Estuarine, Coastal and Shelf Science (1987) **25**, 677–691

Geomorphological Control of Subsurface Hydrology in the Creekbank Zone of Tidal Marshes

Judson W. Harvey, Peter F. Germann[a] and William E. Odum

Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22903, U.S.A.

Received March 1987 and in revised form 19 July 1987

Keywords: salt marshes; *Spartina*; hydrology; pore waters; interstitial water; soil properties; groundwater; wetlands; Chesapeake Bay

A combination of field and numerical modeling methods was used to assess pore-water movement in a narrow (20 m) *Spartina* marsh which was flooded regularly by tidal waters. Soil composition and soil hydraulic properties did not vary across the marsh or with depth. Hydraulic head was monitored on a transect perpendicular to the creekbank. During exposure of the marsh surface, hydraulic gradients were predominantly horizontal; vertical gradients were small or zero. Subsurface flow was directed from the marsh interior toward the creekbank. Approximately 14 l of pore water were discharged laterally to the adjacent tidal creek per meter of creekbank over a complete tidal cycle.

A numerical hydrological model was modified to simulate subsurface hydraulics in the creekbank vicinity of regularly flooded tidal marshes. The model was parameterized to represent soil conditions, tidal fluctuations and topography at the field site. Observed changes in hydraulic head over complete tidal cycles were accurately predicted by the model. Model simulations identified the vertical infiltration of creek water into the marsh surface at the onset of tidal flooding as the primary source (66%) for the replacement of water drained at the creekbank. Significant replacement (31%) also occurred as discharge from the interior marsh. Horizontal recharge at the creekbank was minimal (3%).

A sensitivity analysis was conducted with the model to assess the relative importance of geomorphological factors and soil properties in controlling pore water export at the creekbank of tidal marsh soils. Each parameter was varied systematically over a realistic range for field conditions. Changes in marsh elevation exerted greater control over creekbank discharge than changes in soil hydraulic properties. More rapid turnover of pore water near creekbanks of higher elevation marshes is hypothesized.

Introduction

A thorough understanding of hydrological transport processes is essential to the accurate estimation of material and energy budgets in wetlands. The presence of highly

[a] Present address: Department of Soils and Crops, P.O. Box 231, Rutgers University, New Brunswick, NJ 08903, U.S.A.

0272–7714/87/060677+15 $03.00/0

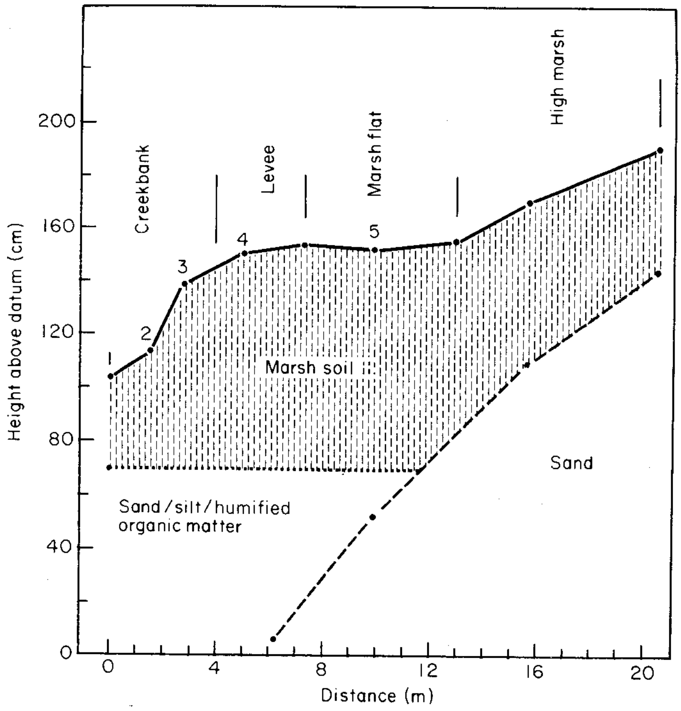

Figure 1. Topography, stratigraphy and location of hydrological instrumentation at Carter Creek Marsh, VA. Measurement stations are numbered.

concentrated pools of dissolved constituents in the interstitial waters of tidal marsh soils (Nixon, 1980) suggests that even small volumes of pore water drainage could carry significant loads of nutrients and other materials into open waters. Material exchanges between marsh substrates and adjacent surface waters have been identified as significant components of nutrient budgets in several tidal creek systems (Gardner, 1976; Valiela *et al.*, 1978; Jordan & Correll, 1985).

Research to characterize subsurface fluxes of pore water in tidal marsh soils began almost half a century ago (Chapman, 1938), but knowledge has advanced beyond an elementary understanding only in the past decade. Water removal from tidal marsh soils has been shown to take place by evapotranspiration (Hemond & Fifield, 1982; Dacey & Howes, 1984; Nuttle, 1986) and by drainage at the creekbank (Gardner, 1976; Jordan & Correll, 1985; Agosta, 1985; Yelverton & Hackney, 1986). Water replacement to marsh soils occurs by inflow at the creekbank (Jordan & Correll, 1985), vertical infiltration of flooding tidal water and precipitation (Hemond & Burke, 1981; Hemond *et al.*, 1984; Yelverton & Hackney, 1986; Carr & Blackley, 1986; Nuttle, 1986), and by groundwater input (Valiela *et al.*, 1978; Carr & Blackley, 1986).

Preliminary budgets for the export of dissolved constituents from tidal marsh soils have been developed for several marshes (Gardner, 1976; Jordan & Correll, 1985; Yelverton & Hackney, 1986). The authors utilized steady-state discharge formulae and water-table data to calculate pore-water fluxes at the creekbank. This method relies upon assumptions of homogeneity of soil hydraulic properties and an assumed predominance of horizontal fluxes of pore water. Dye tracer studies by Jordan and Correll (1985) suggested these assumptions were reasonable; here we report the results of a field and modeling approach to test these assumptions further. In addition, we used a modeling analysis to explore the relative importance of geomorphology and soil hydraulic properties in controlling pore water export at creekbanks of tidal marshes.

The present study was conducted in a narrow and regularly flooded *Spartina alterniflora* marsh. Hydraulic conductivity did not differ statistically with depth or distance across the marsh. Measurements of hydraulic head collected over complete tidal cycles showed that subsurface flow took place when the marsh surface was exposed; fluxes were predominantly horizontal and directed toward the creekbank. An unconfined aquifer model with Dupuit (horizontal flow) assumptions accurately predicted measured fluctuations in hydraulic head. Model and field data showed that creekbank discharge was an effective mechanism of pore water removal from the soil at this site. Water replacement occurred by vertical infiltration of tidal water and horizontal discharge from the interior marsh. These findings contrast with results from expansive and irregularly flooded marshes where a vertical flux (evapotranspiration) represents the critical pore water export mechanism over the marsh as a whole (Hemond & Fifield, 1982; Dacey & Howes, 1984; Nuttle, 1986).

Standard terminology is needed to describe fluxes in tidal marsh soils. The following definitions are from Freeze (1969). *Discharge* is the removal of water from the saturated zone by movement across the water table, together with the associated flow toward the water table in the saturated zone. *Recharge* is the entry of water into the saturated zone by movement across the water table, together with the associated flow away from the water table within the saturated zone. *Infiltration* is the entry of water into the marsh surface when it is unsaturated, together with associated downward flow in the unsaturated zone.

Site description and methods

Study site

A *S. alterniflora* marsh at Carter Creek, Va. (37°20′N, 76°35′W) was selected for study. Carter Creek is located within the lower York River, a sub-estuary of the Chesapeake Bay. The mean and spring ranges of the astronomical tide are 80 and 100 cm, respectively, in the vicinity of the study site (U.S. Department of Commerce, 1984). The majority of the marsh at Carter Creek is low marsh vegetated by *S. alterniflora* of medium height (1 m). Tidal predictions (U.S. Department of Commerce, 1984) indicate that creek water inundates the low marsh on approximately 340 days per year. The narrow high marsh is dominated by *Distichlis spicata* and *Scirpus robustus*. *Typha angustifolia, Rumex verticillatus* and *Polygonum* sp. are present at the base of the hillslope.

Soil structure

Stratigraphy was assessed by core sampling to a depth of 2 m and qualitatively describing soil layers. Soil bulk density was measured *in situ* in the top 50 cm of soil by γ-ray attenuation (Rawitz *et al.*, 1982). Replicate soil cores (20 cm deep, 7·7 cm diam) were removed from the creekbank, levee, and marsh flat zones. Cores were weighed, split longitudinally and reweighed prior to analysis. Half of each core was dried at 105 °C for 24 h and reweighed for the determination of bulk density. Organic matter content was determined for 3 subsamples (roots and rhizomes removed) by weight loss through ignition (500 °C for 5 h). Macro-organic content was determined by washing the second half of each core over a 5-mm screen. Roots and rhizomes were washed repeatedly to remove sediment, then dried at 105 °C for 24 h and weighed. Mineral matter content was calculated as the difference between the dry weight of each core sample and the sum of the weights of organic matter and roots and rhizomes. Dry weights of soil components were converted to volumes by assuming mineral matter to have a particle density of 2·65 g cm^{-3} (Hillel, 1982) and organic matter and roots and rhizomes to have a particle density of 1·0 g cm^{-3} (Knott *et al.*, 1987). Porosity was determined as the ratio of the volume of voids to the total volume (Hillel, 1982).

Subsurface hydrodynamics

Mini-piezometers (Lee & Cherry, 1978) were constructed from extruded acrylic tube (1 cm i.d.). Piezometer tips were milled with densely drilled holes (0·25 cm diam.) over a length of 10 cm and then capped with conical acrylic tips; holes were drilled over the entire length of the well tubes. Wells and piezometers were installed from an elevated catwalk in nested arrays at five locations (Figure 1) across the marsh surface. At each location piezometers were installed to three depths (25, 45 and 75 cm). Three additional wells were installed at equally spaced intervals along the transect between stations 3 and 4.

A theodolite and stadia rod were used to measure the elevation of the top of each piezometer; within each instrument water-level measurements were made from the top to the water surface using a graduated rod, electrical current and voltmeter. The combined error in measuring piezometric head was estimated to be ± 1 cm. Lag times in the equilibration of piezometric head were evaluated for a subset of the piezometers according to the method of Hvorslev (1951). The mean time constant was 8·5 min which indicated that instrument response to changing head conditions in the marsh soil was rapid. Head data from instruments with unacceptably long time constants (>20 min) were not included in further analyses.

To assess subsurface flow dynamics over short time periods, hydraulic heads were measured repeatedly within piezometers and wells over complete tidal cycles on 11 July, 26 July, 11 August and 9 September 1985. Instruments were revisited at approximately 15-min intervals. Pathways of pore-water drainage and replacement to the marsh soil were identified using plotted time records of piezometric head. Volumes of pore-water discharge and recharge to the marsh soil were calculated by integrating over short interval (6 min) discharge calculations using the formula and procedure reported in Jordan and Correll (1985).

Piezometers were also used to estimate the saturated hydraulic conductivity of the soil at 36 points by the method of Luthin and Kirkham (1949). Non-parametric statistics (Conover, 1971) were used to test for vertical differences in hydraulic conductivity between the root zone, deeper marsh soil, and underlying stratigraphic unit. Horizontal stratification of hydraulic conductivity across the marsh was also tested for.

Changes in soil density were measured *in situ* over complete tidal cycles using γ-attenuation techniques (Rawitz *et al.*, 1982). Water-content changes were calculated by assuming that density changes resulted only from water loss or gain in the soil. Specific yield was calculated as the change in water content per unit surface area of marsh divided by the depth to the water table at low tide.

Results

Stratigraphy and soil composition

The stratigraphy at the Carter Creek marsh is illustrated in Figure 1. The marsh soil is less than 1 m thick; it has a low bulk density (0·30 g cm^{-3}), high porosity (0·83) and high organic content (15·7%). Bulk density, porosity and organic content of surface samples did not differ statistically between the creekbank, levee, and marsh flat zones. Beneath the marsh soil at Carter Creek is sand intermixed with fine material of mineral and organic origin; measured increases in bulk density at depth corresponded to the transition in the profile to this less porous and less organic layer beneath the marsh soil (Harvey, 1986).

Soil hydraulic properties

The mean hydraulic conductivity measured within the marsh soil at Carter Creek ($7{\cdot}4 \times 10^{-4}$ cm s^{-1}) was comparable to that of a fine sand or silty sand (Freeze & Cherry, 1979). Hydraulic conductivity did not differ significantly between the root zone and deeper marsh soil (Wilcoxson Rank Sum Test; $n=24$, $Z=0{\cdot}3176$, $P\leqslant 0{\cdot}7508$). However, the mean hydraulic conductivity of the underlying sand strata was approximately an order of magnitude lower than both the root zone (25 cm) and deeper marsh soil (Wilcoxson Rank Sum Tests; $n=24$, $Z=3{\cdot}75$, $P\leqslant 0{\cdot}0002$; $n=24$, $Z=3{\cdot}52$, $P\leqslant 0{\cdot}0004$). Differences between the mean hydraulic conductivity of the creekbank, levee and marsh flat locations were not statistically significant (Kruskal-Wallis Test, $n=36$, $\chi^2=1{\cdot}954$, $P\leqslant 0{\cdot}582$).

Increases in soil density subsequent to flooding of the marsh surface indicated that desaturation of the soil occurred during low tide at Carter Creek (Harvey, 1986). The low value of specific yield (0·032) calculated from changes in density indicated that most pore water remained under tension in soil capillaries above the draining water table.

Subsurface hydraulics

Figure 2 exhibits changes in tidal stage and changes in hydraulic head that occurred at stations 2–5 over a complete tidal cycle. Hydraulic head, water-table height, and elevation of the marsh surface are referenced to a common datum in this figure and can be compared directly. Note that when the marsh surface was completely flooded, hydraulic heads everywhere within the soil approximately equalled the height of the tide. Hydraulic gradients were therefore small or zero when the low marsh was flooded, and subsurface flow was negligible.

When the marsh surface was exposed at any station, the water table was located beneath the soil surface and hydraulic heads measured at three depths were similar to the water table height. Vertical differences in hydraulic head were generally less than 1 cm (detection limit). Most variation in head occurred horizontally between stations. Subsurface flow was therefore predominantly horizontal within the marsh. The gradient in hydraulic head between stations was approximately equal to the gradient in the elevation of the marsh surface (Figure 2).

An exception to horizontal flow occurred near the creekbank at station 3. The 5 cm vertical difference in hydraulic head between 75 and 45 cm at station 3 may have been the result of hydraulic bypassing of a localized zone of low conductivity or it may indicate that the predominant flow was upward at the creekbank. Other evidence for significant vertical hydraulic gradients was not encountered.

Water remained ponded behind the levee on the marsh flat throughout the falling tide. The elevation of the ponded surface dropped by an average of 6·8 mm during the period of tidal exposure over the four monitored tidal cycles. Evaporation from a class A pan situated on the marsh surface at Carter Creek averaged 1·6 mm per tidal exposure on those days. Evapotranspiration in herbaceous wetlands has been observed to be greater or less than pan evaporation, yet evapotranspiration did not exceed pan evaporation by more than a factor of four in 10 studies reviewed by Dolan *et al.* (1984). In the present case, the

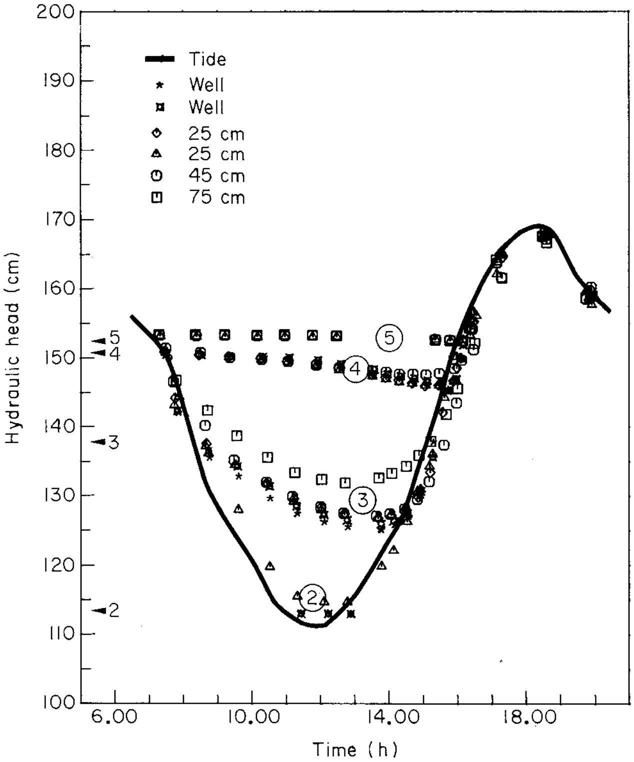

Figure 2. Changes in tidal stage and hydraulic head over a complete tidal cycle in the low marsh: 11 August 1985. Measurement stations are numbered and circled. The solid line represents tidal stage and symbols represent instrument type where depths are installation depths of piezometer inlets (key—upper left). Numbered arrows on the ordinate point to the marsh surface elevations for each measurement station.

change in head in the pond exceeded pan evaporation by more than four times. Thus, water loss in the pond during the exposure cycle cannot be accounted for by evapotranspiration alone. Vertical infiltration from the ponded surface therefore probably replaced pore water beneath the pond that had been advected toward the creekbank.

A net horizontal flux of pore water toward the creek occurred from the creekbank and levee over all monitored tidal cycles (Figure 3). At the creekbank (station 3) the average cumulative discharge was 13·8 ± 1·0 l per meter of creekbank per tide (SD, $n=4$). Horizontal recharge at station 3 was less than 1 l. At station 4 on the levee, 11·2 ± 1·3 l of water was discharged toward the creekbank. Recharge at station 4 was less than 0·1 l. Cumulative discharge was greater at station 3 on the creekbank, but discharge occurred for a longer time from the higher elevation of station 4 on the levee. Subsurface flow was bi-directional in the creekbank zone during the rising tide when recharge began at the creek while discharge continued from the interior marsh (Figure 3).

Three distinct stages in the process of pore-water discharge and replacement to the soil were identified by field monitoring. These stages are summarized in a schematic diagram in Figure 4. Stage 1 [Figure 4(a)] began when receding tidal waters exposed the marsh surface. Thereafter the hydraulic head at all depths within the soil exceeded the creek stage which indicates discharge occurred from the soil to the creek. As the tide continued

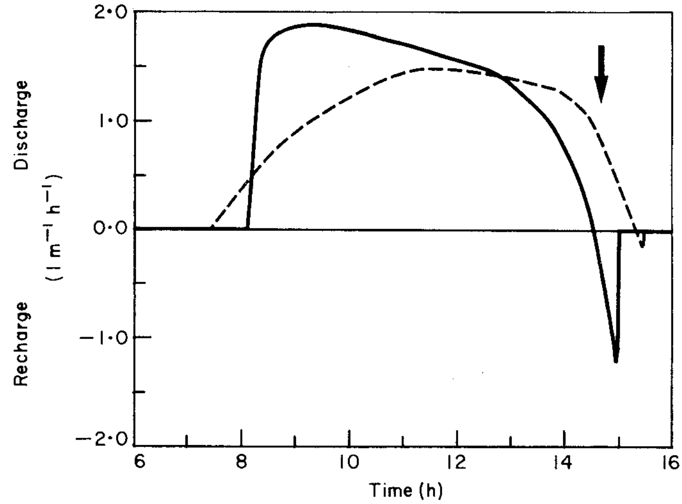

Figure 3. Subsurface discharge and recharge at the creekbank (station 3) and levee (station 4) over a complete tidal cycle: 11 August 1985. Note that both discharge and recharge were greater at the creekbank station; however, discharge occurred over a longer time period at the levee station. Also note that when recharge began at the creekbank discharge continued from the levee (arrow). ———, creekbank; – – –, levee.

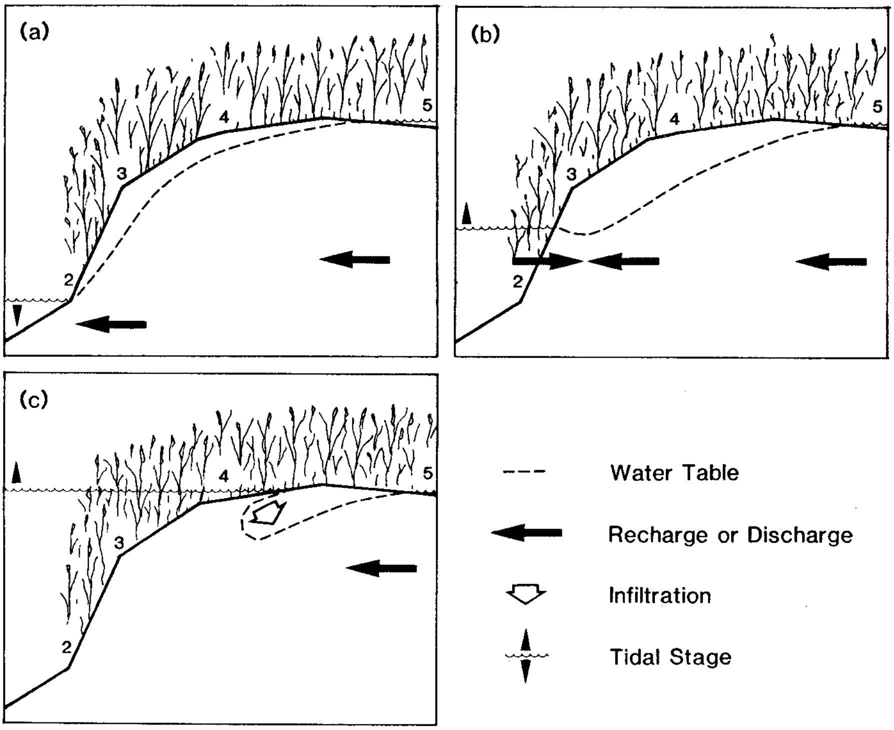

Figure 4. Schematic flow diagram illustrating three stages of discharge and recharge of pore water to the low marsh. (a) Stage 1: falling tide; discharge from the interior marsh. (b) Stage 2: early rising tide; simultaneous recharge at the creekbank and discharge from the interior marsh. (c) Stage 3: late rising tide; infiltration completes the replacement process. The vertical axis is exaggerated ten-fold.

to fall the water table of the exposed portion of the marsh was drawn down from the marsh surface; the maximum drawdown (12 cm) occurred at station 3 at the top of the creekbank. The hydraulic gradient between stations 4 and 5 indicates that discharge from interior portions of the marsh replaced much of the water discharged at the creekbank during stage 1.

Stage 2 [Figure 4(b)] began as the creek stage exceeded the height of the water table at the creekbank. The direction of the hydraulic gradient reversed causing lateral recharge from the creek to the soil. During the same time period, field data from stations 4 and 5 showed that discharge toward the creekbank continued from the levee and marsh flat. Subsurface flow in the creekbank zone was bi-directional during this stage; the convergence point of the flow paths was located close to station 3. During stage 2 water replacement to the drained soil therefore occurred simultaneously by creekbank recharge and by discharge from the interior marsh.

At the inception of stage 3 [Figure 4(c)] the water level of the creek exceeded the surface elevation at station 4. Flooding tidal waters quickly spread across the desaturated upper layer of the marsh soil. The sudden rise and vertical spreading of hydraulic head values at 15.00 h (Figure 2) indicates that soil water was replaced by vertical infiltration. Precise measurement of the time required to complete the pore-water replacement process was not possible with intermittent monitoring, although complete recharge to the soil appears to have occurred within 20 min of the initiation of surface infiltration.

Hydrological model

Darcy's law relates the discharge of pore water in a flow system to the gradient in hydraulic head. The influence of physical properties of soil and water on subsurface flow are operationally treated as an intrinsic characteristic of the soil called the hydraulic conductivity. Darcy's law is written

$$q = -K\frac{\mathrm{d}h}{\mathrm{d}x}$$

where q is the discharge per unit area, K is the hydraulic conductivity, and $\mathrm{d}h/\mathrm{d}x$ is the gradient in hydraulic head in the x direction.

Darcy's law must be combined with the continuity equation (Bear, 1979) in order to describe transient (i.e. time-dependent) fluxes of pore water. There are many forms of the resulting differential equation; the predominance of saturated conditions in tidal marsh soils suggests use of the governing equation for saturated flow. The governing equation for two-dimensional, transient, saturated flow through a cross-section in a soil medium is

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K}\frac{\partial h}{\partial t}$$

where x and z represent the respective horizontal and vertical directions in the flow field. Specific storativity (S_s) is defined as the volume of water that an unconfined aquifer releases from storage per unit volume of the aquifer per unit decline in head (Freeze & Cherry, 1979).

Field observations indicated that subsurface flow was predominantly horizontal within the marsh soil at our study site. Simplification of the above equation for application in tidal marshes is therefore possible. Dupuit theory assumes that equipotentials are vertical within a cross-section in an unconfined aquifer. Only horizontal flow is possible in a Dupuit aquifer because flow lines always cross equipotentials at right angles. As a consequence of the Dupuit assumption, hydraulic head is invariant with depth, and hydraulic head gradients can be equated simply with water-table gradients. Though not strictly a valid descriptor of two-dimensional flow, Dupuit theory has been shown to provide highly accurate approximations to flow conditions within a variety of subsurface flow systems (reviewed in Kirkham, 1967).

Bear (1979) provides a derivation of the governing equation for Dupuit flow. Under transient conditions the governing equation is

$$\frac{K}{2}\frac{\partial^2 h^2}{\partial x^2} = S_y \frac{\partial h}{\partial t}$$

where specific yield (S_y) is defined as the volume of water released from storage per unit surface area of aquifer per unit decline in the height of the water table.

A finite difference form of the governing equation and algorithm for solving the equation were available in Wang and Anderson (1982). The existing FORTRAN code was modified to simulate changes in hydraulic head over a complete tidal cycle in the low marsh at Carter Creek. The boundaries of the modeled flow system were station 2 on the creekbank (left boundary) and station 5 on the marsh flat (right boundary). The base of the marsh soil at Carter Creek, located directly above the transition to the underlying material of lower hydraulic conductivity, was specified as the lower boundary of the flow field. Arithmetic means of field measurements of hydraulic conductivity and specific yield were used for the K and S_y parameters, respectively.

Changes in the height of the tide were simulated on each time step by interpolation of staff gauge values read in the field. The extent of flooding in the marsh was determined on each time step by comparing the height of the tide with elevations of the marsh surface at each horizontal node. Hydraulic gradients and water fluxes in the flooded portion of the marsh were assumed to equal zero; this equality was specified at all flooded nodes at the beginning of each time step. In the ponded zone and at the right boundary, hydraulic heads were assumed to be constant and equal to the elevation of the marsh surface at station 5. The location of the front edge of the modeled ponded zone was shifted slightly through time to account for the slow landward migration of the front edge of the ponded zone observed in the field. Specification of the above conditions meant that, on any time step, the numerical solution needed only to be carried out for the portion of the marsh currently exposed by the tide.

The model was validated by comparison of field and simulation data. Only measured values of the parameters were used in the validation, i.e. values were not adjusted to improve model accuracy. A sensitivity analysis was conducted to help identify controls of creekbank discharge in tidal marshes.

Model-generated fluctuations in hydraulic head were compared graphically to values measured in the field. In Figure 5 model predictions for the shape of the water table and the distribution of hydraulic head are compared with measured water-table heights and hydraulic heads. Agreement between model and field data was excellent early in the tidal cycle but deviations increased over time. Nevertheless, differences between observed and predicted head values were small (<3 cm) in a flow system that was 80 cm deep. The overall qualitative behavior of the flow system was well represented by the model. For example, bi-directional flow during the rising tide (i.e. recharge to the soil at the creekbank, continuing discharge at interior regions) was correctly predicted (Figure 5).

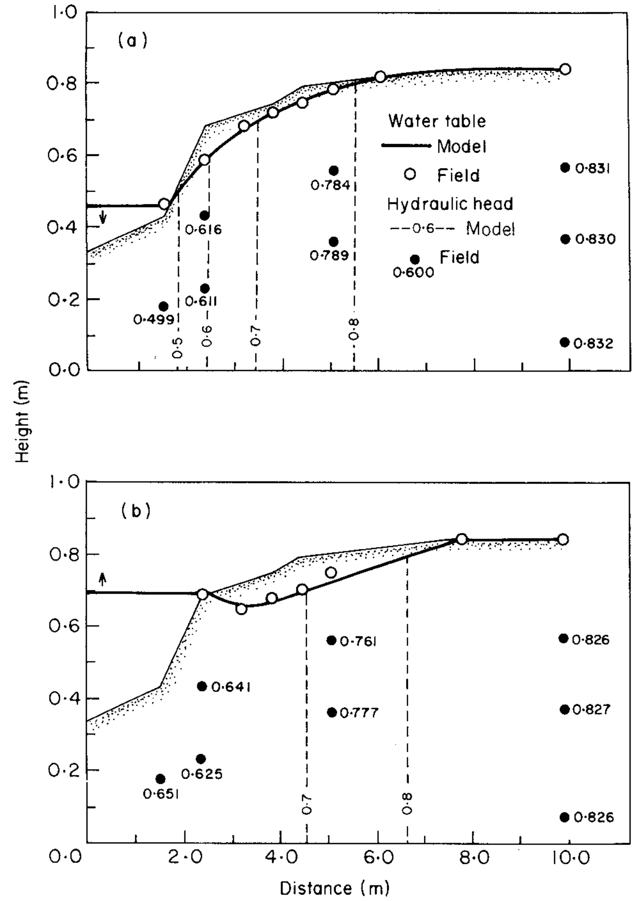

Figure 5. Model validation: comparison of the measured and modeled hydraulic head distribution on 11 August 1985: (a) falling tide; (b) rising tide. The solid line beneath the marsh surface represents the predicted height of the water table. Dashed lines are predicted equipotentials. Symbols represent measured heights of the water table and hydraulic heads at depth.

Measured and modeled discharges at the creekbank over four complete tidal cycles were also compared. The average model prediction (11·0 l per meter of creekbank per tide) was 20% less than the average measured discharge (13·8 l per meter of creekbank per tide). Discharge was underpredicted because modeled hydraulic gradients were smaller given the overprediction in the drawdown of the water table.

Model simulations indicated that horizontal replacement of pore water by inflow at the creekbank was negligible (Figure 6). Vertical infiltration and lateral discharge from the interior marsh replaced approximately 70 and 30% of the volume of water drained at the creekbank, respectively (Figure 6).

Sensitivity analysis

Values of model parameters were changed systematically in the course of repeated model runs to investigate the relative sensitivity of the total volume of creekbank discharge to each model parameter. A generalized marsh profile, 20 m across with a horizontal

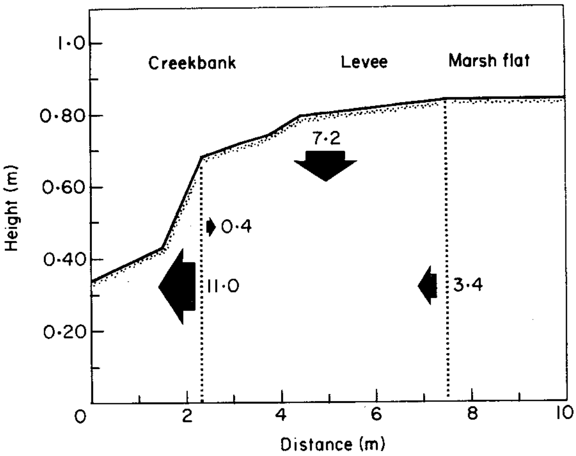

Figure 6. Model budget of pore-water transport over a complete tidal cycle. Data represent cumulative fluxes of water per tidal cycle in units of liters per meter of creekbank per tide. Mean values of creekbank discharge, creekbank recharge and interior marsh discharge were averaged over four modeled tidal cycles; standard deviations were less than 1 l. Vertical infiltration was calculated by difference.

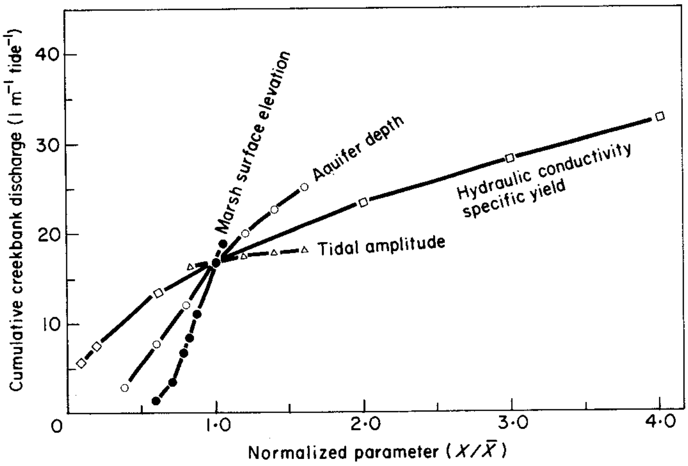

Figure 7. Model sensitivity of creekbank discharge to changes in geomorphological variables and soil properties. During repeated model runs each parameter was varied to represent the range of conditions known to exist in the field. A comparison of slopes indicates that marsh surface elevation is the primary control of the volume of creekbank discharge in our model.

surface and vertical creekbank, was used in the simulation. Ranges from which to choose parameter values were based on literature values and field experience. To allow the comparison of the sensitivity of creekbank discharge to different parameters, values of the parameters were normalized by dividing each by the mean value measured in the field. Figure 7 indicates that changes in two geomorphological parameters, surface elevation and aquifer depth, exerted maximal effect upon modeled discharge from the marsh. The flow parameters, hydraulic conductivity and specific yield, exerted moderate and equal effects upon discharge from the marsh. Tidal amplitude had only a slight effect.

Discussion

The organic matter content of the soil at the Carter Creek study site (16% by weight) is typical of mid-Atlantic and south-eastern salt marshes but less than some northern salt marshes (Frey & Basan, 1978). The mean hydraulic conductivity of the soil at Carter Creek ($7{\cdot}4\times10^{-4}$ cm s^{-1}) was intermediate among values previously reported for *Spartina* marshes, which range from $1{\cdot}7\times10^{-4}$ to $1{\cdot}2\times10^{-3}$ cm s^{-1} (Yelverton & Hackney, 1986; Nuttle, 1986; Knott *et al.*, 1987). Taken together these data represent measurements from five *Spartina* marshes located between Massachusetts and North Carolina. A range in values spanning less than an order of magnitude indicates remarkable similarity between sites for this inherently variable hydraulic property.

When sample estimates from Carter Creek were grouped by stratigraphic unit, hydraulic conductivity was found to be an order of magnitude higher in the relatively porous marsh soil than in the dense sand/silt/organic mixture that underlies it. Other workers (Jordan & Correll, 1985; Yelverton & Hackney, 1986; Nuttle, 1986; Knott *et al.*, 1987) identified soil strata of lower hydraulic conductivity beneath their sites. The hydraulic conductivity of strata at the base of tidal marsh soils appears to be generally lower than that of the marsh deposits, even when the lower strata is predominantly composed of sand (as it is at Carter Creek). Knott *et al.* (1987) hypothesized that the porous interstices of sandy strata beneath tidal marshes may become sealed with very finely humified organic matter over time.

The lack of systematic variation in hydraulic conductivity with depth and distance across the Carter Creek marsh indicated that the assumption of a uniform soil for the purpose of calculating discharge was valid. This assumption was made by two previous groups of researchers without testing for uniformity in hydraulic conductivity between layers of the soil (Jordan & Correll, 1985; Yelverton & Hackney, 1986). The predominance of horizontal hydraulic gradients was noted in field observations at Carter Creek, particularly in the interior marsh. The above findings lend support to the use of water table data and one-dimensional discharge equations to calculate pore-water movement in tidal marshes (Jordan & Correll, 1985; Yelverton & Hackney, 1986).

Subsurface hydrology at the Carter Creek study site was modeled numerically as horizontal flow in an unconfined aquifer that responded to tidal fluctuations. The magnitude and timing of changes in hydraulic head in the Carter Creek soil were accurately predicted on the time scale of a complete tidal cycle. Fang *et al.* (1972) used a subsurface flow model with Dupuit assumptions to predict head changes and water fluxes in a tidal beach. When these authors compared their results against model versions which accounted for two-dimensional flow in the saturated zone, only slight improvements were noted in model accuracy. Dupuit assumptions appear to provide an equally useful approximation of flow conditions in the creekbank vicinity of tidal marshes.

An analytical expression to describe the lateral movement of pore water in tidal marshes was recently developed by Nuttle (1986). He used the expression to estimate that the zone of influence of tidal fluctuations at the creekbank should extend no more than about 15 m into the marsh. A 15-m zone of influence is consistent with observations at Carter Creek, where that zone represents a significant area of the marsh as a whole. Other work has shown that away from creekbanks pore-water fluxes are predominantly vertical (Hemond

& Fifield, 1982; Nuttle, 1986). The results of our study, therefore, best represent controls of hydraulics in fringing marshes such as Carter Creek or in the vicinity of creekbanks in expansive marshes.

Using measured water-table gradients and steady-state discharge calculations, Jordan and Correll (1985) showed evidence that at the creekbank of their brackish tidal marsh, horizontal discharge exceeded horizontal recharge over a complete tidal cycle. Field measurements and model simulations for the Carter Creek study site corroborated this observation.

A net horizontal export of pore water occurred at Carter Creek because a significant portion of the water that drained from the creekbank was replaced by subsurface flow from the levee and marsh flat. Our field data showed that, on each tidal cycle, pore water in the interior marsh experienced a net movement toward the creekbank. Over a number of tidal cycles, water which originally infiltrated the soil in the marsh interior made step-by-step progress on successive low tides toward the creekbank until it was eventually exported. Pore water in creekbank vicinities is thereby renewed by a one-way system of lateral transport that operates during tidal exposure. Pore water residence times and volumes of discharge at the creekbank are controlled by the hydraulic properties of the soil and by geomorphological factors.

In the model it was geomorphological variables, rather than hydraulic properties of the soil, that exerted the most control over the volume of pore water exported at the creekbank. Simulated hydraulic gradients were larger (between the marsh soil and creek) in higher marshes. In addition, higher marshes were exposed for longer periods of time; creekbank discharge therefore occurred over a greater percentage of the tidal cycle in higher marshes. The result was that pore water export was found to be most sensitive to changes in marsh elevation among all parameters. In the sensitivity analysis, an increase in the hydraulic conductivity of the modeled soil was not accompanied by a substantial increase in modeled pore water export. This result was at first surprising for hydraulic conductivity, which is directly related (in Darcy's Law) to fluxes of water. However, a negative feedback existed when hydraulic conductivity was varied. In high conductivity systems, fluxes were initially large but the water table was drawn down rapidly so that hydraulic gradients and fluxes decayed quickly over time. In low conductivity systems the initial fluxes were small but the steep hydraulic gradient was maintained over time and fluxes decayed slowly. These factors minimized the effect of changes in hydraulic conductivity on the modeled pore water export at the creekbank.

As marshes mature they tend to build in elevation (Frey & Basan, 1978). The sensitivity analysis, therefore, revealed potential differences in pore water processing between marshes at different stages of geomorphological development. Model simulations suggested that regularly flooded marshes of higher elevation may export substantially larger volumes of pore water at their creekbanks. This hypothesis needs to be field tested in marshes of differing elevation.

At some critical elevation a tidal marsh will cease to flood on all neap tides; in some cases marshes may go a week or more without inundation. The drawdown in the water table in the creekbank vicinity would continue without interruption by tidal flooding although creekbank fluxes would be expected to decline with time as the slope in the water table decayed in the draining marsh soil. In addition, the zone of creekbank influence should expand each day during a non-flooding period as drainage at the creekbank continued without regular replenishment by the vertical infiltration of tidal water. Precipitation would also undoubtedly be a more important water delivery mechanism in irregularly flooded marsh soils. All of these factors suggest added complexity in pore-water processing in the creekbank zone when tidal flooding is infrequent.

Acknowledgements

This work was supported by a Moore Research Grant awarded through the Department of Environmental Sciences, University of Virginia. The authors thank E. B. Blizard, R. M. Chambers, L. P. Rozas, and H. D. Bruns for field assistance and W. K. Nuttle for helpful comments on the manuscript. We also thank the Greaves family and the Gloucester Historical Society for permission to use the Carter Creek site.

References

Agosta, K. 1985 The effect of tidally induced changes in the creekbank water table on pore water chemistry. *Estuarine, Coastal and Shelf Science* **21,** 389–400.

Bear, J. 1979 *Hydraulics of Groundwater*. McGraw-Hill, New York.

Carr, A. P. & Blackley, M. W. L. 1986 The effects and implications of tides and rainfall on the circulation of water within salt marsh sediments. *Limnology and Oceanography* **31,** 266–276.

Chapman, V. J. 1938 Studies in salt marsh ecology: sections I to III. *Journal of Ecology* **26,** 144–179.

Conover, W. J. 1971 *Practical Non-parametric Statistics*. Wiley, New York.

Dacey, J. W. H. & Howes, B. L. 1984 Water uptake by roots controls water table movement and sediment oxidation in short Spartina marsh. *Science* **224,** 487–489.

Dolan, T. J., Hermann, A. J., Bayley, S. E. & Zoltek, J. 1984 Evapotranspiration of a Florida, U.S.A., freshwater wetland. *Journal of Hydrology* **74,** 355–372.

Fang, C. S., Wang, S. N. & Harrison, W. 1972 Groundwater flow in a sandy tidal beach. 2. Two-dimensional finite element analysis. *Water Resources Research* **8,** 121–128.

Freeze, R. A. 1969 The mechanism of natural groundwater recharge and discharge. 1. One-dimensional, vertical, unsteady, unsaturated flow above a recharging or discharging groundwater flow system. *Water Resources Research* **3,** 153–171.

Freeze, R. A. & Cherry, J. A. 1979 *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.

Frey, R. W. & Basan, P. B. 1978 Coastal salt marshes. In *Coastal Sedimentary Environments* (R. A. Davis, ed.). Springer-Verlag, New York, pp. 101–159.

Gardner, L. R. 1976 Exchange of nutrients and trace metals between marsh sediments and estuarine waters—a field study. *Report No. 63*. Water Resources Research Institute, Clemson University, Clemson, South Carolina.

Harvey, J. W. 1986 Subsurface hydrology in a regularly flooded *Spartina alterniflora* marsh. Master's Thesis, Department of Environmental Sciences, University of Virginia, Charlottesville, VA.

Hemond, H. F. & Burke, R. W. 1981 A device for the measurement of infiltration in intermittently flooded wetlands. *Limnology and Oceanography* **26,** 795–800.

Hemond, H. F. & Fifield, J. L. 1982 Subsurface flow in salt marsh peat: a model and field study. *Limnology and Oceanography* **27,** 126–136.

Hemond, H. F., Nuttle, W. K., Burke, R. W. & Stolzenbach, K. D. 1984 Surface infiltration in salt marshes: theory, measurement and biogeochemical implications. *Water Resources Research* **20,** 591–600.

Hillel, D. 1982 *Introduction to Soil Physics*. Academic Press, London.

Hvorslev, M. J. 1951 Time lag and soil permeability in groundwater observations. *Waterways Experimental Station Bulletin 36*. U.S. Army Corps of Engineers, Vicksburg, Miss.

Jordan, T. E. & Correll, D. L. 1985 Nutrient chemistry and hydrology of interstitial water in brackish tidal marshes of Chesapeake Bay. *Estuarine, Coastal and Shelf Science* **21,** 45–55.

Kirkham, D. 1967 Explanation of paradoxes in Dupuit-Forchheimer seepage theory. *Water Resources Research* **3,** 609–622.

Knott, J. F., Nuttle, W. K. & Hemond, H. F. 1987 Hydrologic parameters of salt marsh peat. *Hydrological Processes* **1,** 211–220.

Lee, D. R. & Cherry, J. A. 1978 A field exercise on groundwater flow using seepage meters and mini-piezometers. *Journal of Geological Education* **27,** 6–10.

Luthin, J. N. & Kirkham, D. 1949 A piezometer method for measuring permeability of soil *in situ* below a water table. *Soil Science* **68,** 349–358.

Nixon, S. W. 1980 Between coastal marshes and coastal waters—a review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. In *Estuarine and Wetland Processes* (P. Hamilton & K. B. McDonald, eds). Plenum Press, New York, pp. 437–525.

Nuttle, W. K. 1986 Elements of salt marsh hydrology, Ph.D. dissertation, Department of Civil Engineering, M.I.T. Cambridge, MA.

Rawitz, E., Etkin, H. & Hazan, A. 1982 Calibration and field testing of a two-probe gamma gauge. *Soil Science of America Journal* **46,** 461–465.

U.S. Department of Commerce 1984 *Tide Tables 1985: High and Low Water Predictions for the East Coast of North and South America, Including Greenland.* NOAA National Ocean Survey, Rockville, MD.

Valiela, I., Teal, J. M., Volkmann, S. B., Shafer, D. & Carpenter, E. J. 1978 Nutrient and particulate fluxes in a salt marsh ecosystem: tidal exchanges and inputs by precipitation and groundwater. *Limnology and Oceanography* **23,** 798–812.

Wang, H. F. & Anderson, M. P. 1982 *Introduction to Groundwater Modeling: Finite Differences and Finite Element Methods.* W. H. Freeman, San Francisco.

Yelverton, G. F. & Hackney, C. T. 1986 Flux of dissolved organic carbon and pore water through the substrate of a Spartina alterniflora marsh in North Carolina. *Estuarine and Coastal Shelf Science* **22,** 255–267.