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Water tables in Slipway Beach, Lake Manapouri: controls and effects on the beach system

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ABSTRACT

The results from a continuous 42-d study of water table levels in Slipway Beach, Lake Manapouri, 12 November–23 December 1974, are described, and correlation and multiple regression analyses are used to identify controlling processes. Groundwater fluctuations are largest on the upper and lower foreshore, where the elapsed rainfall and position of the shoreline are the dominant controls. Fluctuations are smallest in the mid foreshore; this pattern is the reverse of that found in oceanic beaches where tidal oscillations in sea level control the level of the water table in the foreshore. Beach morphology is affected by the groundwater in two ways: spring sapping of the water table from the top of the foreshore during heavy rains produces rill channels, and shore-normal exchanges of sediment associated with changes in lake level are accelerated.

INTRODUCTION

Beaches around Lake Manapouri have been subjected to periodic degradation thought to have been caused by the alterations in lake level since the completion of the power station at West Arm. One of the processes controlling beach morphology is the beach water-table system. As part of a broader study of the stability of the lakeshore beaches (Pickrill unpublished 1976) the beach morphology and water table in one beach was studied over a continuous 42-d period, from 12 November to 23 December 1974.

Research on oceanic beaches has shown that high water tables reduce the available pore space for the percolation of the swash uprush into the beach face. As a result the volume of water in the backwash is increased and the foreshore downcombed. Conversely, dry foreshores promote deposition through an increased capacity for percolation of the swash into the beach face and a reduction in the backwash (Grant 1948). In a recent quantitative study, Harrison (1972) demonstrated beach groundwater to be second in importance to ocean still water level in controlling the volume of material on the foreshore.

On tidal coasts, the level of the water table in the beach is controlled by and typically lags 1–3 h behind the tidal cycle; this time lag increases landward. The magnitude of the water table fluctuations decreases up the beach such that under the foredune groundwater movements are negligible. The magnitude of the fluctuations also decreases with decreasing beach slope, permeability, grain size, and tidal range (Emery & Foster 1948; Duncan 1964; Ericksen 1970). By contrast, very little is known about groundwater fluctuations and controls on tideless shores. This paper describes groundwater fluctuations in a low energy, non-tidal beach. Possible controls of the water table are suggested, and the effects of groundwater fluctuations on the foreshore morphology outlined.

PHYSICAL SETTING

Lake Manapouri, in the Fiordland National Park, fills a glacial over-deepened basin, dammed at its eastern boundary by moraine outwash deposits (Fig. 1). Water table studies were carried out at Slipway Beach on the eastern shore. Lake Manapouri is in an area of high rainfall, with 7 600 mm.y^{-1} being recorded at West Arm. Rainfall decreases rapidly eastward, away from the mountains, with only 1 200 mm.y^{-1} being recorded at Manapouri township, close to Slipway Beach. Lake level responds directly to this rainfall. Manapouri has a mean level of 177.64 m above mean sea level and a natural range of 4.8 m, although extreme high and low levels are rarely recorded. The range for 98% of the time is 3.3 m and the standard deviation 0.73 m. Fluctuations of at least 0.2 m.d^{-1} are recorded during storms. Level changes of 0.42 m were recorded during the 42-d study period.

The beaches around Lake Manapouri have a distinctive shelf form. The width of the beach, the beach slope, and maximum elevation of the beach above mean lake level are a product of the combined effects of the range of lake levels and the exposure of the shoreline to wave activity (Pickrill 1978). Slipway Beach is a well-sorted medium-fine sand beach (2.0ϕ) formed in outwash moraine material. Beach morphology has developed in response to prevailing northwesterly winds generating waves across a 10 km fetch. Above mean lake level the beach is 20 m wide, with a slope of 6°; this slope extends a further 55 m off shore (Fig. 1). The outer edge of this sublimnic shelf is marked by an abrupt change in slope (to 22°) and a change from sands to muds. The water table study was carried out on the subaerial beach where unstratified well-sorted medium-fine sand extends at least 2 m beneath the surface.

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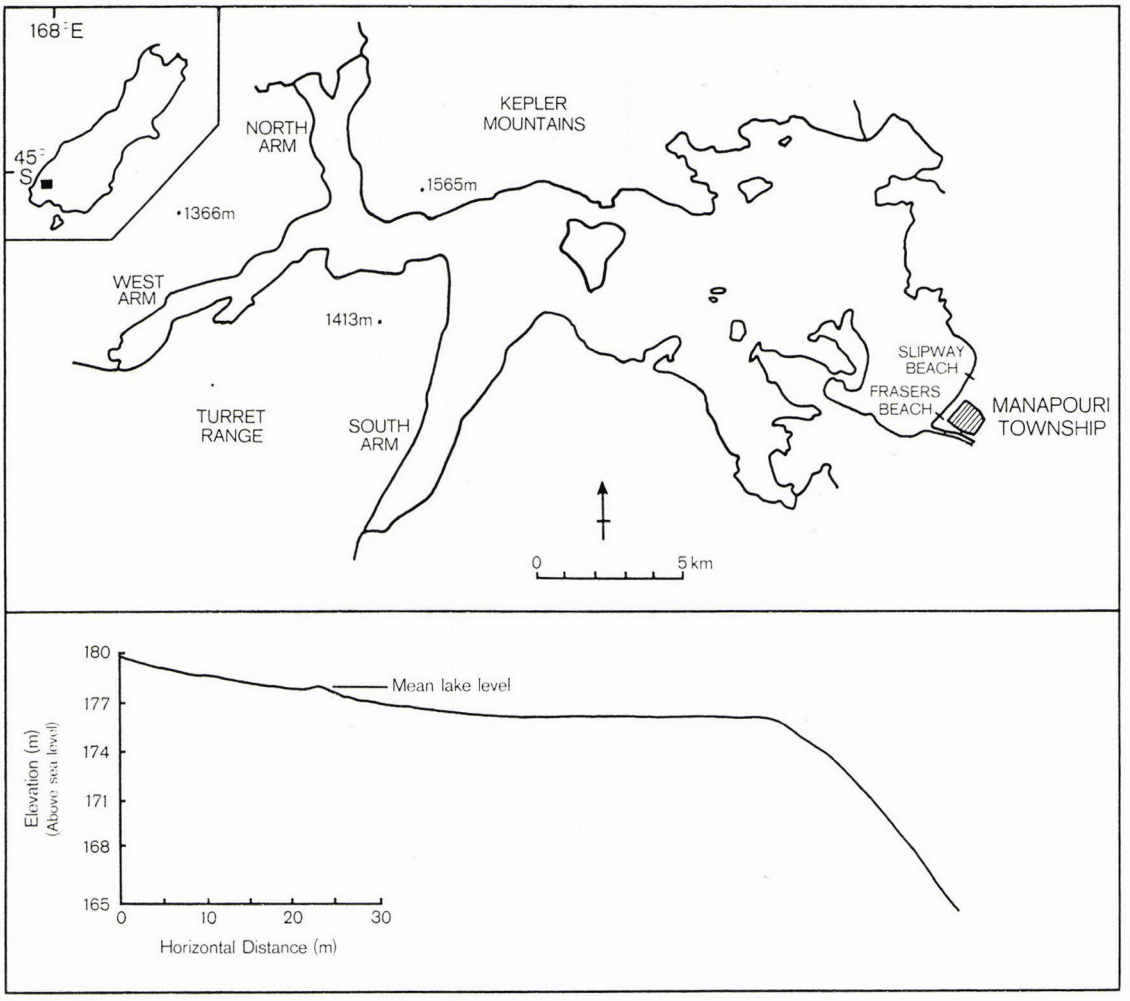


FIG. 1—(*Upper*) Location of Slipway Beach, Lake Manapouri; (*Lower*) Shore-normal profile through Slipway Beach.

METHODS

Six groundwater pipes, similar to those used by Emery & Foster (1948), were placed at 4 m intervals down a profile surveyed normal to the shoreline. Each pipe consisted of 25-mm-diameter water pipe, tapered and closed at one end. The bottom of the pipes were perforated to allow water to enter; gauze squares welded over the perforations kept the pipes free of sand. The depth of the water table in each pipe was measured daily with a cork float and thread. In addition, a rain gauge was installed at the site and read daily. The beach profile was surveyed daily with a Hilger & Watts quick-set level, and visual estimates of significant wave height were made.

RESULTS

The daily record of elevations (Fig. 2) shows the water table to be extremely variable with time: long periods of near-static levels are punctuated by short rapid fluctuations of up to 30 $cm.d^{-1}$. Rates of rise are faster than rates of fall. Mean water table depths and standard deviations from the mean (Fig. 3) show the depth of the water table beneath the sand surface to increase up the beach. In the lowest pipe, close to mean water level, the water table was only at 1–2 cm depth, but this depth increased uniformly up the beach to more than 50 cm at the top of the beach, at Pipe A. Variation in the depth of the water table, as described by the standard deviation, was

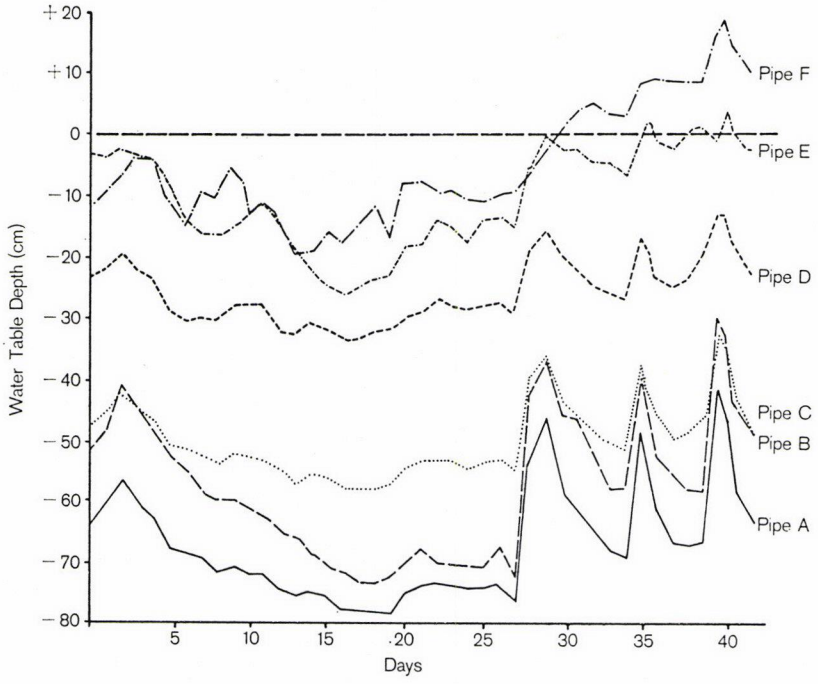


FIG. 2—Daily water-table levels in Slipway Beach over a continuous 42-d period, 12 November–23 December 1974. The position of the six pipe stations (A–F) on the foreshore is marked in Fig. 3. All water-table depths are measured to the sediment surface on Day 1.

lowest near the centre of the beach at Pipe D and increased in both landward and lakeward directions (Fig. 3).

The form of the water table fluctuations in Slipway Beach is quite different from that in oceanic beaches. In ocean beaches, fluctuations either decrease landward, or reach a maximum on the mid-foreshore and then decrease landward. The reverse was found at Manapouri; water table fluctuations were at a minimum on the mid-foreshore and increased both lakeward and landward. On the open coast, the level of the water table in the beach and rhythmic changes in the level are controlled directly by tidal fluctuations in water level. In the absence of tidal movements in the limnic environment, four processes were considered to be possible controls of the beach water table.

1. *Lake level* (*LL*): the position of the lake still water surface in the vertical plane, i.e., elevation above mean sea level as measured during the daily beach survey.
2. *Shoreline position* (*SP*): the position of the lake surface in the horizontal plane, i.e., horizontal distance from a datum peg on the top of the foreshore. Intuitively, lake level and shoreline position might be expected to vary systematically together, and therefore both to merely reflect changes in still water level. However, changes in beach morphology, associated with storms and fluctuations in still water level mean that changes in lake level do not necessarily produce uniform changes in the position of the shoreline, therefore both lake level and shoreline position have been included in the statistical analysis.
3. *Wave amplitude*: as measured by the significant wave height, i.e., height of the highest one-third of all waves arriving at the beach at the time of survey. Wave height was estimated against a survey staff.
4. *Elapsed rainfall* (*ER*): Elapsed rainfall for any day is the sum of the rainfall on that day plus a proportion of that fallen on the preceding 10 d. This proportion is the rainfall on a given day, divided by the number of days since that rain fell, i.e., it is assumed that the effect of rain on the beach system decreases exponentially with time. This rather arbitrary parameter was computed to incorporate into the rainfall statistics the time-lag beween rainfall and run off, because trial runs of the statistical analysis indicated that such a parameter produced better results than raw rainfall data.

DISCUSSION

For each of the six pipe stations, correlation and multiple step-wise regression analysis (Burroughs Basic Package 1974) was carried out between the dependent variable, namely water table depth (WD), and the four process variables: lake level, shoreline position, wave energy and elapsed rainfall (Table 1).

CORRELATIONS

All stations show a strong negative correlation between the dependent variable, the depth of the

Day	Shoreline Position (m)	Lake Level (m)	Elapsed Rainfall (mm)	Significant Wave Height
1	24.92	177.07	12.2	2
2	24.45	177.11	10.8	5
3	23.80	177.14	10.8	5
4	23.72	177.06	7.4	4
5	23.72	177.12	7.4	4
6	23.27	177.06	5.3	1
7	26.40	176.97	4.0	1
8	25.70	177.02	3.3	3
9	25.75	177.02	2.8	1
10	24.90	177.06	2.4	4
11	24.50	177.06	2.1	7
12	24.40	177.05	1.9	5
13	25.15	177.00	1.7	2
14	25.20	177.00	1.5	1
15	25.10	177.04	1.4	1
16	25.00	177.04	1.3	1
17	25.40	176.99	1.2	1
18	25.60	176.94	1.1	1
19	25.40	177.00	1.1	4
20	24.8	177.11	1.4	1
21	24.8	177.08	1.5	1
22	24.6	177.08	2.4	2
23	24.2	177.08	1.9	4
24	24.4	177.07	2.0	4
25	24.45	177.02	1.6	1
26	23.95	177.06	1.5	2
27	23.50	177.09	1.2	5
28	23.35	177.14	24.4	3
29	23.00	177.15	24.4	3
30	22.90	177.20	17.9	2
31	22.50	177.26	11.4	1
32	22.30	177.28	8.4	1
33	22.30	177.24	6.8	1
34	22.15	177.27	7.8	1
35	21.85	177.29	17.0	2
36	21.60	177.30	10.5	1
37	21.25	177.32	8.1	4
38	21.25	177.28	7.7	5
39	20.65	177.29	6.4	5
40	20.10	177.34	21.0	4
41	20.10	177.30	11.0	1
42	20.10	177.36	5.9	1

TABLE 1—Summary of variables affecting the beach ground-water system in Slipway Beach, Lake Manapouri. Shoreline position, lake level, and significant wave height were taken from the daily beach survey. Wave heights were recorded in 7 class intervals 1 = flat calm; 2 = 0–5 cm; 3 = 5–10 cm; 4 = 10–15 cm; 5 = 15–20 cm; 6 = 20–25 cm; 7 = 25–30 cm. Elapsed rainfall was calculated from the daily rainfall records collected on site. Period covered is 42 d. 12 November–23 December 1974.

water table within the beach, and the elapsed rainfall; the greater the rainfall, the closer the water table gets to the beach surface (Table 2). A positive correlation between shoreline position and water table depth indicates that as the position of the shoreline moves landward (either as a result of higher lake levels or as a result of erosion of the foreshore) the depth of the water table shallows. Wave height and lake level only show significant (but inverse) correlations for the lowest pipes close to still water level. With higher wave heights, the swash extends further up the beach, water is added to the beach groundwater system, and the level of the water table in the lower foreshore is raised. At higher lake levels, the lowest pipe (F) was beneath the still water level. In this situation the water table level is the lake level. The high correlation between water table depth and lake level is therefore spurious and results from Pipe F are excluded from any further analysis.

There are some interesting trends in the correlation coefficients down the beach. The correlation between shoreline position and water table depth increases down the beach. Conversely, there is a decrease in the coefficient between elapsed rainfall and depth to the water table. These correlations tend to suggest that on the top of the foreshore the water table is influenced mostly by the elapsed rainfall, but

TABLE 2—Correlation matrix of ground-water depths at the five pipe stations and four variables at Slipway Beach, Lake Manapouri (elapsed rainfall, shoreline position, lake level and significant wave height). (NS = not significant; * = significant at the 0.05 level: ** = significant at the 0.01 level.) Period covered is 42 d, 12 November–23 December 1974.

	Elapsed Rainfall	Shoreline Position	Lake Level	Significant Wave Height
Pipe A	-0.88**	0.35*	-0.004NS	-0.19NS
Pipe B	-0.94**	0.40*	-0.004NS	-0.21NS
Pipe C	-0.93**	0.46*	0.04NS	-0.25NS
Pipe D	-0.89**	0.55*	0.09NS	-0.31*
Pipe E	-0.72**	0.61*	0.09NS	-0.29NS
Pipe F	-0.63**	0.91*	-0.92**	-0.33*

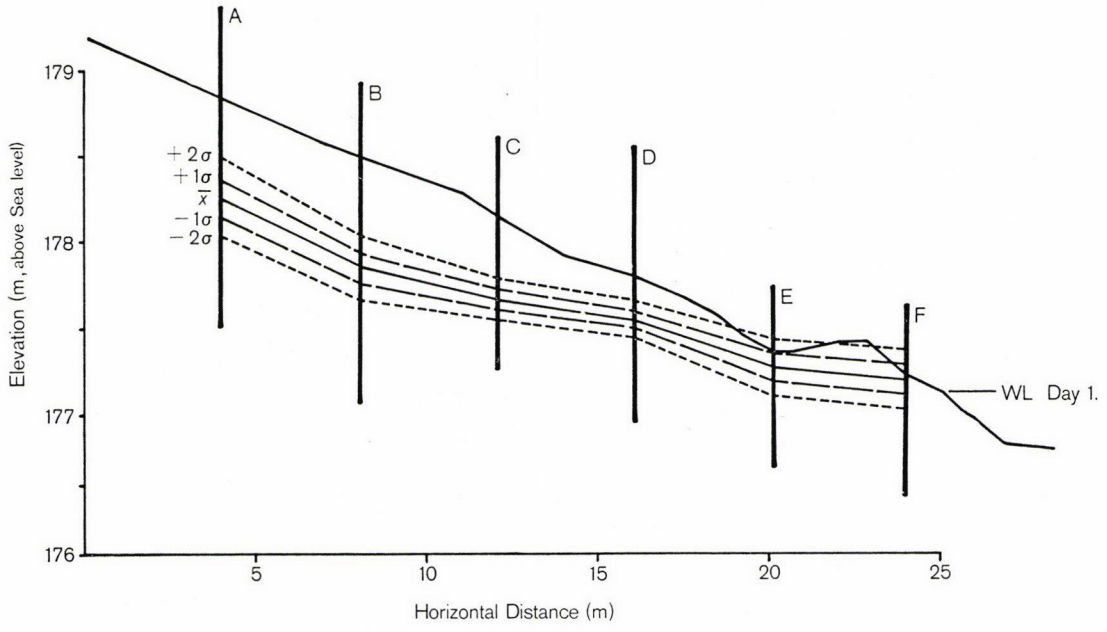


FIG. 3—Foreshore profile at Slipway Beach showing the position of the six ground-water pipes and the water level at time of installation. Mean water table depths ($\bar{X}$) and standard deviations (σ) for each pipe over the 42-d period are shown.

on the lower foreshore, closer to the lake, the position of the shoreline plays a more significant role.

MULTIPLE REGRESSION

In all pipes, elapsed rainfall is entered in the first step of the regression analysis as explaining the greatest percentage of variability in the water table depth. For the four pipes on the top of the beach, F values are significantly reduced for a small increase in the percentage variation explained by the last three steps of the regression. Elapsed rainfall (ER) on its own is the best predictor of water table depths (WD) in these pipes:

Pipe A: $WD=68.97-1.59ER$ (explains 77.4% of variation at $P = <0.01$)

Pipe B: $WD=76.44-1.32ER$ (explains 87.4% of variation at $P = <0.01$)

Pipe C: $WD=56.02-0.88ER$ (explains 85.7% of variation at $P = <0.01$)

Pipe D: $WD=30.96-0.71ER$ (explains 79.2% of variation at $P = <0.01$)

Despite elapsed rainfall being the best indicator, there is an increase in the percentage variation explained by the remaining three independent variables down the beach such that at Pipe E step three produces the highest F ratio, and elapsed rainfall, shoreline position (SP), and lake level (LL) all combine to produce the best indicator:

Pipe E: $WD=10.67-0.48ER + 3.23\ SP-0.28LL$ (explains 76.6% of variation at $P = <0.01$)

On the upper foreshore, significant correlations were recorded between shoreline position and water table depth (Table 2). Despite this, the addition of shoreline position with elapsed rainfall in the subsequent steps of the regression did not significantly increase the percentage variation explained. This apparent anomaly points to a high degree of covariance between the process variables. This is probably to be expected on the shore of an enclosed body of water such as Lake Manapouri, where rainfall, lake level, shoreline position, and wave energy are all closely tied to the passage of weather systems across the lake. Nevertheless, the results point to the groundwater in the top of the foreshore being controlled primarily by elapsed rainfall. Progress down the beach decreases the controlling influence of rainfall and increases that of shoreline position and lake level.

BEACH MORPHOLOGY

Water tables promote erosion or deposition on oceanic foreshores: high water tables facilitate erosion through an increased backwash flow, resulting from reduced percolation; low water tables facilitate deposition through increased percolation of the backwash into the beach face.

Slipway Beach is a low-energy beach exposed to waves arriving from one dominant direction, northwest. Most of the beaches around Lake Manapouri are similarly exposed, and on all of them the lake level is the dominant process controlling changes in

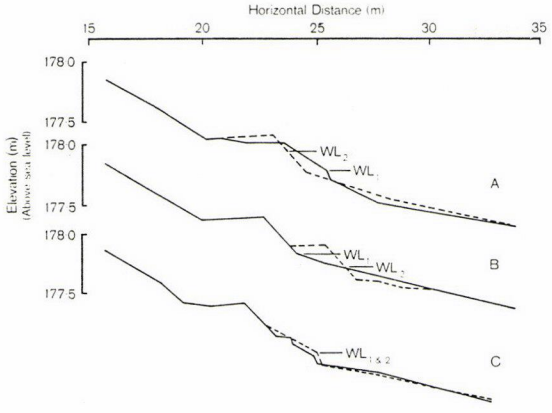


FIG. 4—Changes (- - - -) in beach morphology at Slipway Beach, 12 November–23 December 1974:
(A) Over a 4-d period in response to a 0.17 m rise in water level (WL);
(B) Over a 4-d period in response to a 0.10 m fall in water level; and
(C) Over a 4-d period of static water level.

beach morphology (Pickrill unpublished 1976). Results from the daily beach survey (Fig. 4) show that, during periods of static lake levels, changes in the beach profile are very small, regardless of the wave conditions. Maximum changes in profile are produced during periods of rising and falling levels. Bruun (1962) put forward a model predicting changes in the shoreline following a rise in sea level. Schwartz (1967) confirmed the existence of this model in wave tank experiments, while McLean (1973) suggested some minor alterations. The changes in beach morphology during rising lake levels at Slipway Beach confirm the broad principles of this model, while on falling levels the sequence of changes is reversed (Fig. 4). McLean summarised these changes following a rise in sea level:

(1) There is a shoreward displacement of the beach profile relative to fixed geographical co-ordinates.
(2) The material eroded from the central beach is equal to the sum of material deposited on the upper beach (swash limit) and nearshore bottom.
(3) The rise in elevation of the upper beach (swash berm) resulting from deposition is equal to the rise in sea level.
(4) The rise in elevation of the nearshore bottom as a result of deposition is equal to the rise in sea level.
(5) The geometry of the final profile is similar to the geometry of the initial profile.

As a result of these transfers, rising lake levels produce a nett lakeward redistribution of material, and falling levels a nett landward movement. The passage of storms across the lake is associated with high rainfall, rising lake levels, a landward movement of the shoreline position, and high water table levels in beaches. High water tables and the associated reduction in the available pore space for percolation during rising lake levels could be expected to accelerate shore-normal lakeward transfers of sediment associated with the Bruun effect. Conversely, low water tables and high porosity during periods of falling lake levels would accelerate landward sediment transfers.

On the upper foreshore where the water table is controlled by precipitation the water table may rise to the surface, and the resulting spring sapping may cause elutriation of fine material from the foreshore, and the development of incised rill channels lined with coarse lag material (Fig. 5). Linear relationships between water table depths and elapsed rainfall, derived in the regression analysis, point to variable rates of water table rise down the beach (Fig. 6). The slopes of these curves are a measure of the rate of water table rise in the foreshore. During the period of study, rainfall was never sufficient to produce spring sapping from any but the lowest two pipe stations. This is probably to be expected as the sediment cover at mean water table depths is shallowest on the lower foreshore and deepens up the beach. However, the predictor equations in Fig. 6 suggest that rates of water table rise increase up the beach, and that, if these relationships between water table depth and rainfall are assumed to remain linear, then, given sufficient rain, the water table will emerge first at Pipes D and E on the lower half of the foreshore, and then at Pipe A on the top of the beach. Such a process of spring sapping starting at the top of the foreshore could account for the development of incised rill channels down the entire length of the profile and not just close to the water level.

CONCLUSIONS

Water table fluctuations in Slipway Beach, Lake Manapouri, take on a different form from those in oceanic beaches. In the lake, the depth of the water table beneath the surface increases up the foreshore. The fluctuations in water table depth are smallest on the mid-foreshore and increase both lakeward and landward. This is a direct reversal of the seashore pattern, where fluctuations either reach a maximum at the mid foreshore and then decrease landward, or simply decrease landward. Movements in seashore water tables are regular and rhythmic, as a result of their direct control by tides. In the lake, movements in beach water tables are extremely irregular and long periods of near-static levels are punctuated by short, rapid fluctuations.

Differences in the behaviour of the limnic and oceanic systems are attributed to differences in the controlling processes. In the lower foreshore of Slipway Beach, the depth of the water table is controlled by the relative position of the shoreline. Progression up the beach traces a decrease in the influence of the shoreline position and an increase in control by elapsed rainfall.

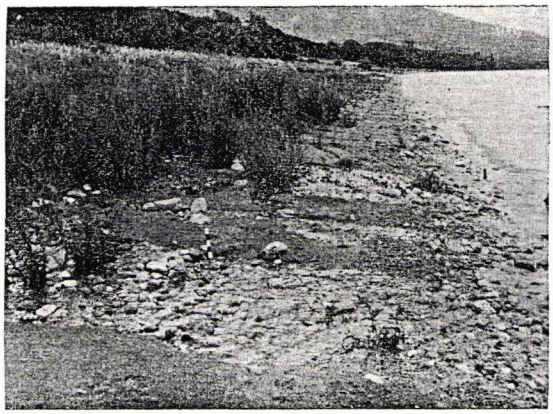


FIG. 5—Water-table spring sapping during heavy rainfall at Frasers Beach, Lake Manapouri, 20 December 1974. Ground-water springing has started at the top of the foreshore and produced incised rill channels. Fine sediments have been washed down the foreshore, leaving a gravel-lined lag deposit in the channel.

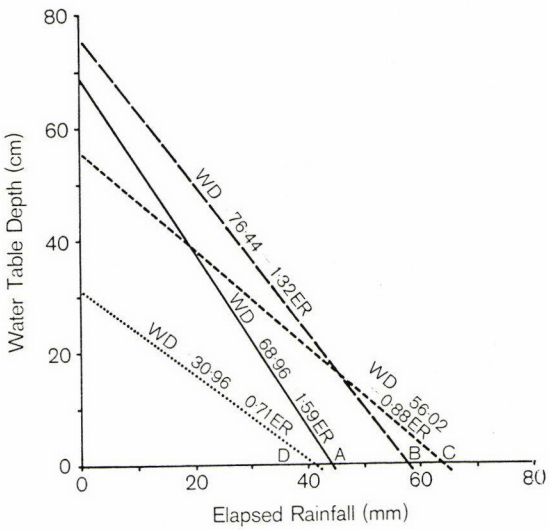


FIG. 6—Relationship between water-table depth (WD) and elapsed rainfall (ER) as derived from regression analysis for the 4 pipe stations on the mid and upper foreshore of Slipway Beach, Lake Manapouri. Minimum elapsed rainfalls for spring sapping of the water table occur when the water table depth is zero, i.e., Pipe A = 43 mm ER; B = 58 mm; C = 63 mm; D = 43 mm; E = 19 mm.

Beach morphology is influenced by the ground-water system in two ways. First, shore-normal sediment transfers in response to rising and falling lake levels follow the pattern predicted by Bruun (1962) for changes in sea level. Water table fluctuations are such that they may reinforce and accelerate the shore normal exchanges of sediment associated with the Brunn effect. Second, incised rill channels on the upper foreshore, well above the swash limit, may be attributed to spring sapping of the beach ground-water table. During periods of high elapsed rainfall, rates of water table rise are highest on the top of the foreshore, thereby providing a possible mechanism for the initiation of rilling.

ACKNOWLEDGMENTS

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Lake Te Anau Profile Information, February 1989

Profile Label	Profile Name	Profile Bearing°	Length of Marker Exposed (m)	Bearing ° to Fixed Locations From Marker	
1	Fence North Rodeo	326.5	0.550		
2	Rodeo	316	0.300		
3	Marina West	309.5	0.300		
4	Marina South	195.5	0.400		
5	No Entry SLipway	266			
6	Float Plane Landing	237			
7	Steamer Beach	313.5	0.450		
8	Dock Bay	12		To Kepler sign	140
9	Ski-lane Beach	186	0.395		
10	Brod Bay	44	0.360		
11	Garnet East	300	1.280		
12	Garnet West	32	0.693		
13	Moonlight Mark Point	202	0.595		
14	Trig B South	273	0.150		
15	Trig B East	83	0.523		
16	Deadmans Point	28	Old 0.680 New 0.480		
17	North, North Patience	227	0.578	To Dome Island	264
18	East Patience	263	0.440		

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