ground water

# Effects of Sea-Level Rise on Ground Water Flow in a Coastal Aquifer System

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## Abstract

The effects of sea-level rise on the depth to the fresh water/salt water interface were simulated by using a density-dependent, three-dimensional numerical ground water flow model for a simplified hypothetical fresh water lens that is similar to shallow, coastal aquifers found along the Atlantic coast of the United States. Simulations of sea-level rise of 2.65 mm/year from 1929 to 2050 resulted in an increase in water levels relative to a fixed datum, yet a net decrease in water levels relative to the increased sea-level position. The net decrease in water levels was much greater near a gaining stream than farther from the stream. The difference in the change in water levels is attributed to the dampening effect of the stream on water level changes in response to sea-level rise. In response to the decreased water level altitudes relative to local sea level, the depth to the fresh water/salt water interface decreased. This reduction in the thickness of the fresh water lens varied throughout the aquifer and was greatly affected by proximity to a ground water fed stream and whether the stream was tidally influenced. Away from the stream, the thickness of the fresh water lens decreased by about 2% from 1929 to 2050, whereas the fresh water lens thickness decreased by about 22% to 31% for the same period near the stream, depending on whether the stream was tidally influenced. The difference in the change in the fresh water/salt water interface position is controlled by the difference in the net decline in water levels relative to local sea level.


## Introduction

Residents of coastal areas are becoming increasingly concerned about the effects of sea-level rise. These concerns include possible higher rates of erosion than at present, flooding from higher storm surges (Theiler and Hammar-Klose 2000), and landward intrusion of sea water in coastal marshes and wetlands (Nuttle and Portnoy 1992; Donnelly and Bertness 2001). The National Oceanic and Atmospheric Administration (2003) reports a rising trend in sea level at the Boston Harbor tidal gauge, Boston, Massachusetts, which has been in operation since 1921, of about 2.65 +/−0.1 mm/year. The Intergovernmental Panel on Climate Change (IPCC) predicts that global seas may rise by an additional 0.2 to 1.0 m by 2100, with a best estimate of 0.5 m (IPCC 2001). This rate of rise would be nearly double the rate of rise observed at Boston Harbor over the past 80 years.

Previous studies from the Godavari Delta and Agatti Island in India (Bobba 1998, 2002) and in the coastal areas of the Netherlands (Oude Essink 1999) have determined that increased flooding from a rising level of saline surface water in areas of low topographic relief will result in contamination of underlying fresh water coastal aquifers. These coastal aquifers are affected by the mixing from above of saline water that has either inundated low-lying coastal areas or encroached upon large riverine systems. It is believed that some coastal aquifers such as those of Cape Cod, Massachusetts (Figure 1) are not susceptible to salt water intrusion from a rising sea level because they are not dominated by large, tidally influenced riverine systems that extend inland to great distances and are not areas of low topographic relief (Theiler and Hammar-Klose 2000).

The Cape Cod aquifer system consists of six hydrologically separate flow lenses that are underlain by thick deposits of sand, gravel, silt, and clay similar to the

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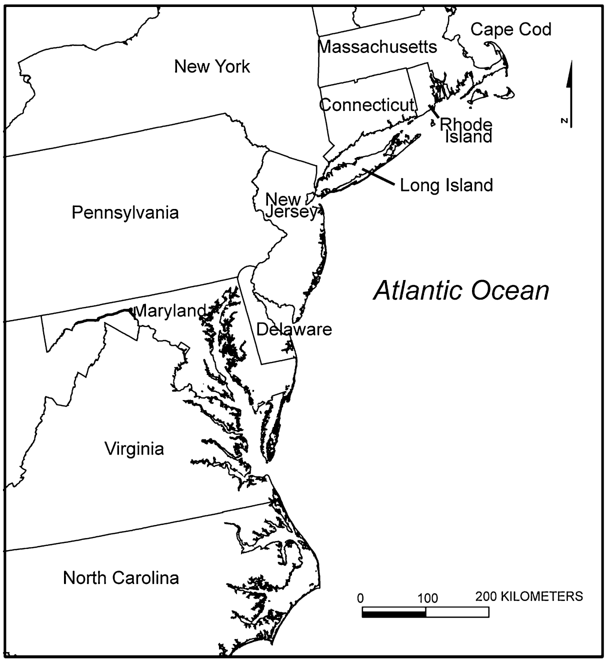


**Figure 1. Location of a portion of the Atlantic coastline of eastern United States.**

coastal aquifer systems found in eastern Long Island, New York, and the barrier island complexes along the Atlantic coast of the United States (Figure 1) (Barlow 2003; Trapp and Meisler 1992). The northeastern portion of Cape Cod is narrow, and the depth to bedrock is generally > 150 m (Oldale 1969). As a result, the fresh water lenses in this aquifer system are bounded below by salt water similar to an island aquifer system (Figure 2). The transition between fresh water and salt water is narrow relative to the total thickness of the fresh water lenses on Lower Cape Cod and, therefore, is often referred to as the fresh water/salt water interface (Guswa and LeBlanc 1985; LeBlanc et al. 1986; Masterson 2004).

In general, the depth to the fresh water/salt water interface bounding the flow lenses of Lower Cape Cod is

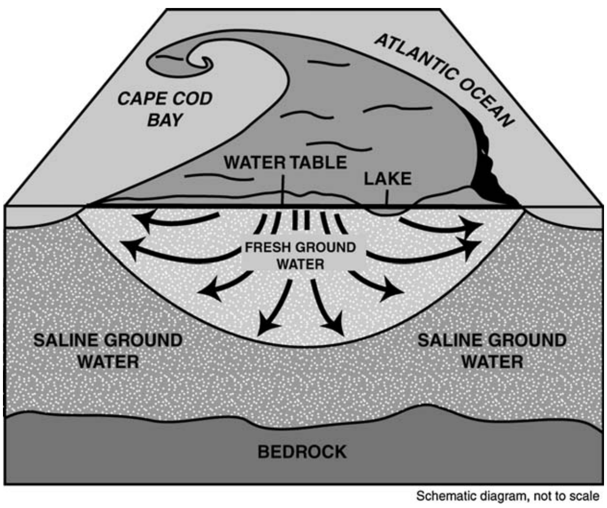


**Figure 2. Schematic diagram of the Lower Cape Cod Aquifer system, Cape Cod, Massachusetts (modified from Strahler 1972).**

directly proportional to the altitude of the overlying water table such that if the altitude of the water table above sea level ($z_w$) is lowered by 1 m, the depth to the fresh water/salt water interface below sea level ($z_s$) decreases by 40 m (Ghyben 1888; Herzberg 1901): $z_s = 40z_w$.

The Ghyben-Herzberg relation is based on the density difference between fresh and salt water and is a general approximation, subject to many simplifying assumptions, of the actual interaction between fresh water and salt water flow. For instance, the assumption that hydrostatic heads exist in the vertical dimension results in an overprediction of the depth of the fresh water/salt water interface near the center of the flow lens where downward flow is substantial, and underpredicts the depth of the fresh water/salt water interface near the coast where upward flow is substantial. Anisotropic conditions in the aquifer also exacerbate these errors, as do the vertical flow conditions beneath large pumping wells or surface water bodies.

Because the fresh water lenses of northeastern Cape Cod are bounded laterally and below by salt water, it is generally assumed that the water levels in the fresh water aquifers will rise in unison with the rising sea level, resulting in no change in the height of the water table above local sea level and, therefore, no change in the depth to the fresh water/salt water interface below sea level. This hypothesis is supported in part by the analysis of the long-term change in water levels at a USGS observation well about 300 m from Cape Cod Bay in northeastern Cape Cod. McCobb and Weiskel (2003) calculated a rate of water level rise of about 2.1 mm/year at this observation well from 1950 to 2001 relative to the National Geodetic Vertical Datum of 1929 (NGVD 29). This rate is similar to the rate of sea-level rise observed at Boston Harbor about 80 km northwest of the well site across Cape Cod Bay (National Oceanic and Atmospheric Administration 2003); however, no corresponding information on the depth of the fresh water/salt water interface was available for the area near this well.

Masterson (2004) reported that the observed water table altitudes at most other long-term monitoring wells not affected by pumping or other stresses are increasing with time in the northeastern portion of the Cape Cod aquifer. This increase in water levels may be a response to rising sea level, and the magnitude of the increase appears to be related to the proximity to nontidal portions of ground water fed streams. What has not been determined at these sites is whether sea-level rise over time could affect the position and movement of the underlying fresh water/salt water interface.

This article presents an analysis of a hypothetical aquifer consisting of a shallow, permeable, fresh water lens system similar to those found along the Atlantic coast of the United States to demonstrate that the nontidal portions of ground water fed streams can affect the changes in nearby water levels and the depth to the underlying fresh water/salt water interface resulting from sea-level rise. For the purpose of this analysis, a future rate of sea-level rise from 2005 to 2050 was based on the average measured rate of rise (2.65 mm/year) at the Boston Harbor tide gauge from 1921 to 2000 (National Oceanic and Atmospheric Administration 2003).

## Method of Analysis

A numerical model of ground water flow was developed to simulate fresh water and salt water flow in a hypothetical aquifer surrounded by and underlain by salt water similar to those found in fresh water lenses of Lower Cape Cod, Massachusetts (Masterson 2004), and the eastern forks of Long Island, New York (Misut et al. 2004). The USGS computer program SEAWAT-2000 (Langevin et al. 2003) was used for this analysis. SEAWAT-2000 simulates variable-density, transient ground water flow in three dimensions based on the empirical relation between salt concentration and salt water density developed by Baxter and Wallace (1916): $\rho = \rho_f + EC$, where the density of salt water ($\rho$) is calculated by adding the product of salt concentration ($C$) multiplied by a dimensionless constant ($E$) of about 0.7143 (for salt concentrations ranging from zero to that of sea water [35 kg/m$^3$]) to the density of fresh water ($\rho_f$:1000 kg/m$^3$).

The simulation of solute transport was made by using an implicit finite-difference solution with advective transport only (no specified dispersion) to calculate the position and movement of the transition zone between fresh water and salt water. The numerical dispersion in these simulations produced a transition zone similar in thickness to the observed transition zone from the field data (generally < 12 m thick) on Cape Cod for nonpumping conditions (LeBlanc et al. 1986). In these instances, we assumed that the 50% salt concentration contour was a reasonable approximation of the interface between fresh water and salt water for the purpose of determining changes in the position of the interface with time.

The measured sea-level rise data were incorporated into the model simulations by specifying an annual increase of 2.65 mm/year in the simulated mean sea-level altitude, which is a model boundary condition. This rate resulted in a total increase of 0.32 m from 1929 to 2050. These simulations were made to assess the effects of the changing salt water boundary condition on water levels, streamflow, and the position of the fresh water/salt water interface in response to sea-level rise.

The effect of increases in stream stage with rising sea level was also considered in this analysis. In one scenario, it was assumed that the stream was not affected by increases in mean sea level and that the stream stage remained constant throughout the simulation period. In a second simulation, the stream stage and the area that is tidally affected increased in response to increases in mean sea level.

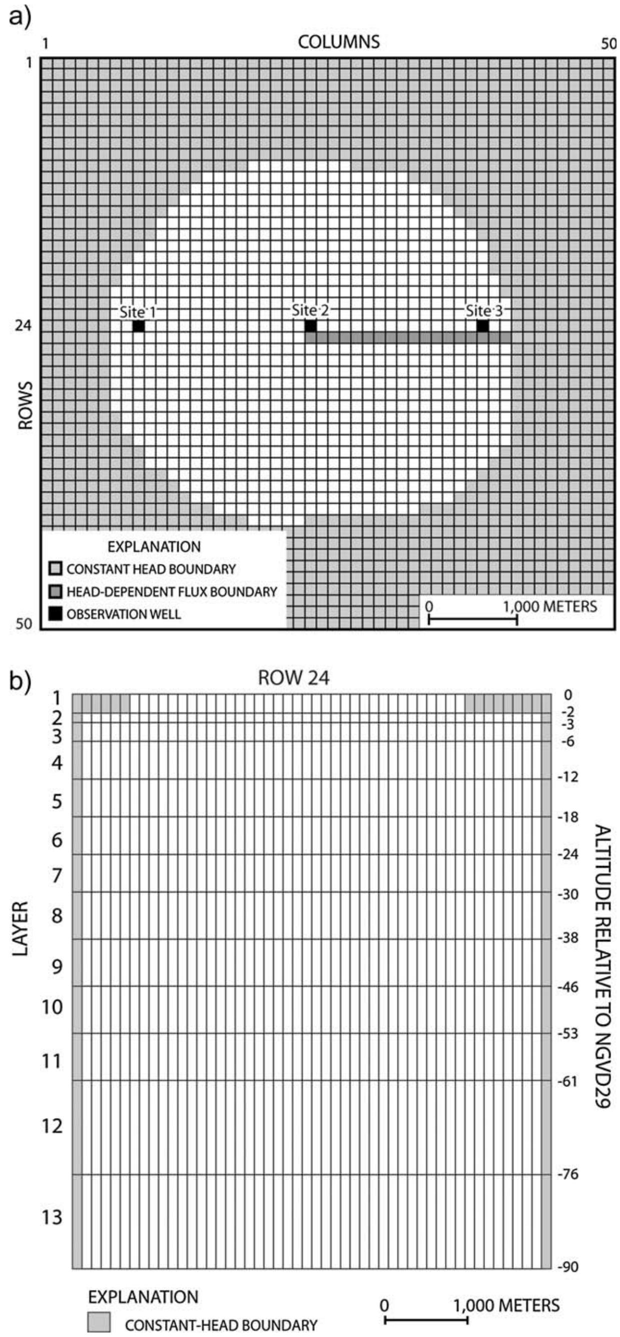


**Figure 3. (a) Model extent, location of sites 1, 2, and 3 and distribution of simulated boundary conditions of ground water flow model. (b) Vertical discretization and distribution of simulated boundary conditions along row 24 of ground water flow model.**

## Model Description

The finite-difference grid for the numerical model consists of uniformly spaced model cells that are 120 m on a side (Figure 3a). The grid consists of 50 rows, 50 columns, and 13 layers that extend from the water table to a uniform depth of about 90 m below NGVD 29, with the thickness of the layers ranging from about 2 to 15 m (Figure 3b).

The simulated area is similar in size and thickness to the northernmost fresh water lenses of the Cape Cod aquifer system. Although the unconsolidated sand and gravel and silt and clay sediments that constitute the northern part of the Cape Cod aquifer system extend to bedrock, the depth to bedrock is in most places much greater than the depth to the fresh water/salt water interface (Figure 2). Therefore, the fresh water flow system is bounded below by the transition between fresh water and underlying salt water rather than bedrock.

The boundaries of the numerical model represent the physical boundaries of an island aquifer system similar to the hydraulically independent fresh water flow lenses of northeastern Cape Cod. The upper boundary of the model is the water table, which is a free-surface boundary that receives a spatially uniform recharge rate of about 70 cm/year which is consistent with the assumed recharge rate in coastal aquifers along the Atlantic coast of the United States (Trapp and Meisler 1992; Masterson 2004; Misut et al. 2004; Walter and Whelan 2004).

The lower boundary of the fresh water flow system is the transition between fresh water and salt water; the position of this boundary was calculated by the numerical model. An arbitrary bottom altitude of about 90 m below NGVD 29 was specified as a no-flow boundary for this analysis because it was similar to that of northeastern Cape Cod (Masterson 2004) and is sufficiently deep to not affect the model-calculated position and movement of the fresh water/salt water interface.

The lateral boundaries of the model are the coastal discharge areas that represent the salt water-surface water bodies which surround coastal island systems. These discharge areas are represented as constant head/constant concentration boundaries in the top model layer (Figure 3a) and laterally along the outermost extent of the model in each of the underlying layers (Figure 3b). The fresh water equivalent heads were accounted for and increased with depth along these lateral model boundary cells.

A fresh water stream was simulated in layer 1 of the model as a head-dependent flux boundary that receives ground water discharge and removes it from the aquifer. The stream extended 2 km from the center of the island to the coast (Figure 3a) with a total change in stage of about 1 m (Figure 4).

Two scenarios were simulated to determine what effect increases in stream stage may have on the flow system as sea level rises. In the first simulation, we assumed that the stream was not tidally influenced and, therefore, the stream stage remained constant throughout the simulation period. In the second simulation, the stream stage was increased with time to account for the effect of a laterally encroaching tidal prism as sea level rose. We assumed that the tidal effect of a mean sea level of 0 m in 1929 (NGVD 29) on stream stage would extend about 60 m upstream from the coast. By 2005, the tidal effect of a mean sea level of 0.2 m above NGVD 29 would extend upstream to about 430 m, and by 2050, this tidal effect would extend 670 m upstream for a mean sea level altitude of 0.32 m above NGVD 29 (Figure 4).

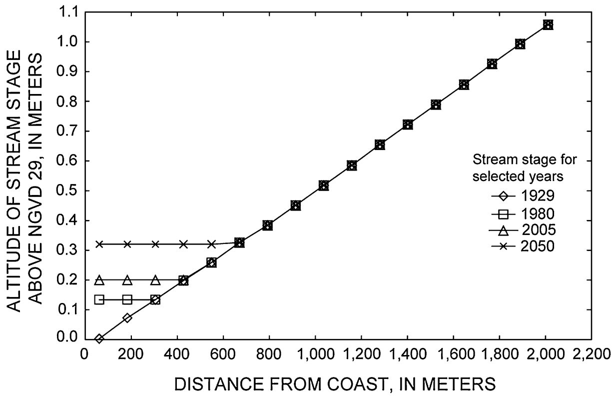


**Figure 4. Change in stream stage with distance from coast. As sea level rises with time, the stream stage increases and the tidal effect progresses inland with the rising sea level.**

## Hydraulic Properties

The aquifer hydraulic properties required as input data for the ground water model in this investigation are horizontal hydraulic conductivity, vertical hydraulic conductivity, porosity, specific yield, and storage coefficient. The hydraulic properties simulated in this analysis were based largely on the previous investigation of eastern Cape Cod (Masterson 2004); however, we greatly simplified the distribution of these hydraulic properties in our model simulations to avoid the site-specific effects on our results of the complex hydrogeologic framework of Cape Cod. As a result, our simulations included a uniform distribution of a hydraulic conductivity value of 0.106 cm/s with an anisotropy ratio of 3:1, a porosity value of 0.3, a specific yield value of 0.25, and a specific storage value of $1 \times 10^{-5}$.

The simulated streambed hydraulic conductance ($C$) of 2208 m$^2$/d was derived from an assumed stream width ($W$) of 3 m, a length ($L$) of 120 m, a thickness ($M$) of 1.5 m, and a vertical hydraulic conductivity ($K$) of 9.2 m/d:

$$C = \frac{KLW}{M}$$

[Correction added after online publication January 30, 2007: KLM corrected in this equation to KLW.] These parameters are consistent with estimates of streambed characteristics from previous modeling investigations on Cape Cod (Guswa and LeBlanc 1985; Masterson 2004; Walter and Whelan 2004).

## Initial Conditions

The analysis of changes owing to sea-level rise must be compared to a physically realistic starting condition. To obtain this condition, a quasi-steady state simulation was made that began with an initial estimate of the altitude of the interface between fresh water and salt water (Langevin et al. 2003). The initial position of the interface was assumed to be vertical at the coast to a uniform altitude of the bottom of the lens of about 50 m below NGVD 29.

A transient simulation was made for 200 years from this initial condition until the model reached a quasi-steady state condition with respect to the simulated change in solute mass with time. The resulting distribution of water levels and position of the fresh water/salt water interface was assumed to represent our initial estimate of hydrologic conditions in equilibrium with a sea-level position of 0 m above NGVD 29. This initial condition then was used for the subsequent analysis of changing sea level from 1929 to 2050.

## Simulation of the Effects of Sea-Level Rise

The effects of sea-level rise on water levels, streamflow, and the position and movement of the fresh water/salt water interface were determined by simulating a change in the altitude of sea level of 2.65 mm/year from 1929 to 2050. The effect of the resulting increase in tidal influence in the stream with rising sea level was determined by two simulations—stream stage remaining constant through the simulation period and stream stage increasing with an increase in sea level.

In the first simulation, it was assumed that the stream was not tidally influenced and, therefore, the stream stage was held constant for the simulation period. This condition may occur in areas where tidal gates are used to restrict the inland encroachment of salt water to control mosquito populations and to allow for development in low-lying coastal areas. Numerous examples of tidally restricted streams and estuaries can be found along the eastern seaboard of the United States (Roman et al. 1984; Portnoy 1999).

In the second simulation, we allowed the stream stage and the upstream extent of the tidal influence to increase as sea level rises. We assumed that in 1929, the tidal effect on stream stage extended upstream by about 60 m. By 2005, this tidal effect was extended upstream to about 430 m, or about 21% of the entire stream reach, and by 2050, the portion of the stream that was assumed to be tidally affected was 670 m upstream from the coast, about 33% of the total stream reach (Figure 4).

The equivalent fresh water head in the stream was recomputed for each stress period using the calculated salinity of the model cells containing the stream and the specified stream stage. The calculated salinity in the stream increased from a uniform salinity concentration of 0.0 kg/m$^3$ in 1929 to salinity concentrations in 2050 that ranged from 25 kg/m$^3$ near the coast to 7 kg/m$^3$ about 670 m upstream from the coast.

A potential third scenario, one that was not simulated in this analysis, would be if the tidal effect extends upstream for the entire stream reach. Under this condition, the stream presumably would be a saline surface water body with a stage that likely will rise in conjunction with sea level at a rate equal to the rise in water levels in the aquifer. As a result, any changes in ground water discharge because of increasing ground water levels would be negligible, especially in comparison to that of nontidal surface water bodies.

## Effects on Water Levels and Streamflows

Results of the model simulations indicate that the water levels in both simulations increased from 1929 to 2050 in response to the increase in sea level from 0.0 m in 1929 to 0.32 m above NGVD 29 in 2050. The extent to which the water levels increased was directly related to location within the aquifer, distance from the stream, and whether the stream was tidally influenced. Three sites (1, 2, and 3) were selected to assess changes in water levels and the position of the fresh water/salt water interface. Sites 1 and 3 are each about 300 m from the coast, and site 2 is located in the center of the island (Figure 3a).

In first simulation, where it was assumed that the stream was not tidally influenced, the water table altitude at site 1, located away from the stream, increased by 31 cm, about 97% of the simulated 32 cm of regional sea-level rise from 1929 to 2050. At site 2, in the center of the island, the water table altitude increased by 20 cm, about 63% of the simulated 32 cm of regional sea-level rise. At site 3, located adjacent to the stream, the water table altitude increased 17 cm, about 53% of the simulated 32 cm of regional sea-level rise (Figure 5).

Although the water levels increased at each of the three sites from 1929 to 2050, the net change in water levels is negative because the simulated local sea-level position is 32 cm higher in 2050 than it was in 1929. For example, the increase in water levels of 31, 20, and 17 cm relative to NGVD 29 at the three sites actually are net declines of about 1, 12, and 15 cm relative to the increased sea level in 2050 (Figure 6).

The decline in the water table altitude relative to local sea level can be explained by the presence of the ground water fed stream, which prevents the surrounding water table from rising appreciably above the altitude of the streambed. As the water table rises in response to sea-level rise, the amount of ground water discharge to the stream increases because the increased height of the water table adjacent to the stream results in increased streamflow rather than a higher water table altitude at the stream.

The amount of increased streamflow depends on the magnitude of water table rise in response to the sea-level change. The model-calculated ground water discharge to the stream nearly doubled from 3445 to 6814 m$^3$/d in response to sea-level rise from 1929 to 2050. This increase in streamflow is directly related to the increased water table altitude in the vicinity of the river. As a result, the water levels have risen by a much lower rate at site 3 (1.41 mm/year) than at site 1 (2.56 mm/year) because of the proximity of site 3 to the stream.

The rate of rise at site 1, however, is still slightly less than the simulated rate of sea-level rise of 2.65 mm/year. This difference suggests that although site 1 is farther from the stream than site 3, the effect of the increased

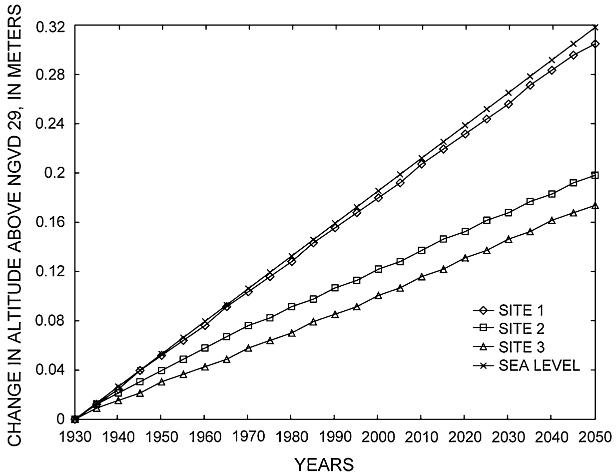


**Figure 5. Changes in model-calculated water levels at sites 1, 2, and 3 in response to a simulated sea-level rise of 2.65 mm/year from 1929 to 2050.**

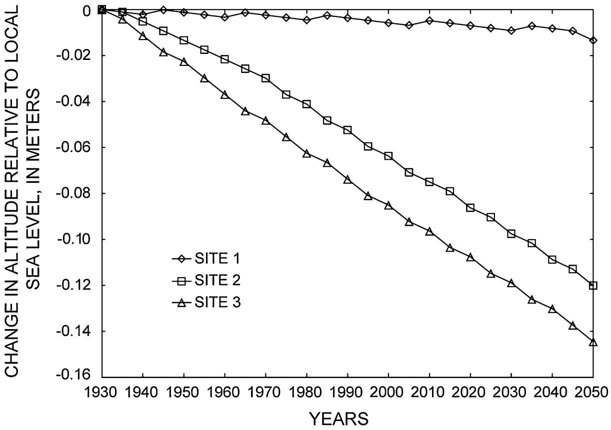


**Figure 6. Changes in the model-calculated water levels at sites 1, 2, and 3 relative to local sea level in response to a simulated sea-level rise of 2.65 mm/year from 1929 to 2050.**

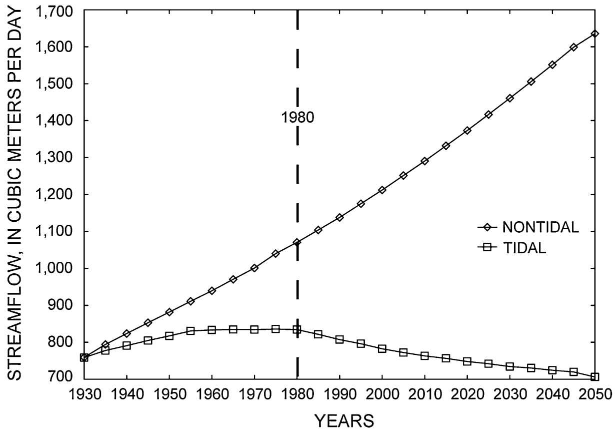


**Figure 7. Changes in model-calculated streamflow in the lower stream reach for tidal and nontidal conditions from 1929 to 2050.**

streamflow with sea-level rise has a regional effect on water levels throughout the island aquifer system.

The effect of rising sea level on water levels and streamflows is complicated by the fact that the stream stage may increase, and the areas of the stream affected by this change could extend inland from the coast as sea level rises. This condition was simulated in the second scenario and compared to the first scenario in which the stream stage was held constant.

Results indicate that although streamflow continues to increase as sea level rises and the extent of the tidal influence propagates farther inland, there is an overall difference in streamflow of about 15% between the nontidal and tidal simulations by 2050. The total decrease of 1050 $m^3/d$ between the nontidal and tidal simulations occurred in the tidally influenced portion of the stream, indicating that as the stream stage rose with the rising sea level, there was successively less ground water discharge occurring in the stream.

The difference in the amount of ground water discharge to the stream between the nontidal and tidal simulations is reflected in the change in streamflow in a portion of the stream from the coast to about 300 m upstream, adjacent to site 3 (Figure 3a). Although ground water discharge continues to increase along this portion of the stream until about 1980, it does so at a much lower rate for the tidal simulation as compared to the nontidal simulation (Figure 7). After 1980, the year in which the tidal influence propagates upstream to the position of site 3 (Figure 4), the entire lower reach of the stream is tidal and ground water discharge to the stream begins to decrease as stream stage begins to rise (Figure 7).

Water levels in the surrounding aquifer rise as the stream stage rises because less ground water discharge occurs along the lower stream reach. This effect is illustrated in a comparison of water table altitudes calculated for site 3 for tidal and nontidal simulations (Figure 8). The water table altitude at site 3 rises at a rate of 2.13 mm/year from 1980 to 2050 for the tidal simulation compared to a rate of rise of 1.48 mm/year for the nontidal simulation. By comparison, the rate of stream stage rise in the stream adjacent to site 3 is 2.65 mm/year, the simulated rate of sea-level rise. Because the rates of rise at site 3 for the tidal and nontidal simulations are less than that of sea level, there is a net decrease in the water table altitude at this site for both conditions relative to sea level (Figure 9).

The difference in the rates of rise between site 3 in the tidal simulation and that of the stream stage suggests that the surrounding water table near the stream has not yet reached equilibrium with the rising stream stage and, therefore, the decrease in streamflow in the lower stream reach (Figure 7) will continue in the future. Once the water table altitude and the stream stage are in equilibrium, such that they both rise at a rate comparable to that of sea level, streamflow will no longer change with time. The rate of constant ground water discharge to this lower reach of the stream will be determined by the steady-state difference in water table altitude and the adjacent stream stage.

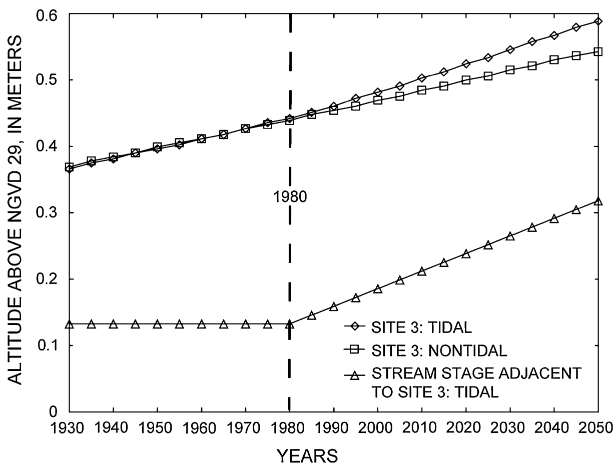


**Figure 8. Model-calculated changes in water table altitude at site 3 for tidal and nontidal conditions from 1929 to 2050. As the tidal effect on stream stage extends inland, the water table altitude increases at a greater rate than for nontidal conditions.**

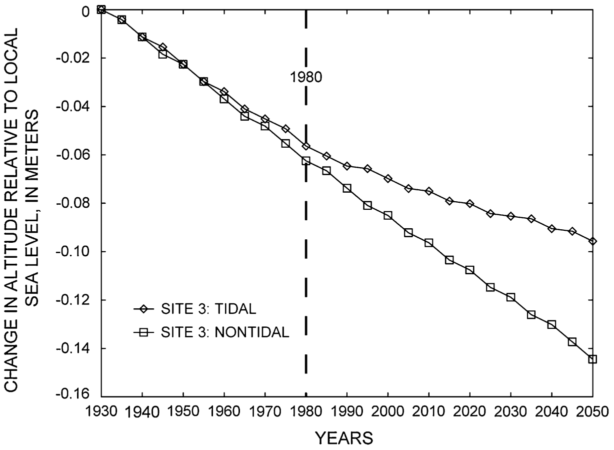


**Figure 9. Changes in the model-calculated water levels at sites 3 relative to local sea level in response to tidal and nontidal conditions with a simulated sea-level rise of 2.65 mm/year from 1929 to 2050.**

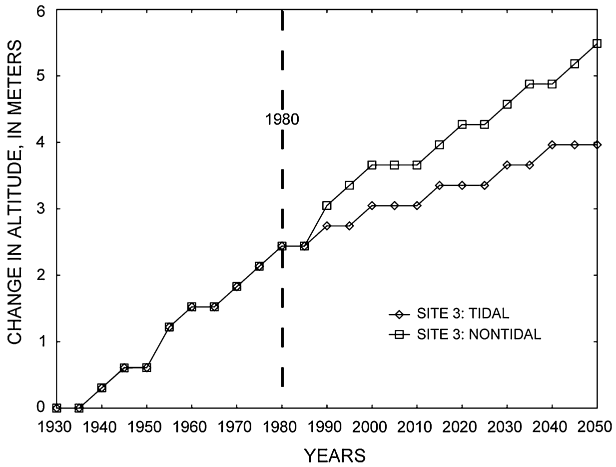


**Figure 10. Changes in the model-calculated position of the fresh water/salt water interface beneath site 3 in response to tidal and nontidal conditions with a simulated sea-level rise of 2.65 mm/year from 1929 to 2050.**

## Effects on Fresh Water/Salt Water Interface

The flow model was used to analyze the position and movement of the fresh water/salt water interface beneath the three sites to determine the response of the interface to the rise in sea level from 0.0 m in 1929 (NGVD 29) to its projected altitude of +0.32 m (NGVD 29) in 2050. The position of the interface beneath sites 1, 2, and 3 in 1929 was calculated to be about 26.2, 43.6, and 16.8 m below NGVD 29, respectively. The altitude of the interface increased at the three sites by about 0.8, 5.8, and 5.5 m in response to a rise in sea level of 0.32 m for the simulation in which it was assumed that the stream was not tidally influenced.

Correcting for the increased sea level altitude of 0.32 m, the net change in the position of the fresh water/salt water interface beneath sites 1, 2, and 3 relative to the local sea level in 2050 is about 0.5, 5.5, and 5.2 m, respectively. These simulated changes in the position of the fresh water/salt water interface are similar in magnitude to the 0.2, 4.5, and 5.5 m values predicted by the Ghyben-Herzberg relation, showing that this relation is a reasonable approximation of the change in interface position in response to changes in the altitude of the water table.

In the second scenario, when stream stage increased with the rising sea level, the altitude of the fresh water/salt water interface increased by the same amount at sites 1 and 2 as in the nontidal scenario. At site 3, the difference in the interface altitude was about 1.5 m by 2050 between the tidal and nontidal simulations (Figure 10). From 1929 to 1985, the change in the altitude of the fresh water/salt water interface was the same between the tidal and nontidal simulations. After 1985, the interface rose at lower rate for the tidal simulation than the nontidal simulation (Figure 10). This difference in the interface altitude at site 3 between the two simulations coincides with the change in net water table altitude at site 3 (Figure 9) and streamflow in the lower stream reach (Figure 7). The net decrease in water table altitude relative to local sea level lessened as streamflow decreased, resulting in a lower rate of rise in the altitude of the fresh water/salt water interface.

The results of the analysis described previously suggest that sea-level rise over time results in a thinning of the fresh water lens in this hypothetical coastal aquifer. This thinning occurs because the rate at which the water table rises is less than the rate at which sea level rises. The disparity in these rates results a net decline in the water table altitude relative to local sea level and a corresponding increase in the altitude of the fresh water/salt water interface. The areas where the effects on the position of the fresh water/salt water interface is greatest are those areas where the water table rise is limited by the presence of the nontidally influenced portion of a ground water fed stream.

A similar effect on the depth to the fresh water/salt water interface possibly could occur beneath low-lying areas such as wetlands and inland marshes, where the depth to water is shallow and increases in the water table altitude may result in enhanced evapotranspiration; however, this potential effect was not addressed in this analysis.

## Discussion

The model simulations that incorporated an increase in the altitude of sea level with time revealed a corresponding increase in ground water levels and streamflow, yet a decrease in the depth to the fresh water-salt water interface. Proximity to a ground water fed stream and whether the stream was tidally influenced had the largest effect on the changes in water levels and the position of the fresh water/salt water interface. In our simulations, we assumed that for nontidal conditions, the stream stage remains unchanged with time and any increases in ground water discharge to the stream with time will result in more streamflow with no appreciable change in stage. For tidal conditions, we assumed that the stage in lower reach of the stream increased in response to increases in mean sea level. In 1929, this effect only extended upstream by 60 m, and by 2050, as mean sea level rose 0.32 m above NGVD 29, the tidal effect extended upstream about 670 m, or 33% of the entire stream reach (Figure 4).

Although water levels in both simulations increase with time relative to the fixed datum of NGVD 29 (Figure 5) in response to the rising sea level, the actual change in the water levels is a net decrease relative to the increased local sea level (Figure 6). This net decrease in water level relative to local sea level was much greater at the sites close to a ground water fed stream (sites 2 and 3) than at the site farther from the stream (site 1).

Ground water fed, or gaining, streams prevent the adjacent water table from rising much above the altitude of the streambed. As the water table rises in response to sea-level rise, the amount of ground water discharge to the stream increases because the increased height of the water table adjacent to the stream generates more streamflow rather than a higher water table altitude.

Our simulation results show that the discharge to this stream when we assumed that the stream was not tidally influenced nearly doubled in response to sea-level rise from 1929 to 2050. As stream stage rose in the lower reach of the stream during the tidal simulation, there was a corresponding decrease in streamflow. The difference in total streamflow between the tidal and nontidal simulations was about 15% by 2050.

The depth to the fresh water-salt water interface also decreased in response to the decreased water level altitudes relative to local sea level at the three sites. The difference in the model-calculated change in the depth of the fresh water-salt water interface among the sites is controlled by the differences in the net decline in water levels relative to local sea level. Because the greatest net declines in water level were calculated for sites 2 and 3, the greatest decreases in the depth to the interface also occurred beneath these sites.

In our simulation of tidal conditions where stream stage increased in the lower reach of the stream with rising sea level, the effect on water levels and the position of the fresh water/salt water interface differed between the two sites near the stream. In the case of site 2 at the headwaters of the stream near the center of the island, the change in water level and position of the interface was unaffected by the changing stream stage in the lower reach of the stream in response to rising sea level. The change in water level and the depth of the fresh water/salt water interface responded the same as in the nontidal simulation, resulting in a total decrease in the depth of the fresh water/salt water interface in the center of the island of about 5.8 m. This change in the depth of the interface, once corrected for a local sea level of 0.32 m above NGVD 29, is a reduction of the fresh water lens of about 13% by 2050.

In the case of site 3, which is adjacent to the lower reach of the stream, the change in water level and the position of the fresh water/salt water interface increased similar to that of the nontidal condition until the simulated tidal influence extended upstream near site 3. At that point, the rate of net decrease in water table altitude and the resulting rate of increase in altitude of the fresh water/salt water interface began to lessen (Figures 9 and 10).

The resulting effect of the increased tidal influence on the water table altitude and position of the fresh water/salt water interface is attributed to the decreased rate of ground water discharge to the stream as the stream stage increases at a rate greater than that of surrounding water table (Figure 8). Once the changes in stream stage and water table altitude are in equilibrium, ground water discharge to the stream will remain constant and the altitude of the fresh water/salt water interface relative to local sea level will not change. The depth of the interface beneath site 3 by 2050 for the tidal simulation was about 4 m above the position of 1929, which when corrected for local sea level in 2050 is about a 22% reduction in the thickness of the fresh water lens as compared to the 31% reduction determined for the nontidal simulation.

The results from our analysis of a hypothetical island flow system indicate that the change in the depth to the fresh water/salt water interface occurred rapidly with the changes in water levels and streamflow brought on by the change in sea level. The analysis of the Cape Cod aquifer reported in Masterson (2004) showed that although water levels and streamflows responded rapidly to simulated sea-level rise, the change in position of the underlying fresh water/salt water interface did not become substantial until many years into the future. The model-calculated lag in the response of the fresh water/salt water interface in the Cape Cod aquifer may be the result of the slow movement of fresh and saline water in the low-transmissivity zone simulated deep in the aquifer and, therefore, may be a function of the subsurface geology. Similarly, Kooi and Groen (2000) have determined that salt water encroachment can significantly lag behind sea-level rise, depending on the aquifer substrate.

The effect of the subsurface geology is more pronounced in the complex Atlantic Coastal Plain aquifer system where thick, layered aquifers are separated by intervening confining units. In the New Jersey Coastal Plain aquifer, Pope and Gordon (1999) report that the position of the fresh water/salt water interface is still responding to changes in sea level from the effects of the last glaciation approximately 71,000 years ago in which the position of the interface is much deeper and seaward of where it would be if it were in equilibrium with current sea level.

## Conclusions

The assumption that the primary threat to coastal aquifer systems from rising sea levels is the increased potential for surface inundation of saline water in low-lying areas does not consider the potential for a decrease in fresh water lens thickness from a net decrease in water levels relative to an increased sea-level position. This net decrease in water levels results in a decrease in the depth to the fresh water-salt water interface as described by the Ghyben-Herzberg relation.

The extent to which water level altitudes decline relative to an increased sea-level position is directly related to the proximity of ground water fed streams and whether the streams are tidally influenced. As the water table rises in response to a rise in sea level, the amount of ground water discharge to streams increases because the increased height of the water table adjacent to the streams generates more streamflow rather than a higher water table altitude. The effect that ground water fed streams have on water levels and the depth to the fresh water-salt water interface diminishes as the extent of tidal influence in streams propagates inland with the rising sea levels.

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