

SALT WATER MOVEMENT WITHIN THE WATER TABLE AQUIFER FOLLOWING HURRICANE HUGO¹

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Abstract--Hurricane Hugo generated a tidal surge approximately twenty feet high which inundated a strip of coastal forest from Charleston to just south of Myrtle Beach. On the Hobcaw Forest, east of Georgetown, the surge was about 10 feet above sea level and inundated a strip about 3500 feet wide. Salt water infiltrated directly into the forest soil and water table aquifer during the surge and from ponded areas for a period after the storm. Early auger hole measures of water table aquifer salinity reflected the deposition of salt within the aquifer throughout the surge area. Later multi-level sampling indicated that salt concentrations have remained high (2000 mg Cl/l) through 1992. Higher concentrations have persisted deep (12 ft) in the aquifer but groundwater flow has also carried high concentrations into hardwood drainages. Forest mortality was more closely related to salinity determinations in multi-level samplers than earlier auger hole data.

INTRODUCTION

Southern coastal forested wetlands are subject to hurricanes sometime during the lifetime of most of the tree vegetation (Conner In press). Tidal surges are associated with most hurricanes and affect coastal wetlands with the same frequency. The extent of flooding associated with a tidal surge depends on the tidal stage when the hurricane approaches the coast and the slope of the upland adjacent to the coast. Since much of the coastal landscape has very small relief a tidal surge occurring near high tide may cause flooding miles landward from the coast. Salt water carried into the forest will infiltrate into the soil and potentially move within the water table aquifer. Trees may be killed if water conductivity exceeds 5 millimhos/cm (approximately 3000 mg

Cl/l) around their roots (Franscois 1980). The fate of salt water within the water table aquifer will determine both mortality and the rate of forest recovery.

Hurricane Hugo struck the coast of South Carolina on September 21, 1989, approximately 2 hours before the astronomical high tide (Brennen 1991). The eye of the storm crossed the coast just north of Charleston, S.C. The tidal surge extended northeast of the storm center with a maximum height of twenty feet above sea level near McClellanville, S.C., about thirty miles northeast of the center of the eye (Coch and Wolff 1991). Elevated tidal stages extended to Garden City about 75 miles northeast of the center of the eye.

The Hobcaw Forest is located approximately 50 miles northeast of the storm center. The forest is located directly behind a barrier beach and salt marsh. Tidal surge at this location was between 9.5 and 10.5 feet above sea level (7.5 feet above mean high tide) and extended into the forest up to 3500 feet landward of the salt marsh edge (Gardner and others 1991). Salinity

¹ Paper presented at Seventh Biennial Southern Silvicultural Conference, Mobile, AL, Nov. 17-19, 1992. Belle W. Baruch Forest Science Institute Technical Contribution 93-5.

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measured in auger holes in this zone immediately after the storm ranged from >100 to 4000 mg Na/l. The maximum was equivalent to 40% of the Na concentration in sea water.

INITIAL DAMAGE

Wind damage from Hurricane Hugo was moderate on Hobcaw Forest. The most severely damaged tall oaks experienced less than 30% mortality while the more resistant trees had less than 10% mortality (Gresham and others 1991). Initial damage due to salt stress was noted in November of 1989. By February 1990 many pines were showing severe stress with yellowing foliage and defoliation throughout the portion of the forest with elevations below 10 feet above sea level. Defoliation continued throughout the spring of 1990. By late spring pines with yellowing crowns were also heavily infested with southern pine beetle (*Dendroctonus frontalis* Zimmerman) and engraver beetles (*Ips* spp.) and the role of salt stress became ambiguous. Many deciduous trees within the same zone failed to produce foliage in the spring of 1990. Except for a few cypress (*Taxodium distichum* (L.) Rich.) that produced new sprouts in late 1990 and early 1991 these trees subsequently died. Aerial photographs taken in early February 1991 revealed the pattern of initial mortality within the zone of tidal surge flooding (Figure 1).



Figure 1--Distribution of living (gray) and dead timber (black) on Hobcaw Forest (February 1991) as a result of soil salinity.

The pattern of survivors in 1990 was not predictable from the auger hole salinity measures taken by Gardner and others (1991). Salinity in auger holes was highest near the edge of the marsh and generally higher on pine ridges. Most surviving trees were on

ridges and there was a fringe of living trees along much of the marsh edge. The distribution of mortality suggested that salt had moved from the highest and best drained areas and accumulated in lower topographic positions. This suggested that a large portion of the tidal surge waters had moved within the water table aquifer.

Salt water within the water table aquifer poses a threat to the present survivors and to regeneration, either natural or planted. This study had the objective of determining three aspects of salt distribution in the aquifer: (1) What was the present distribution of salt in the aquifer? (2) What were the rates and direction of water movement and was salt moving with the groundwater flow? (3) What was the rate of salt removal from the system and when would salt no longer threaten forest health?

METHODS

The premise of this research was that sea salt movement would be most easily characterized by piezometric potential and distribution of chloride ion. Piezometric potential measures allow determination of flow directions. Chloride is a major constituent of sea salt and most closely approximates a conservative tracer.

The study was conducted within a small watershed in conjunction with Gresham (this volume) and Conner (this volume). The watershed is located adjacent to the North Inlet salt marsh and is labeled marsh road in each paper. It is oriented from southwest to northeast with an outlet to the marsh northeast of the study site. A small stream draining the watershed to the northeast flows within a stand of cypress (*Taxodium distichum* (L.) Rich.) and swamp tupelo (*Nyssa sylvatica* var. *biflora* (Walt.) Sarg.). Elevations within the stream wetland vary from 4.5 to 6 feet above sea level. The bottom of the best-defined channel slopes from 4.8 to 4.5 feet above sea level within the study area. The wetland is separated from the marsh by a ridge on the eastern side that ranges from 7 to 8 feet above sea level. A ridge along the western side separates the watershed from another stream to the west. The western ridge also ranges from 7 to 8 feet above sea level.

Groundwater was sampled from five transects along the stream section (Figure 2). A piezometer station was placed in the center of each vegetation plot

established by Conner (this volume). Four more piezometer stations were established on a line perpendicular to the stream forming five transects from the top of the eastern ridge to the top of the western ridge each with five piezometer stations. Each piezometer station followed a design which had accurately measured water chemistry and piezometric potential in a layered sandy aquifer near the study area (Williams and McCarthy 1990). At each station, piezometric potential was measured at depths of 5, 7.5, 10, and 15 feet below the surface in capped 3/4 in piezometers screened with #10 well screen for an interval of 4 in at the appropriate depth. Water chemistry samples were collected from 1/2 in x 4 in samplers screened with #10 well screen and connected to the surface by 1/4 in polyethylene tubing. Water chemistry samplers were at 4, 6, 8, 10, and 12 feet below the soil surface.

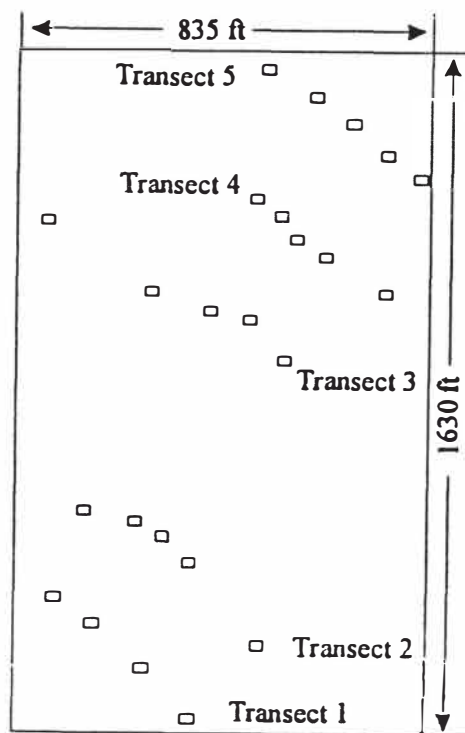


Figure 2--Distribution of sampling piezometers.

Piezometric potential was measured weekly from April 1, 1991 through March 31, 1992. Piezometer top elevations were surveyed from a nearby benchmark. Water levels in each piezometer were measured with an electrical resistance probe.

Water chemistry samples were withdrawn from the soil on a monthly basis

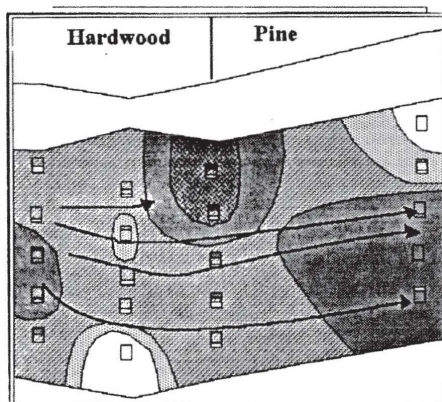
during the same time period. Samples were withdrawn from the samplers with a peristaltic pump. Water was pumped from each sampler and discarded until three to five sampler plus tubing volumes were removed. Then a 60 ml sample was taken in a NHCl washed polyethylene sample bottle which had been rinsed with distilled water to remove all traces of NHCl. Samples were returned to the laboratory and refrigerated until analysis. Chloride analysis was performed on a Technicon II auto analyzer using the ferri-cyanide method (American Public Health Association).

RESULTS

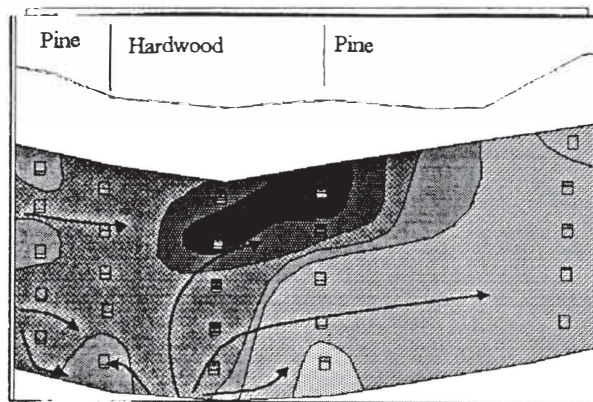
Twenty-four sampling stations were actually installed. The western ridge was indistinct on transect 1 and a station was not installed. Piezometric potentials were collected for 52 weeks from April 1, 1991 until March 31, 1992. Potentials varied with weekly changes in rainfall and potential evapotranspiration. Large weekly variability is normal for shallow water tables (Lipscomb and Williams 1989). During high rainfall periods piezometric potentials within the wetland were relatively uniform and equal to the height of water standing on the surface.

Groundwater chloride concentrations showed spatial as well as temporal variability. Individual measures varied from less than 50 mg/l to over 3000 mg/l during the year. Highest values were found during drier summer months while lowest values were found during high water in April, 1991. However, any inverse relation of groundwater chloride concentration to antecedent rainfall was weak and obscured by spatial variability.

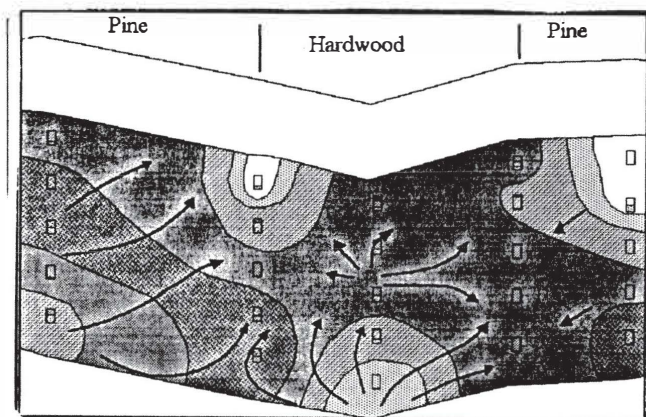
Chloride distribution and groundwater flow directions can be summarized as annual averages. The study site can be circumscribed by a 1630 feet by 835 feet by 20 feet thick block. Figure 2 shows the position and orientation of the five piezometer transects within this block. Figure 3a shows five cross-sections of the block at each of the transects. Figure 3b represents horizontal maps of the block at each of the five sampling depths. Figures 3a and 3b each depict three aspects of the experiment. The maps represent a contouring of the mean chloride concentrations. At each actual sample point a small rectangle is shaded to indicate the 95% confidence interval of the mean value at that point. Arrows on each



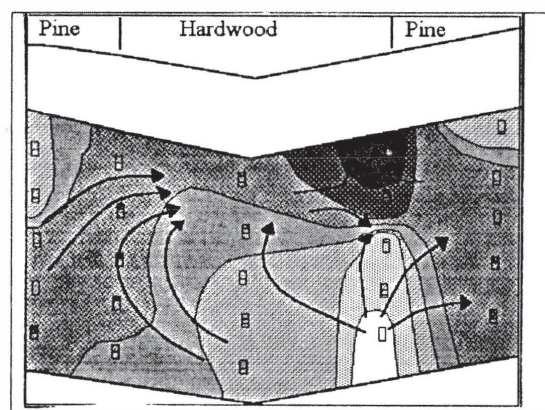
Transect 1



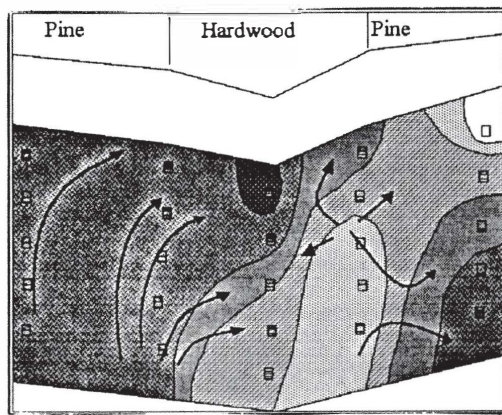
Transect 2



Transect 3



Transect 4



Transect 5

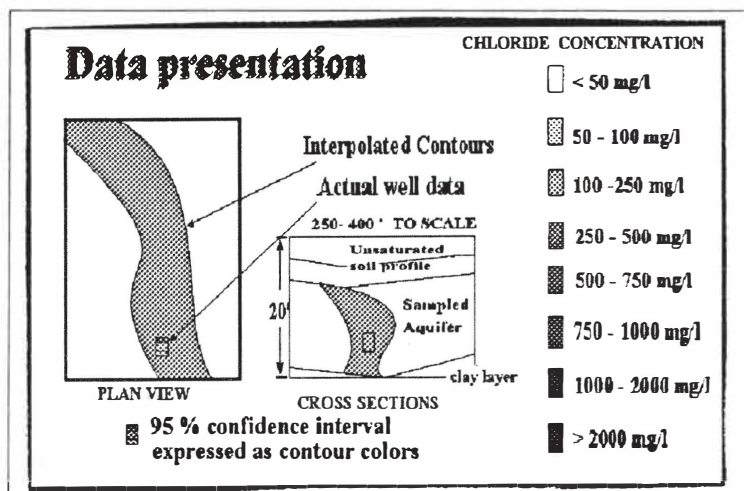
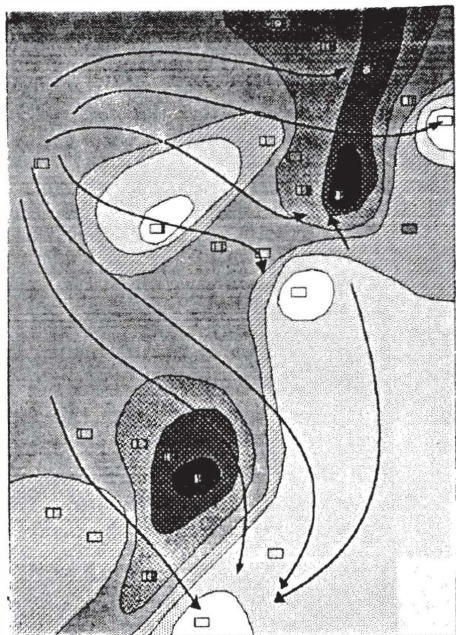
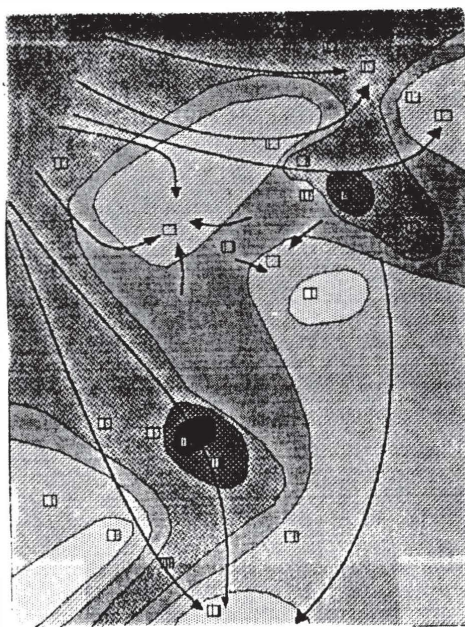


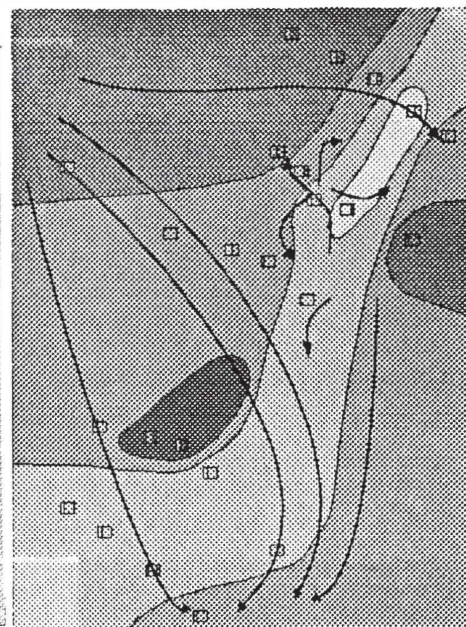
Figure 3a--Cross sections of each transect showing mean chloride concentrations (contoured gray scales), 95% confidence limits on mean values for each sampling site (small rectangles with gray scales) and mean direction of groundwater flow (arrows).



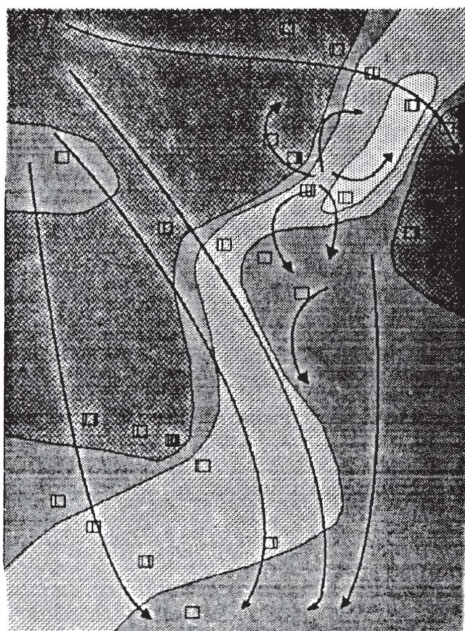
4 ft. Depth



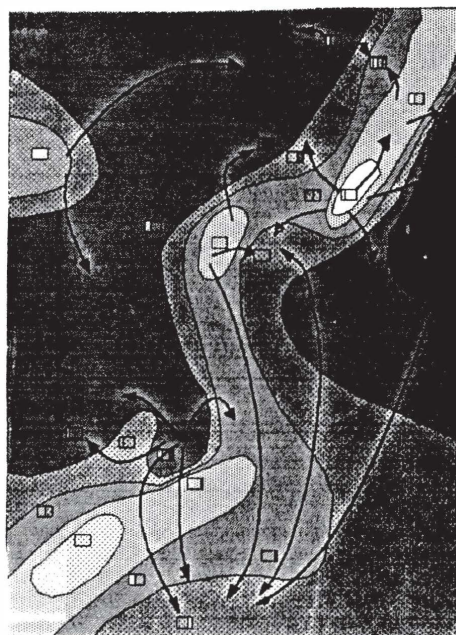
6 ft. Depth



8 ft depth



10 ft. Depth



12 ft. Depth

Figure 3b--Horizontal cross sections of sampled area at each chloride sampling depth. Chloride concentration contours and 95% confidence rectangles use the same scale as Figure 3a. Groundwater flow lines are for piezometer level just below sampling level.

map are a two-dimensional representation of groundwater flow direction determined from average piezometric potential gradients which were significantly (95%) different from zero. There were only four piezometers per station and they were at depths intermediate between chloride samplers. The arrows on Figure 3b are representations of the flow at depths just below the samplers. The 10-foot depth is the exception with flow directions of the 10-foot piezometers (same as the 8-foot depth).

In Figure 4 the mean concentration at the upper level (4 foot) is compared to forest mortality determined from February 1991 color infrared aerial photography. Photography was digitized and rectified to the Hobcaw Forest GIS system base map (Lipscomb and Williams 1990). The base map in its present configuration has an error from true ground position of 7.5 to 10 feet. The digitized photography has a pixel size of 10 feet and a mean error of registration of 1.5 pixels or 15 feet. In the photography living vegetation has a bright red or pink appearance while dead material is dark blue or black. In the gray scale

rendition the darker the gray the less living vegetation in the pixel.

DISCUSSION

Spatial Distribution of Salt in the Aquifer

The contours in Figure 3 clearly indicate heterogeneity in all three dimensions. High concentrations (> 1000 mg/l) are found near the surface in the centers of transects 2, 4, and 5. These high values show greater temporal variability resulting in 95% confidence intervals from 100 to 2000 mg Cl/l. Slightly lower concentrations were found at lower depths under both the east and west ridges. Values over 750 mg/l were found beneath the east ridge at transect 5. An extensive area with concentrations over 500 mg/l was present under the western ridge from transect 2 north all the way to transect 5. High concentrations in these locations were consistent throughout the study and 95% confidence limits were often less than 100 mg/l wide. Concentrations below 50 mg/l were found at the surface under the eastern ridge at transects 1, 3, and 5, and at the surface under the border of the western ridge at transect 4. Values below 100 mg/l were found at the aquifer bottom near the centers of all five transects.



Figure 4--Comparison of photographic mortality (right) estimates and 4-foot depth salinity estimates (left). Salinity map is the same as Figure 3b and uses same gray scale. Mortality is gray scale of digitized February color infrared photograph. White box and markers are study area and well locations. Larger gray squares are 10 x 10 ft pixels with gray level indicating extent of live vegetation. Darker tones indicate greater mortality.

Groundwater Flow Direction and Salinity

Groundwater flow direction combined with the chloride concentration distribution shows a relatively clear explanation of the data collected in this study. The bulk of the high salinity water is located under the west ridge, primarily beneath transects four and five. The bulk of the movement is to the southeast at most depths (Figure 3b). In addition, at transects 2 - 5, there is a strong upward movement from beneath the western ridge. The eastern ridges do not show much movement and the fresh water beneath them is most likely an accumulation of rainfall since the surge. The low salinity areas at the bottom of the aquifer in transects 3, 4, and 5 are all consistent with artesian flow from an aquifer below the clay layer. At the eastern side of transect 4, a very strong gradient is moving fresh water in all directions and blocking the flow from the west. The saline water from the west is turned toward the south and the surface resulting in very high salinity at the surface in transects 4 and 5. Saline water also flows towards transect 2. In transect 2, the same upward movement of saline waters from the west and northwest seems to be caused by a very small upwelling. In this case, relatively little water seems to be entering the aquifer; but a high pressure area caused the waters from the west to rise.

In all cases, high salinity occurred at the surface where upwelling of water from the lower aquifer forced the normal flow in the water table aquifer to the surface. At each of these points, salinity rose rapidly during periods of little rainfall and high evaporation. In some cases the upwelling fresh water moved laterally and vertically. In transect 3, there is a small fresh area that may have resulted from upwelling water in transect 4 moving upward and outward at depths below 6 feet. Such a flow may have forced saline water to both the south and north at the edge of the lowland in transect 3.

Measured Salt Concentrations and Mortality

The similarity of spatial pattern of salt concentration in this study to that of tree mortality (Figure 4) is quite apparent. Those portions of the site where mean chloride concentrations were found to average over 500

mg Cl/l also generally had dead trees. Likewise, the portions where concentrations were less than 100 mg Cl/l were mostly undamaged. Since the salt study was not begun until seven months after overstory death had occurred the measured salinity was not the cause of death. The measured salinity is more a record of groundwater flow patterns that may have also occurred during the period of overstory mortality. Also the mean chloride concentration of all samplers in March 1992 was only 5 mg/l less than that measured in April 1991 indicating relatively little change in overall salinity over the entire year.

CONCLUSIONS

High concentrations of salinity were found up to 30 months after a tidal surge covered a coastal pine and wetland area. Yearly averaged chloride concentrations at the top of the aquifer were found to be above 500 mg/l in most of the study area which experienced overstory mortality during 1990.

Chloride concentrations varied over two orders of magnitude in all three physical dimensions as well as through time. The spatial variability was consistent with measured flow paths and salinity patterns. With elaborate three-dimensional sampling the pattern of overstory mortality was explained post priori.

A consistent finding in this study was that highest salinity and overstory death were found in areas where groundwater flow moved deeper groundwater toward the surface. One might expect that in coastal systems highest salt induced mortality would be along wetland borders where one would normally find perennial wet spots.

ACKNOWLEDGMENTS

Funding was provided by the U.S. Forest Service and the State of South Carolina. Dedicated field sampling and preliminary data reduction on piezometric data were done by Steven Williams and laboratory analyses were conducted by Louwanda Jolley. Their efforts are greatly appreciated.

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