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Effect of Rising Sea Level on Runoff and Groundwater Discharge to Coastal Ecosystems

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Rising sea level can cause an increase in surface runoff from coastal areas by raising the watertable and thus increasing the incidence of saturated soil conditions in low-lying areas. As surface runoff increases, less rainfall will infiltrate into the ground and groundwater discharge to the coast will decrease. The link between sea level rise and runoff is critically dependent on the sensitivity of surface runoff to changes in the elevation of the watertable. A significant relation between the two is demonstrated for a coastal watershed on Cape Cod, where it is estimated that a 10 cm rise in the watertable will increase surface runoff by 70% and decrease groundwater discharge by 20%. Effects on near-shore ecosystems include changes in nutrient fluxes and in the salinity of the sediments.

Introduction

The structure and productivity of nearshore coastal ecosystems is influenced by the inflow of freshwater and nutrients from the land. The influx of nitrogen, which is increasingly affected by sewage disposal practices, is particularly important. Marine ecosystems are thought to be nitrogen limited (see reviews by Howarth, 1988 and Hecky & Kilham, 1988), and many studies have shown that freshwater runoff from coastal areas, including groundwater discharge along the coast, can be a significant source of nitrogen (e.g. Valiela *et al.* 1990; Johannes & Hearn, 1985; Capone & Bautista, 1985; Lee & Olsen, 1985; Valiela & Teal, 1979). Runoff can be important in and of itself if it dilutes the salinity of the receiving water body (see Johannes, 1980 for a review of this topic and earlier work on nutrient inputs by groundwater). Through these processes, the ecology of the nearshore region is coupled to the hydrology of coastal watersheds.

Sea level is rising at 30 cm per 100 years along the East Coast of the United States, and this rate will more than triple if certain predictions of climate change are realized (Gornitz *et al.*, 1982; Hansen, 1985). Some consequences of higher sea levels projected for the next century, i.e. retreat of shorelines, loss of wetlands, and intrusion of salt water into aquifers and estuaries, have been investigated (e.g. Barth & Titus, 1984). However, the effects of higher mean sea level on the hydrology of coastal areas, exclusive of the effects of increased flooding, have not been explored. This paper demonstrates the sensitivity of freshwater

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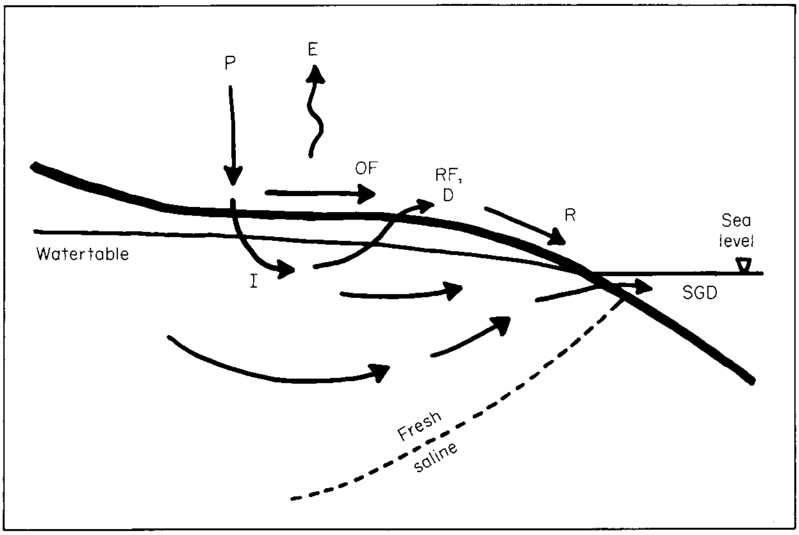

Figure 1. The water balance of a coastal watershed. The input of water by rainfall (P) is balanced by evapotranspiration (E), surface runoff (R) and submarine groundwater discharge (SGD). During a storm, rainfall is divided between infiltration (I) and overland flow (OF). Surface runoff is the sum of the drainage of groundwater into creeks (D) between storms and direct runoff, the sum of overland flow and return flow (RF), immediately following a storm.

runoff to increases in sea level and describes some possible effects on near-shore ecosystems. In particular, we investigate the hypothesis that rising sea level will increase surface runoff and decrease groundwater discharge from a coastal watershed.

Hydrological setting

A watershed is a topographically defined area that water enters through rainfall and leaves through evapotranspiration, surface runoff, and groundwater discharge. In the case of a coastal watershed, runoff and groundwater discharge enter the sea (Figure 1). Rainfall and the potential rate of evapotranspiration are determined by climate. Actual evapotranspiration is limited by the climatically-controlled potential rate, but it is also affected by vegetation and the wetness of the soil. Runoff and groundwater discharge are determined by soil properties, topography, and the history of rainfall and evapotranspiration. For the purpose of this discussion, surface runoff includes both direct runoff, which occurs as stream flow immediately following a rain storm, and drainage of groundwater into creeks, which accounts for stream flow between storms. The amount of direct runoff generated by a storm depends on the amount of rainfall and on the moisture status of the soil. In general, more runoff occurs when the soil is initially wet. Groundwater discharge can be calculated by difference if rainfall, evapotranspiration, runoff, and the change in the amount of water stored on the watershed are known.

A link between rising sea level and changes in the water balance is suggested by a general description of the hydraulics of groundwater discharge at the coast. Fresh groundwater rides up over denser, salt water in the aquifer on its way to the sea (Figure 1), and groundwater discharge is focused into a narrow zone that overlaps with the intertidal zone (Bokuniewicz, 1980; Reilly & Goodman, 1985). The width of the zone of groundwater discharge, measured perpendicular to the coast, is directly proportional to the discharge rate (Glover, 1959). The shape of the watertable and the depth to the fresh/saline interface are controlled by the difference in density between freshwater and saltwater, the rate of freshwater discharge and the hydraulic properties of the aquifer. The elevation of the watertable is controlled by mean sea level through hydrostatic equilibrium at the shore.

We hypothesize that rising sea level will increase surface runoff and decrease groundwater discharge to the coast. Darcy's law states that the rate of discharge of water through the aquifer is proportional to the slope of the watertable. If the rate of groundwater discharge remains constant as sea level rises, then the slope of the watertable remains constant and the elevation of the watertable in the watershed will rise by the same amount. However, as the watertable nears the soil surface, the moisture content at the soil surface increases, and surface runoff from the watershed increases. We assume that in the moist, coastal climate actual evapotranspiration is already at or near the potential rate of evapotranspiration. Therefore, groundwater discharge must decrease to maintain the balance between inflow and outflow.

As groundwater discharge decreases, the slope of the watertable must decrease, and to a first approximation, the height of the watertable above sea level will decrease in the same proportion as discharge. The elevation of the watertable inland from the coast will rise as sea level rises but not by the same amount.

Water balance study

The link between sea level and runoff depends critically on the sensitivity of surface runoff to an increase in the elevation of the watertable in the watershed. This has been investigated using the results of a water balance study on a coastal watershed. Inflows and outflows of water were measured on a small watershed for the period February to October 1989. The objective of the field observations was to describe the response of surface runoff to rainfall; therefore, particular attention was paid to the measurement of rainfall and stream flow. Watertable elevations were also measured to gauge changes in water storage in the watershed. These data and the principal of conservation of mass applied to the watershed as a whole form the basis for extrapolating the effects of higher sea level on runoff and groundwater discharge.

Study site

The Mill Creek watershed is located in Wellfleet, Massachusetts (41°56'N, 70°03'W) on Cape Cod (Figure 2). The total area of the watershed is 1·07 km^2, of which 20% is located between the level of high tide and 3 m above mean sea level (MSL). Most of the low area is covered by relict salt marsh that has been invaded by freshwater, upland vegetation since the construction of a dike across the Herring River, downstream from Mill Creek. The dike decreases the amplitude of the tides (from 1·4 m in Wellfleet Harbor to 0·3 m just upstream of the dike) but does not affect the mean water level in Mill Creek. The portion of the watershed above 3 m MSL is sandy and hilly. Geologically, Cape Cod is a terminal moraine of interbedded silt, sand and gravel. The Mill Creek watershed is underlain by the sandy Older Wellfleet Plain deposits (Oldale, 1976), which extend beneath the salt marsh sediments to a depth of several tens of meters.

Measurements

Both rainfall and surface runoff were measured continuously. Cumulative rainfall was measured with a Belfort gauge at a National Atmospheric Deposition Program (NADP) site in Truro, 4 km from Mill Creek. These data were checked against weekly rainfall totals measured at Mill Creek. Stream flow was measured at a broadcrested weir installed

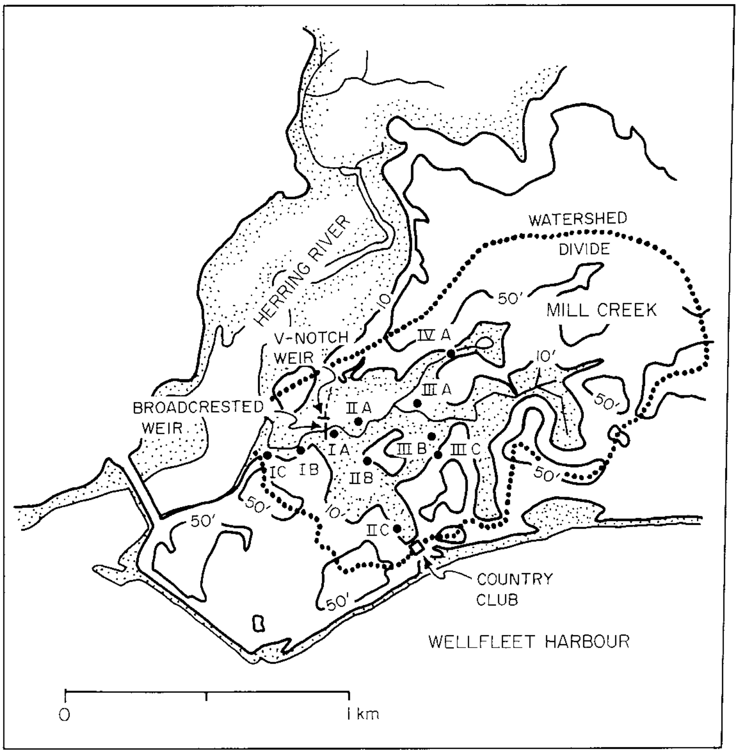

Figure 2. The Mill Creek watershed showing the sites of the two weirs and the watertable wells, ●. The watershed divide is defined by the slope of the soil surface. Also shown is the extent of the area below 3 m MSL (· · · ·).

above the upper limit of tidal influence on Mill Creek (Figure 2). Water levels above the weir were recorded with a Stevens recorder, and discharge across the weir was calculated as prescribed by Ackers *et al.* (1978). The calibration of the weir was checked by direct measurement of flow over the weir. A V-notch weir was installed to monitor surface runoff from the watershed that enters Mill Creek through a small ditch downstream of the broadcrested weir. Flow over the V-notch weir was measured on weekly visits to the site.

Ten shallow (< 3 m deep) wells were installed to measure changes in the elevation of the watertable in the low area of the watershed (Figure 2). The wells were constructed of slotted PVC pipe. The time of recovery from pumping each well dry was measured to confirm that there was a good connection with the watertable. Watertable elevations were read weekly for the entire period of monitoring. During August, elevations were read daily, and hourly on one day, to characterize the short-term, possibly tidal, fluctuations in the watertable. Elevations were referenced to mean sea level.

All instruments were in place and data collection began on Julian date 50 (19 February). Data collection was discontinued on Julian date 297 (24 October) after it was determined that sufficient data had been collected to describe the relation between rainfall and runoff.

Results and analysis

Watertable elevations declined from spring through summer and recovered partially by the end of observations in the fall [Figure 3(a)]. This reflects changes in the rate of

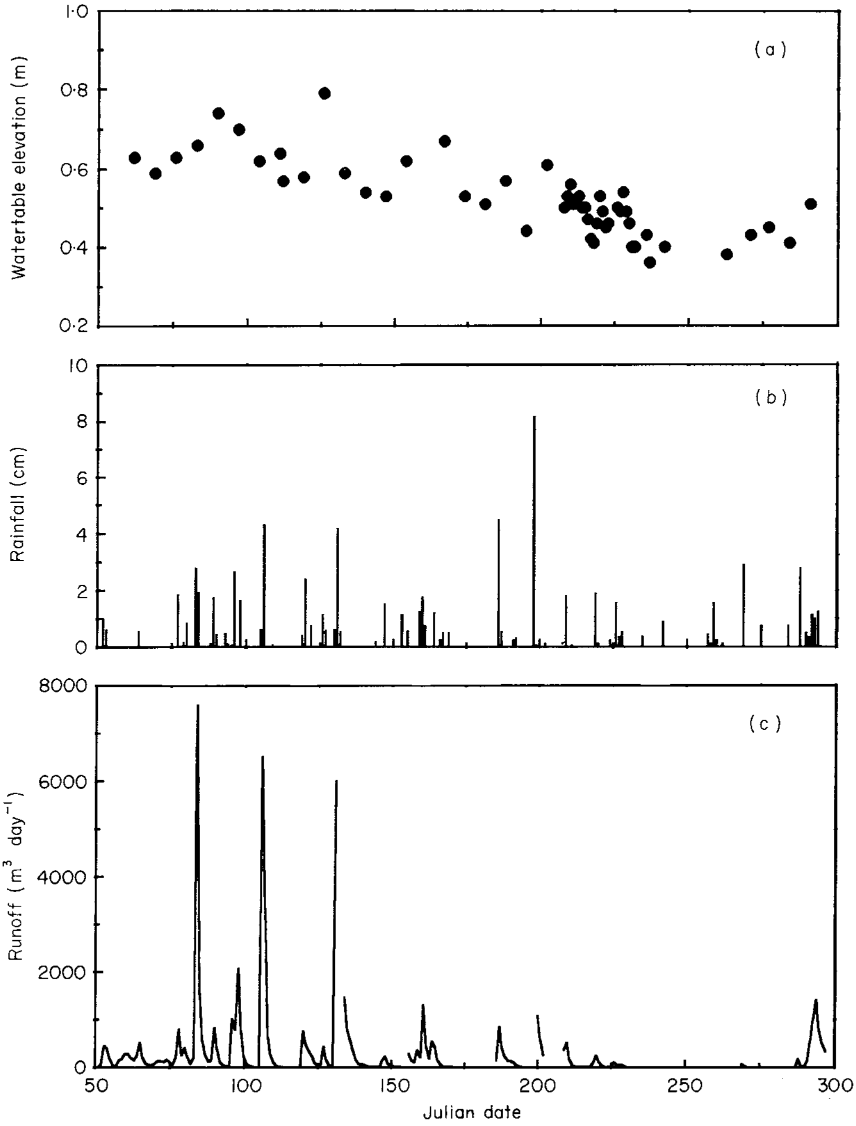

Figure 3. Data from the 9-month water balance study; (a) average of watertable elevations (relative to MSL) measured at 10 wells, (b) daily rainfall measured at the NADP recorder and (c) surface runoff over the broadcrested weir.

evapotranspiration during this period. The records from all 10 wells showed the same fluctuations, so these data were averaged to get a measure of the average watertable elevation throughout the low area of the watershed. Watertable elevations responded to rainfall, but none of the short-term fluctuations appeared to be the result of semi-diurnal tidal forcing.

Rainfall was normal for the period of monitoring [Figure 3(b)]; a total of 82 cm was recorded compared to the normal rainfall of 80 cm for the period February to October. None of the storms delivered extreme amounts of rainfall. The highest measured 24 h

TABLE 1. Summary of rainfall and runoff for selected storms

Julian date	Rainfall (cm)	Runoff (m^3)	Initial watertable elevation (m)
77	1·96	1240	0·63
83	4·75	10100	0·66
98	1·65	3080	0·70
105	4·95	10800	0·62
119	3·61	1880	0·58
147	1·52	368	0·53
155	0·58	545	0·62
209	1·90	1040	0·53
219	2·03	456	0·46
226	2·51	225	0·50
269	2·92	93	0·38
287	2·79	183	0·41
291	3·94	4680	0·51

rainfall was 8·18 cm, which has an estimated recurrence interval of less than 2 years (Hershfield, 1961). No bias towards higher or lower rainfall at the NADP site could be detected when the continuous rainfall record was compared with the weekly totals from Mill Creek.

Measureable stream flow in Mill Creek occurred only for one or two days following a rain storm [Figure 3(c)], except during spring thaw (Julian dates 50 to 75). Flow over the V-notch weir accounted for a small fraction of the total surface runoff from the watershed, and these data were omitted from subsequent analysis. Gaps in the stream flow record occur around Julian dates 132, 154, 182 and 205 because of vandalism and malfunction of the Stevens recorder. Water levels in Mill Creek were below the crest of the weir during the period 242 to 287 and no surface runoff occurred.

Groundwater discharge

Little if any groundwater drains into Mill Creek between storms; therefore a significant portion of the water leaving the watershed must occur as groundwater discharge that bypasses the creek. Total surface runoff for the period of study was 62 000 m^3, or 5·8 cm over the entire area of the watershed. This accounts for 7% of the precipitation input. Annual evapotranspiration for Cape Cod is between 50 and 60 cm (Kohler *et al.*, 1959); most of this occurs in the summer. If the contribution of wintertime evapotranspiration to this figure is neglected, then evapotranspiration accounts for 60 to 70% of rainfall. Storage of groundwater declined, but only slightly [Figure 3(a)]. Groundwater flow out of the watershed accounts for the remaining 20 to 30% of rainfall (February to October), plus a small amount of groundwater lost from storage.

Effect of watertable elevation on surface runoff

Given the intermittent nature of surface runoff in Mill Creek, it can be assumed that all surface runoff occurs as direct runoff from rainfall. Furthermore, an examination of Figure 3 suggests that the amount of runoff generated by a centimetre of rainfall increases as the elevation of the watertable increases. The relation between rainfall, runoff and watertable elevation can be studied by looking more closely at 13 storms for which initial watertable elevations are known and measureable surface runoff occurred (Table 1). The

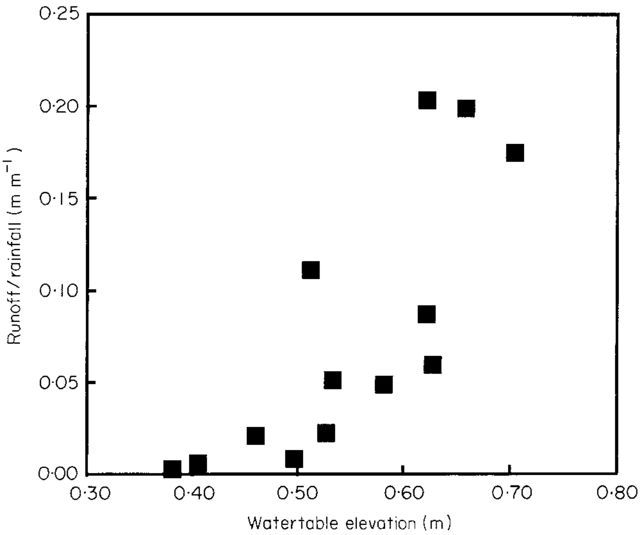

Figure 4. Direct runoff measured as a proportion of rainfall increases with increasing average watertable elevation ($r^2 = 0{\cdot}61$). Data are from only those storms for which measurable runoff occurred and initial watertable elevations are known.

volume of surface runoff following a storm, measured as a proportion of total rainfall, is correlated with initial watertable elevation for these storms (Figure 4, $r^2 = 0{\cdot}61$).

The relation between runoff and watertable elevation can be explained if we hypothesize that direct runoff is predominantly saturated overland flow and return flow (Figure 1). Saturated overland flow is runoff generated by rain falling on saturated soil, and return flow is groundwater that seeps out of rain-saturated areas and runs off overland (Dunne & Leopold, 1978). Both mechanisms depend on the soil in a portion of the watershed becoming saturated; this area is known as the contributing area. The sequence of events during a rain storm is as follows. At the beginning of the storm, all of the rainfall infiltrates into the ground and no runoff occurs. Infiltration increases the amount of water in the soil and causes the watertable to rise. We assume that the pre-storm watertable is close to the soil surface, so that a perched watertable does not form. As the watertable elevation increases past a threshold elevation, near the elevation of the soil surface, the soil surface quickly saturates (Gillham, 1984). After this occurs, all of the rainfall on the contributing area runs off.

The partitioning of the total depth of rainfall, P, on the contributing area, A, between the amount that infiltrates into the soil and the volume of runoff, R, can be expressed as

$$AP = AS_y(h' - h) + R, \tag{1}$$

in which the amount of infiltration is expressed as the product of the specific yield of the soil, S_y, and the difference between the initial elevation of the watertable, h, and the threshold elevation, h'. The volume of direct runoff from a storm is

$$R = 0 \text{ for } P < S_y(h' - h); \tag{2a}$$

otherwise

$$R = A(P + S_y h) - AS_y h'. \tag{2b}$$

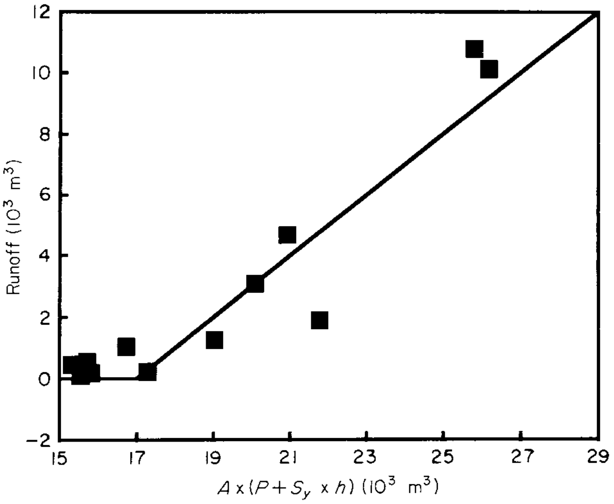

Figure 5. Rainfall–runoff model fitted to the data. Abscissa values are calculated from the first term on the right-hand side of equation (2b). Computed runoff is correlated with observed runoff with an $r^2=0{\cdot}91$.

Approximate values can be assigned to contributing area and specific yield in the Mill Creek watershed *a priori*. The contributing area can be taken as the extent of former salt marsh sediments ($A=0{\cdot}20$ km^2); the low relief and shallow depth to the watertable here are conducive to saturation during storms. Little runoff is expected from the higher parts of the watershed, which are sandy and have a high capacity for infiltration. Specific yield of salt marsh sediments is approximately 0·1 (Nuttle & Hemond, 1988). The remaining parameter, h', can be estimated by fitting the model to the data (Figure 5). A good fit is obtained, $r^2=0{\cdot}91$. Note that the slope of the line is determined by the *a priori* estimates of the contributing area and specific yield. The fitted X-intercept establishes the value of the threshold watertable elevation as $h'=0{\cdot}74$ m. This is 15 cm below the average of the elevations of the soil surface at the sites of the watertable wells, which is consistent with the assumptions made in formulating the model, i.e. shallow watertable.

Discussion

The relation between direct runoff and watertable elevation shown in Figure 4 supports the hypothesis that rising sea level will increase surface runoff from coastal watersheds. This phenomenon will be significant only in areas where a large portion of the watershed is above the level of high tide but not too far above the watertable. In areas that are frequently flooded by tides, the water balance is dominated by the infiltration of tidal water, and the relations between rainfall, runoff and groundwater discharge described previously will not apply. If the soil surface is too far above the range of fluctuation of the watertable, then changes caused by rising sea level will have no effect on the saturation of the soil and runoff will not be affected. Twenty per cent of the Mill Creek watershed meets these conditions. Similar areas occur in the coastal lagoons found along the Atlantic and Gulf coasts of North America. Coastal lagoons account for 18% of the coastline of North America and 13% of the coastline worldwide (Barnes, 1980). Furthermore, coastal dikes create analogous hydrological conditions in the areas that they are constructed to protect, and the use of dikes is expected to increase as a rising coastal population confronts rising sea level.

The rainfall-runoff model [equations (2) and Figure 5] has not been rigorously tested, and we have no independent evidence for the predominance of saturated overland flow and return flow over the other mechanisms for the generation of runoff. However, the data are consistent with the underlying assumptions and the predictions of the model. The magnitude of a sea level induced change in runoff from Mill Creek can be estimated by using equations (2) the observed rainfall for the study period, and the observed water-table elevations incremented by a small amount to simulate the effect of higher sea level. For a 10 cm rise in the watertable over observed values, surface runoff increases by about 70%. Consequently, groundwater flow must decrease by the same amount, assuming that rainfall and evapotranspiration are unchanged; this amounts to about a 20% reduction in groundwater discharge. Groundwater discharge will be further reduced if evapotranspiration increases in response to wetter soil conditions.

For the Mill Creek watershed, sea level would have to rise about 21 cm to raise the watertable by 10 cm; this was estimated by applying Darcy's law as described above. The 20% decrease in groundwater discharge requires a 20% decrease in the average watertable elevation relative to sea level 55 cm [Figure 3(a)]. Therefore the 21 cm rise in sea level is the sum of the 10 cm rise in the watertable plus an 11 cm rise in sea level relative to the watertable. At the predicted higher rates of sea level rise, a 21 cm rise in sea level will occur over 20 years.

Near-shore ecosystems may be affected by the hypothesized changes in surface runoff and groundwater discharge in a number of ways. Submarine groundwater discharge controls the gradient in sediment salinity between terrestrial and marine ecosystems (Johannes, 1980). A decrease in groundwater discharge will increase salinities, and a complementary shift to more salt-tolerant plant species can be expected. Recent research also points to a direct effect of groundwater flow rate on nutrient cycling (Capone & Slater, 1990) and biomass (Lodge *et al.*, 1989 for freshwater lakes). The impact of nitrate discharge from coastal watersheds on the nearshore ecosystem is affected by the dominant hydrologic pathway for nitrate delivery. Nitrogen entering through the sediments in groundwater is available first to the denitrifiers in the sediments (Slater & Capone, 1987) and then to vascular plants, where some of it is bound into refractory organic matter (Valiela & Teal, 1979). In contrast, dissolved nitrogen entering the water column in runoff is immediately available to algae (Nixon, 1981). An increase in surface runoff, derived from groundwater drainage within a watershed at the expense of submarine groundwater discharge, will deliver more nitrate directly to the water column, which promotes conditions for algal blooms.

Given the importance of groundwater discharge to near-shore ecosystems, changes in the hydrology of coastal watersheds may be more important than the direct effects of changes in either sea level or climate. However the sensitivity of near-shore ecosystems to these and other effects of changing sea level and climate is not known and is largely unstudied.

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