylon tubes extending up to 500 metres into the surf zone and a separate line has been laid out through the Brunswick River entrance extending from well upstream of the point where the waves normally die out to about 150 metres outside the entrance breakwaters.
Additional mean water levels in the inner surf zone and the swash zone and

watertable heights inside the beach were taken with simple stilling wells.

Quantitative information about the runup distributions were obtained simply by counting the number n_i of waves which went past each of the stilling wells or other fixed points on the beach face with known elevation z_i.

3. Wave runup

The following includes quantitative data on runup distributions measurd on a wide variety of beaches in New South Wales, Australia.

The runup distributions were, in the present study, measured in terms of the number of waves transgressing certain points on the beach face. It was found (in agreement with Battjes 1971) that the Rayleigh distribution is a good model i e

$$P\{z_{wm}>z\} = \exp[-(\frac{z-z_{100}}{L_R})^2] \qquad \text{for } z > z_{100} \qquad (1)$$

where z_{wm} is the maximum level reached by a given wave, z_{100} is the highest level which was transgressed by all the waves and L_R is the vertical scale of the runup distribution.

Based on the classical work by Hunt (1959) on the runup of regular waves and the subsequent work by Saville (1961) and Battjes (1971) for irregular waves, it seemed reasonable to expect the vertical scale L_R to be close to the offshore rms-wave-height times the surf similarity parameter i e

$$L_R \approx (H_{orms}L_o)^{0.5}\tan\beta \qquad (2)$$

However, the fact that most beach profiles are curved means that the definition of "the beach slope" $\tan\beta$ for use in this formula is not trivial, see Figure 2.

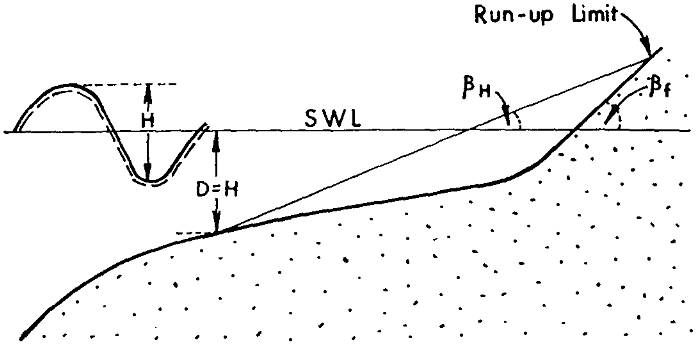


Figure 2: "The beach slope", applicable to the whole surf zone, is not well defined for most beaches, but the beach face slope, $\tan\beta_F$ generally is.

Because of this lack of a good definition, it was decided to leave out the slope in the initial analysis. That is, in order to analyse the measured runup distributions, we plotted the transgression probability in the form $\sqrt{(-\ln n_i/N)}$, where N is the total number of waves, against $(z_i\text{-SWL})/\sqrt{(H_{orms}L_o)}$ and performed linear regression analysis in accordance with

$$\sqrt{(-\ln n_i/N)} = \frac{z_i - \text{SWL}}{C_1 \sqrt{(H_{orms}L_o)}} - C_2 \qquad (3)$$

where the constant C_1 then has taken the place of "the beach slope" in Equation (2) and the second constant C_2 [= $(z_{100}\text{-SWL})/L_R$] is the dimensionless elevation of z_{100} above the still water level, see Figure 3. A summary of the runup distributions collected so far is presented in Table 1. For a detailed description of the field sites see Nielsen & Hanslow (1991).

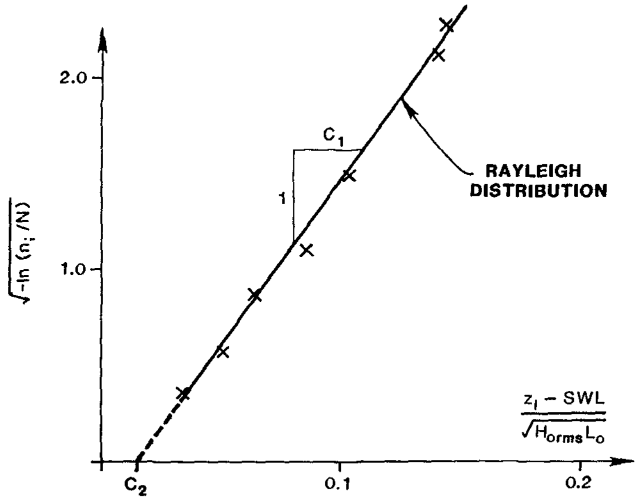


Figure 3: Runup data from Palm Beach north of Sydney, 3/8-1990, 13:40-13:55. The Rayleigh distribution is seen to provide a reasoable model.

The Rayleigh distribution (1) combined with Hunt's formula in the form (2) provides a good model for runup by irregular waves onto steep structures, but for the wide range of beach topographies covered in the present study that is not the case. For very flat beaches, the dependance upon the "beach slope" disappears and a relation of the form

$$L_R = 0.05\sqrt{(H_{orms}\,L_o)} \qquad \text{for } \tan\beta_F \le 0.10 \qquad (4)$$

where $\tan\beta_F$ is the slope of the beach face, seems to hold. See Figure 4.

For the steeper beaches the vertical scale is roughly proportional the slope of the beach face, but because $\tan\beta_F$ is generally larger than "the beach slope" which is probably more like the average slope β_H between the point where $h=H_{orms}$, see Figure 2, a factor of roughly 0.6 applies:

$$L_R \approx 0.6 \tan\beta_F \sqrt{(H_{orms} L_o)} \quad \text{for} \quad \tan\beta_F \geq 0.10 \qquad (5)$$

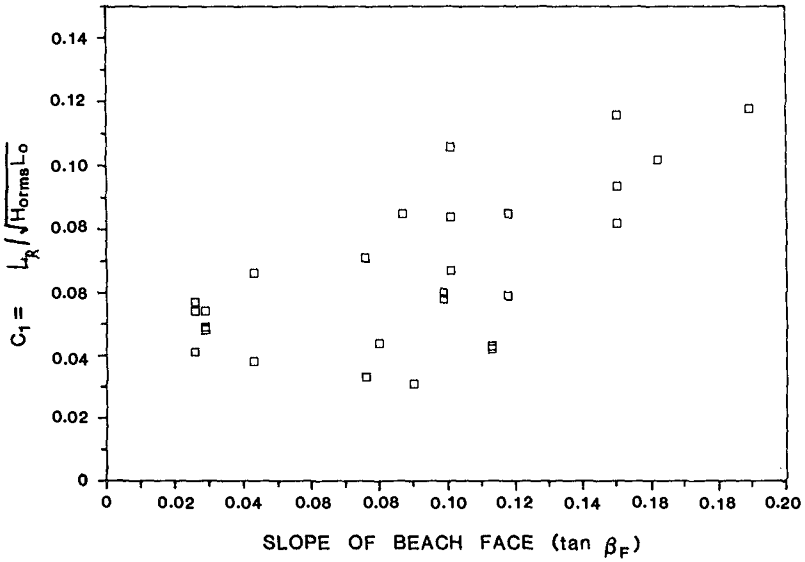


Figure 4: For very flat beaches the vertical scale of the runup distribution is independant of the slope of the beach face.

The second parameter in the Rayleigh distribution (1), namely the highest level z_{100} transgressed by all waves is plotted against the beach face slope in Figure 5. From this figure it can be seen that for very flat beaches ($\tan\beta_F \leq 0.08$), z_{100} is significantly below the still water level, while it is uniformly scattered around the SWL for the steeper beaches. The fact that z_{100} moves seaward of the still water line on very flat beaches is mainly due to the fact that strong surf beats are common on such beaces and; when the surf beat is down, most waves are transformed into bores seaward of the still water line and several pairs of bores will coalesce by overtaking through the surf zone. This deminishes the number of waves which are counted at the still water line.

Table 1. Summary of runup data

Location	Date	Time (EST)	H_{orms} [m]	T_s [s]	$\tan\beta_F$	C_1	r	$P\{z_s\}$	$C_1/\tan\beta_F$	C_2
Brunswick	1/12-88	1040	0.53	7.0	0.043	0.038	0.999	0.33	0.88	-0.45
	22/12-88	1622	1.13	8.1	0.029	0.049	0.990	0.06	1.69	-0.53
	22/12-88	1702	1.13	8.3	0.029	0.054	0.988	0.19	1.86	-0.59
	22/12-88	1808	1.07	8.4	0.029	0.048	0.966	0.27	1.66	-0.67
	21/3-89	1635	1.20	11.5	0.090	0.031	0.987	0.38	0.34	0.29
	31/3-89	1515	1.91	8.0	0.080	0.044	0.993	0.37	0.55	-0.34
	22/8-89	1345	1.30	10.5	0.043	0.066	0.995	0.27	1.53	-0.58
	22/8-89	1515	1.25	10.2	0.043	0.038	1.000	0.04	0.88	-0.12
Dee Why	13/7-89	1010	2.92	11.3	0.113	0.042	0.999		0.37	0.24
	13/7-89	1050	2.95	11.4	0.113	0.043	0.996		0.38	0.23
	26/7-89	1045	2.58	8.5	0.118	0.059	0.984	0.37	0.50	-0.27
	26/7-89	1145	2.17	7.6	0.118	0.085	0.993	0.43	0.72	-0.39
Ocean Beach	24/7-89	1218	0.78	7.1	0.076	0.071	0.998		0.93	-0.37
*	24/7-89	1442	0.74	7.8	0.076	0.033	0.995		0.43	0.15
Palm Beach	18/4-89	1612	0.62	8.3	0.189	0.118	0.992	0.78	0.62	0.00
	19/4-89	743	0.98	7.9	0.162	0.102	0.999	0.91	0.63	0.03
	6/6-90	1415	0.96	6.8	0.101	0.067	0.988	0.24	0.67	-0.28
	6/6-90	1445	0.96	6.8	0.101	0.084	0.997	0.30	0.84	-0.43
	6/6-90	1515	0.96	6.4	0.101	0.106	0.967	0.40	1.05	-0.45
	2/8-90	1445	0.95	9.7	0.087	0.085	0.995	0.51	0.98	0.26
	3/8-90	1348	2.90	9.6	0.099	0.058	0.997	0.32	0.58	0.28
	3/8-90	1445	2.55	9.7	0.099	0.060	0.991	0.46		0.32
Pearl Beach	30/6-89	1615	1.55	8.8	0.150	0.094	0.991	0.60	0.63	-0.13
*	30/6-89	1650	1.58	8.7	0.150	0.116	0.980	0.50	0.77	-0.14
	30/6-89	1713	1.58	8.8	0.150	0.082	0.997	0.51	0.55	0.26
Seven Mile Beach	21/8-90	1645	1.07	7.5	0.026	0.057	0.979	0.07	1.69	-0.84
	22/8-90	1015	1.16	7.0	0.026	0.054	0.979	0.10	2.07	-0.81
	22/8-90	1245	1.10	7.4	0.026	0.041	0.971	0.01	1.57	-1.10

*): Data from Turner (1989).

4. Wave setup on beaches.

While the wave setup data of the present study are geographically restricted to a few beaches on the coast of New South Wales they do form the most comprehensive set of field data available to day.

The first major conclusion to be drawn from the data is that the measured setup profiles are quite different from the ones that result from assuming periodic waves, constant height to depth ration [$H=\gamma(D+B)$] in the surf zone, and radiation stress given by linear wave theory. These are the simplifying assumptions suggested by Bowen et al (1968).

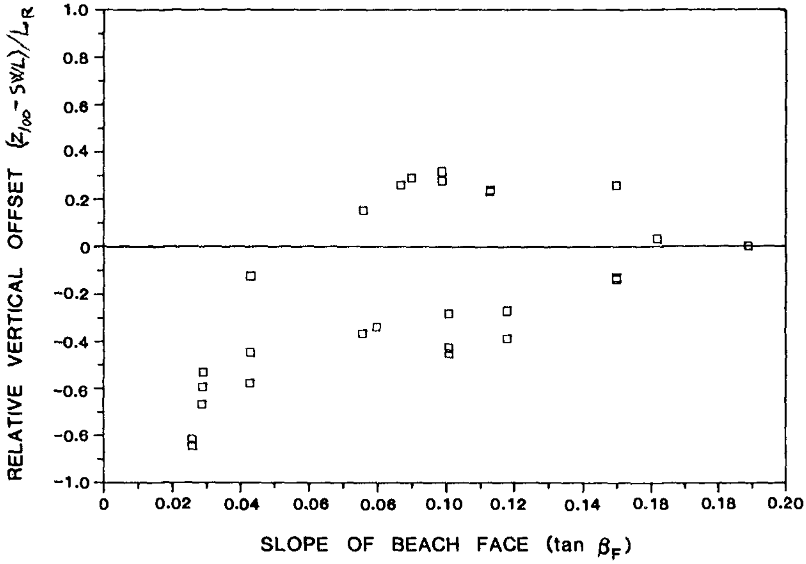


Figure 5: For very flat beaches z_{100} is significantly below the still water level, but for the steeper beaches the deviation is insignificant.

The difference emerges most clearly when the setup B is plotted against total depth, h as in Figures 6. In such a diagram the setup profile according to the above assumptions is a straight line with slope $S = 3\gamma^2/8$ while the typical field data set shows a very different trend. A contributing factor to the difference of shape is wave irregularity as discussed by Battjes and Janssen (1978) and by Nielsen et al (1988). However, wave height variability can only explain the upward concavity of the profile, not the higher values of the shoreline setup, B_s. The measured values of the B_s (= z_s-SWL) are generally about 0.4 H_{orms} which is significantly above the Bowen-et-al-model's prediction of $\frac{3}{8}\gamma H_b$ with reasonable values of γ and H_b/H_o.

The difference between observed and expected setup profiles must result from a combination of the following effects:

1. Real waves near breaking carry much less momentum flux than sine waves of the same height (Nielsen et al 1988 and Dean 1974).
2. The momentum flux does not decay as rapidly as H^2 in the outer surf zone (Svendsen 1984).
3. The bores in the swash zone carry considerably more momentum flux than sine waves of the same height.

A theoretical description of the setup profile which accounts for the observed features is not yet available so the best desigh guidance is probably gained from the data.

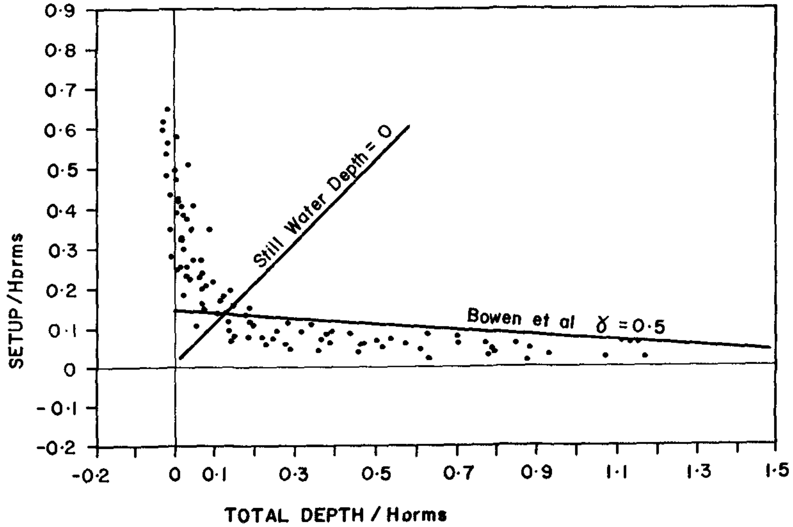


Figure 6: Wave setup at Dee Why Beach, Sydney on August 4 1987, (H_{orms}, T_p) = (1.6m,8.2s).

A close-up look at the setup profile near the shoreline is provided by Figure 7 for a range of beach shapes and wave heights. This plot differs from Figure 6 in

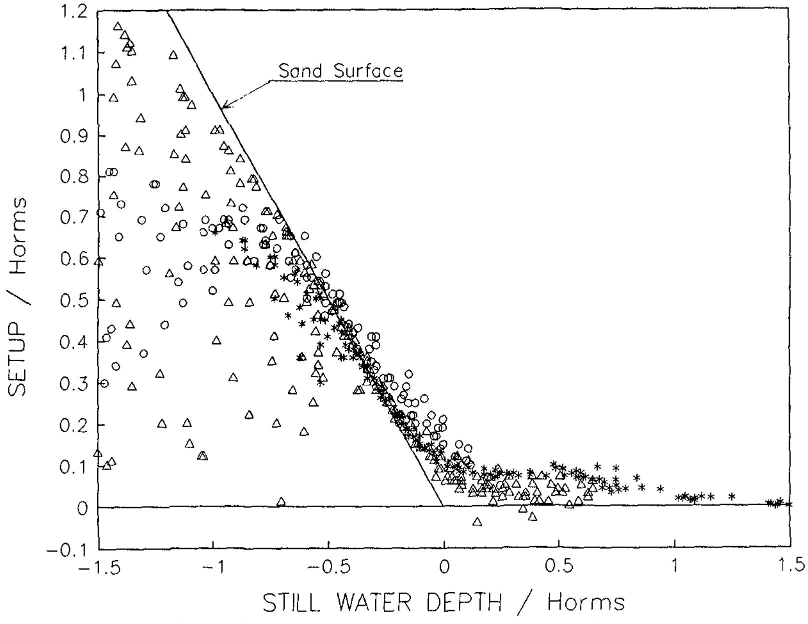


Figure 7: Relative Setup from the swash zones at Brunswick Heads 22/6-89 (*), Palm Beach 6/6-90 (o), and Seven Mile Beach 21/8-90 (Δ). Data details in Table 1.

that the abscissa is the dimensionless still water depth rather than the total depth.

One step towards achieving an integrated picture of wave setup, wave runup and coastal watertable dynamics is to determine the position of the shoreline in the runup distribution i e what fraction of the waves are expected to transgress the shoreline on a given beach. One example involving a steep beach of coarse sand (Palm Beach) is shown in Figure 8. Such beaches drain rather efficiently ad hence the Mean Water Surface will establish itself at a fairly low position relative to the runup/infiltration distribution, with most of the waves transgressing the shoreline. For the shown example, the shoreline was transgressed by about 78 percent of the waves, i e $P\{z_s\} = 0.78$.

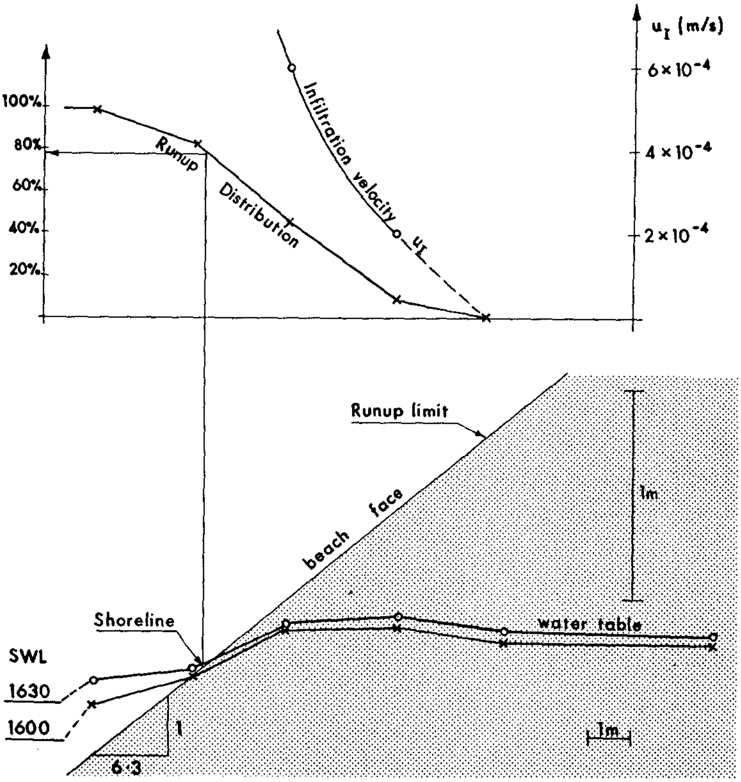


Figure 8: The relation between wave transgression statistics and the position of the shoreline at the Northern end of Palm Beach. The preceeding low tide was at 13:51, the following high at 20:08 with a range of 1.0m. The offshore wave data were $(H_{orms}, T_p) = (0.62m, 8.3s)$.

The position of the shoreline and hence $P\{z_s\}$ is a function of the relative tidal range A_{tide}/H_{rms} and the tidal phase as well as of the beach slope and permeability. Still, the data in Table 1, which correspond to mixed tidal phases show a clear relationship between the relative shoreline elevation and the beach slope, see Figure 9.

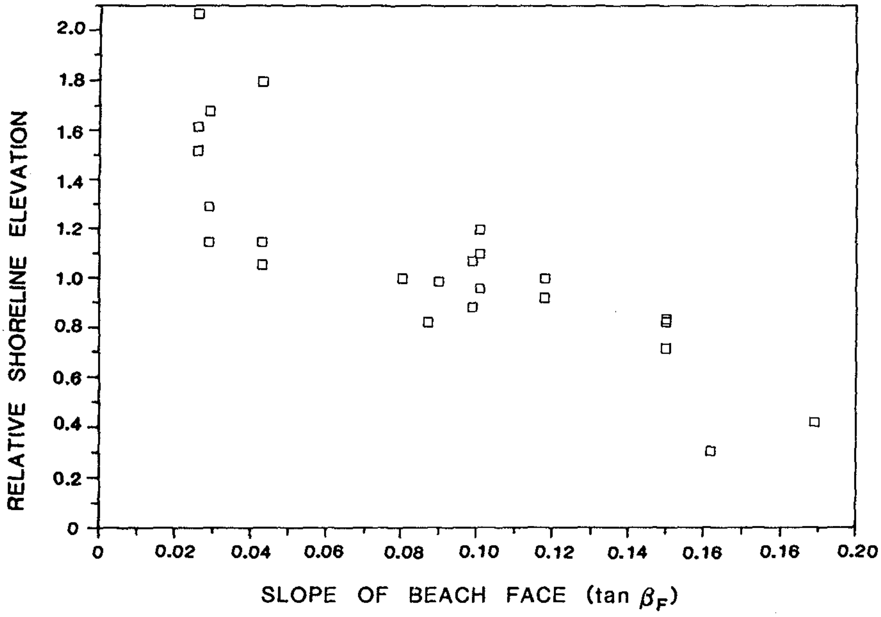


Figure 9: The relative shoreline elevation $(z_s\text{-SWL})/L_R$ is a decreasing function of the beach face slope because steeper beaches generally drain more efficiently than flat beaches.

Although the combination of Figures 4 and 9 points towards a predictive formula of the form

$$B_s = F[\ \sqrt{(H_{orms}\ L_o)},\ \tan\beta_F\ ] \qquad (6)$$

the data can also give a rough indication of B_s as function of the offshore wave height irrespective of beach morphology, namely

$$B_s \ = \ 0.4\ H_{orms} \qquad (7)$$

see Figure 10

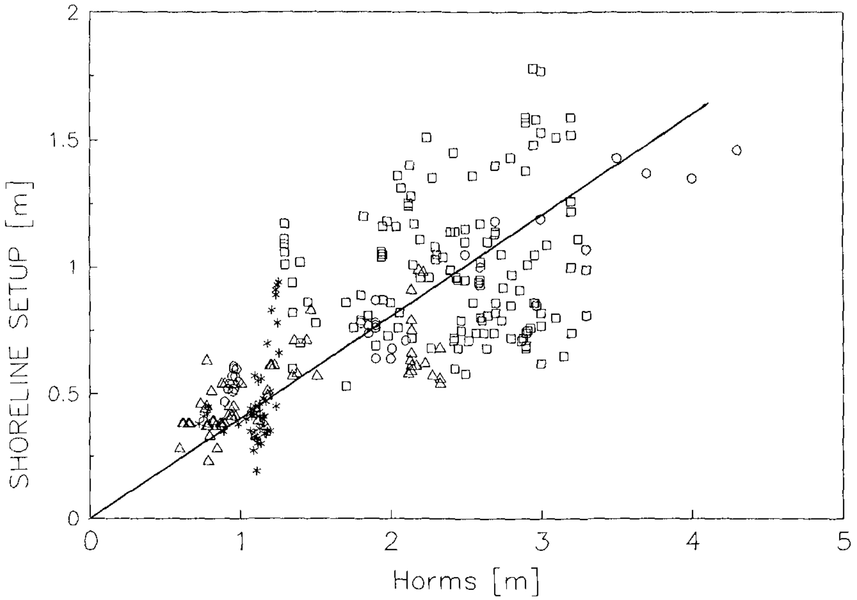


Figure 10: Shoreline setup, B_s as function of offshore wave height. The straight line is given by Equation (7). Legend: * Seven Mile Beach, o Palm Beach, [] Brunswick Heads, Δ Dee Why Beach.

5. Watertable data

Two methods were applied for collecting watertable data. For short records (25 hours or less) an array of simple stilling wells were used. These were monitored with a dip-meter which is a measuring tape with a conductivity sensor on the end. For long term records a self recording pressure sensor in a single well was used.

Figure 11 shows a series of MWS/watertable measurements from Dee Why Beach on the rising tide (high tide at 20:00). Estimated shoreline elevations based on (7) are given on the right. Note that the watertable continues to rise landward of the shoreline due to the infiltration from runup.

One long term record is shown in Figure 12 together with the corresponding wave-, tide- and rainfall data. Rainfall had little impact because the well was located on the narrow sand barrier in front of Dee Why Lagoon but the influence from waves and tides is very clear. We see that the watertable was at all times more than one metre above MSL, and the tidal variation is highly asymmetrical. That is, the watertable rises very sharply and falls of very slowly in response to an essentially sinusoidal tide. A considerable fraction of the overheight as well as the skewness is due to asymmetry in the boundary condition at the beach face. In qualitative terms we may say that the infiltration at high tide is much more efficient than the draining at low tide.

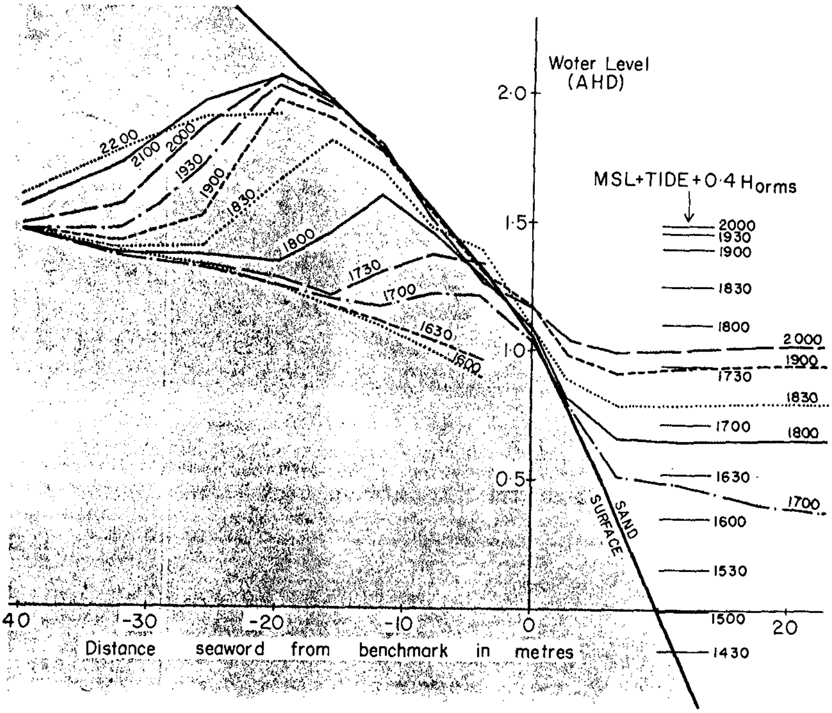


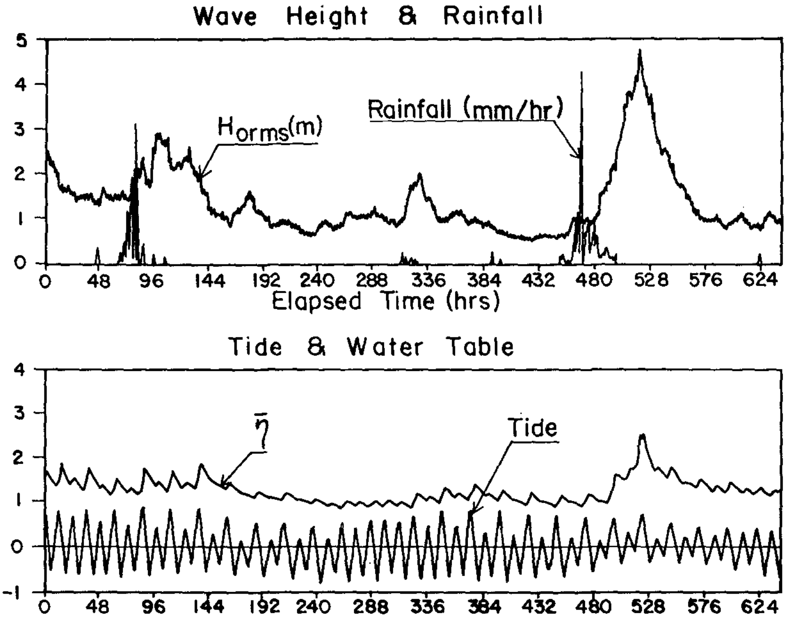
Figure 11: Successive watertable measurements taken at Dee Why Beach 7/9-87, $(H_{orms}, T_s) \approx (1.1\text{m}, 8\text{s})$

6. Watertable modelling

The dynamics of the watertable as forced by waves and tides has been modelled using the following theoretical framework. The flow inside the sand is governed by Darcy's law and the conservation of volume which leads to

$$\frac{\partial \eta}{\partial t} = \frac{KD_a}{n}\frac{\partial^2 \eta}{\partial x^2} + u_I \tag{8}$$

where K is the permeability, D_a is the depth of the sand body below the average watertable, n is the relative pore volume and u_I is the infiltration velocity due to wave runup.


Wave Height & Rainfall

Tide & Water Table

Figure 12: Watertable record from Dee Why Beach. The measurements were taken in a well situated about 30 metres from the average shoreline position where the sand level was approximately 2.6m AHD.

Analytical solutions to (8) can be found for the two special cases of pure wave forcing and pure tidal forcing, under the additional asumption that the shoreline position can be prescribed, see Nielsen et al (1988). For the pure wave case it can then be shown that the asymptotic inland watertable height above the shoreline is proportional to the horizontal length scale of the runup distribution squared divided by the aquifer depth i e

$$\bar{\eta}(\infty) - SWL = \text{const}\ H_{orms}\ L_o/D_a \qquad (9)$$

It is independent of the beach permeability because greater permeability equally enhances infiltration and drainage.

For pure tidal forcing a perturbation solution has been used to describe the average overheight above MSL as well as the skewness shown by the data in Figure 12. It turns out that the magnitude of the overheight is $0.5kA^2\cot\beta$ where k is the wavenumber of the tidal watertable wave and A is the tidal amplitude. With typical k-values of $0.08m^{-1}$ this tidal overheight ranges typically from 0.2 to 0.5 metres on the coast of New South Wales.

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