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Assessment of salinity intrusion in the James and Chickahominy Rivers as a result of simulated sea-level rise in Chesapeake Bay, East Coast, USA

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ABSTRACT

Global sea level is rising, and the relative rate in the Chesapeake Bay region of the East Coast of the United States is greater than the worldwide rate. Sea-level rise can cause saline water to migrate upstream in estuaries and rivers, threatening freshwater habitat and drinking-water supplies. The effects of future sea-level rise on two tributaries of Chesapeake Bay, the James and Chickahominy (CHK) Rivers, were evaluated in order to quantify the salinity change with respect to the magnitude of sea-level rise. Such changes are critical to: 1) local floral and faunal habitats that have limited tolerance ranges to salinity; and 2) a drinking-water supply for the City of Newport News, Virginia. By using the three-dimensional Hydrodynamic-Eutrophication Model (HEM-3D), sea-level rise scenarios of 30, 50, and 100 cm, based on the U.S. Climate Change Science Program for the mid-Atlantic region for the 21st century, were evaluated. The model results indicate that salinity increases in the entire river as sea level rises and that the salinity increase in a dry year is greater than that in a typical year. In the James River, the salinity increase in the middle-to-upper river (from 25 to 50 km upstream of the mouth) is larger than that in the lower and upper parts of the river. The maximum mean salinity increase would be 2 and 4 ppt for a sea-level rise of 50 and 100 cm, respectively. The upstream movement of the 10 ppt isohaline is much larger than the 5 and 20 ppt isohalines. The volume of water with salinity between 10 and 20 ppt would increase greatly if sea level rises 100 cm. In the CHK River, with a sea-level rise of 100 cm, the mean salinity at the drinking-water intake 34 km upstream of the mouth would be about 3 ppt in a typical year and greater than 5 ppt in a dry year, both far in excess of the U.S. Environmental Protection Agency's secondary standard for total dissolved solids for drinking water. At the drinking-water intake, the number of days of salinity greater than 0.1 ppt increases with increasing sea-level rise; during a dry year, 0.1 ppt would be exceeded for more than 100 days with as small a rise as 30 cm.

1. Introduction

The threat of climate change to the environment has become a prominent focus for both government and industry. Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly affected by sea-level rise, with wide-ranging consequences for human societies and ecosystems (IPCC, 2007). Sea-level rise can cause saline water to migrate upstream to points where freshwater existed previously (e.g., National Research Council, 1987; Grabemann et al., 2001; Poff et al., 2002). Several studies indicate that sea-level rise will increase the salinity in estuaries (e.g., Hull and Tortoriello, 1979; Hilton et al., 2008; Bhuiyan and Dutta, 2011), which will result in changes in stratification and estuarine circulation (Hong and Shen, 2012). Such salinity migration could cause shifts in salt-sensitive habitats, thereby affecting the distribution of flora and fauna, and affect water availability for municipal supply, irrigation, and industrial uses.

Analyses of long-term tide-gauge data indicate that the relative sea level in the Chesapeake Bay, on the East Coast of the USA, has been rising for decades (Barbosa and Silva, 2009). The linear trend in relative sea level of the lower Chesapeake Bay is 4.4501 ± 0.1850 mm/year (Boon et al., 2010). Based on data from 1949 to 2006, Hilton et al. (2008) conclude that sea-level rise largely has been responsible for salinity increases in most parts of the Bay. Hong and Shen (2012) demonstrate that average salinity, salt intrusion distance, and stratification in Chesapeake Bay will increase as sea level rises. All of these studies focus on the main channel of Chesapeake Bay. To date, no studies have addressed salinity change in the Bay's tributaries and how such changes may affect floral and faunal habitats or municipal water supply.

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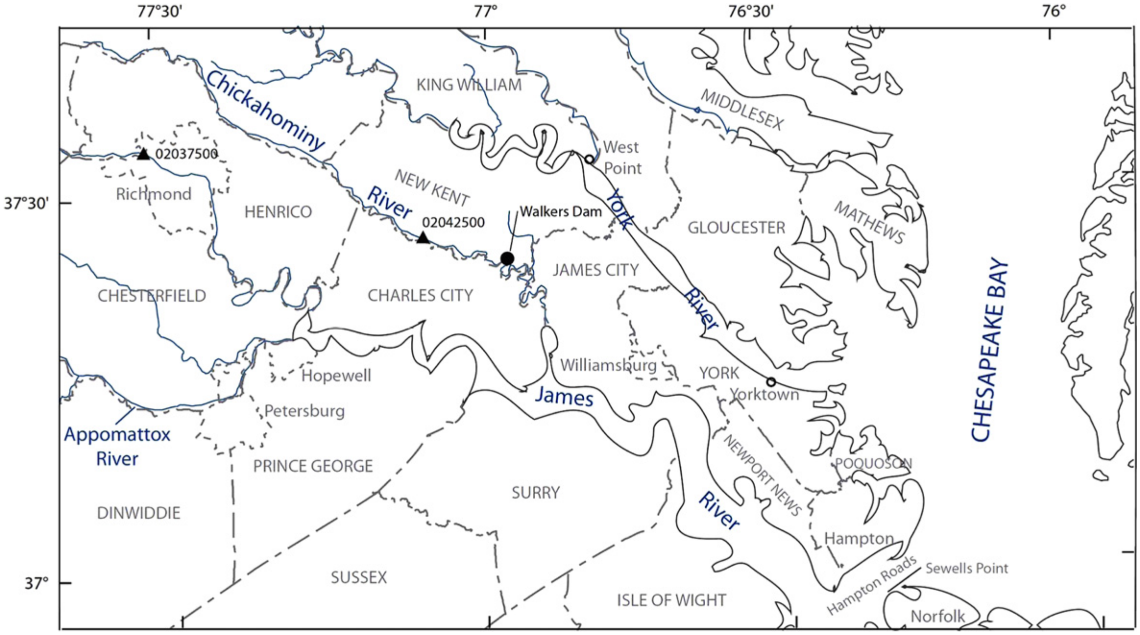

Fig. 1. Location map of the James River and the Chickahominy River.

The James River is the southernmost tributary of Chesapeake Bay (Fig. 1). Salinity in the estuarine part of the James River varies seasonally, which is a common characteristic of estuaries in the mid-latitudes. Near the river mouth, the channel is more than 15 m deep, and salinity typically is around 25 parts per thousand (ppt). The horizontal salinity gradients are usually larger near the head of the river where the freshwater and saltwater converge, referred to, in this paper, as the salinity front. The denser, saline, bottom water enters the James River from Chesapeake Bay and flows upstream, while the less dense surface waters, dominated by freshwater inflow, flow downstream toward the Bay (Pritchard, 1956; Shen and Lin, 2006).

The Chickahominy (CHK) River is one of the main tributaries of the James River near the coast (Fig. 1) and enters the James River approximately 73 km upstream of its mouth. A lake formed by Walkers Dam on the CHK serves as a drinking-water supply for the City of Newport News, Virginia (Fig. 1). Newport News Waterworks is a regional drinking-water utility located on the Virginia Lower Peninsula and serves about 415,000 people, including eight Federal installations. The drinking-water supply intake at Walkers Dam supplies anywhere from 30 to 70 percent of the region's drinking water, depending on the availability of other sources. When freshwater discharge is low, saline water from the James River can

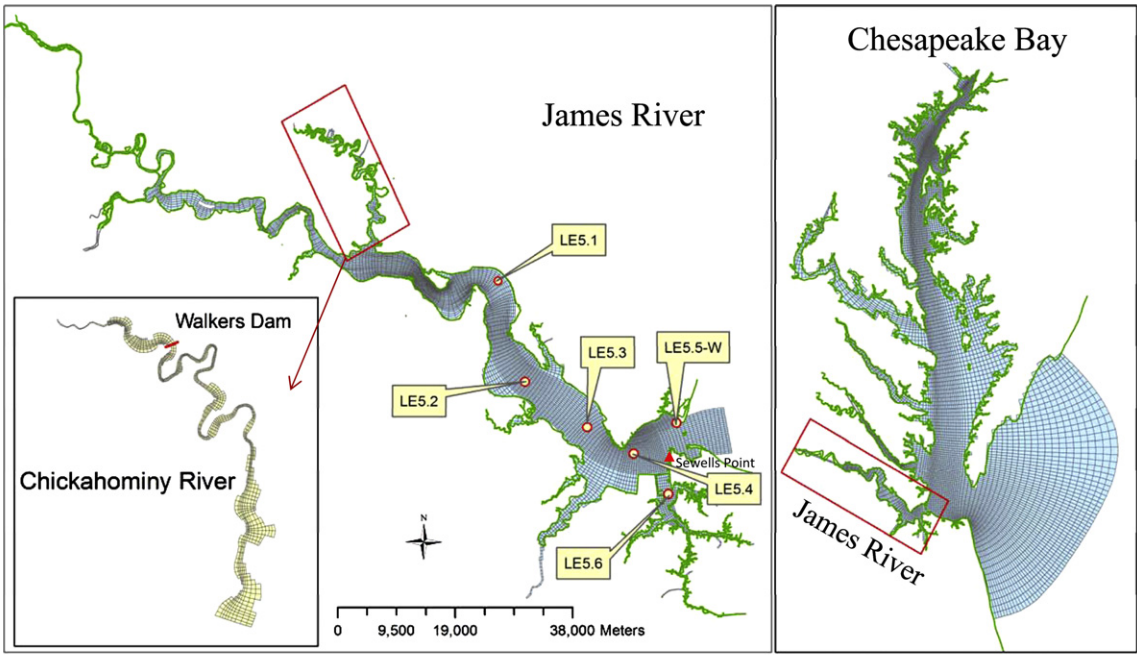

Fig. 2. Diagram of the numerical model grids. Salinity and water level monitoring stations in the James River also are shown.

enter the lower CHK River, increasing its salinity to around 7 ppt. When freshwater discharge is high, saline water seldom reaches the middle CHK River. Evaluating the sea-level rise effect on salinity intrusion in the CHK River is critical to the sustainability of the drinking-water supply.

Tidal freshwater wetlands (TFW) are located at the upper end of estuaries and fill an important ecological niche, because they have high floral and faunal diversities. TFW are sensitive to a wide range of environmental changes and are especially vulnerable to inundation from sea-level rise and salinity intrusion (Rheinhardt and Hershner, 1992), which can cause dramatic state changes by converting tree-dominated swamps to herbaceous-dominated wetlands (Neubauer and Craft, 2009). TFW in the Chesapeake Bay region contain endemic flora, some of which are globally rare, and the James and CHK Rivers hold more than 200 ha of TFW (Odum et al., 1984). Quantifying the salinity change in tributaries to the Bay as a result of sea-level rise is important because flora and fauna that occupy TFW have limited tolerance ranges to salinity, and habitats may shift or be eliminated.

Although salinity monitoring data in the James and CHK Rivers exist, the measurements are too infrequent to quantify the effect of sea-level rise. One way to evaluate potential effects of future sea-level rise in these Chesapeake Bay tributaries is to develop accurate science-based models of present-day environmental system behavior. Once present-day processes can be simulated, the models can be used to investigate a plausible range of future changes. In this study, a calibrated three-dimensional model was used to simulate salinity changes on the James and CHK Rivers caused by

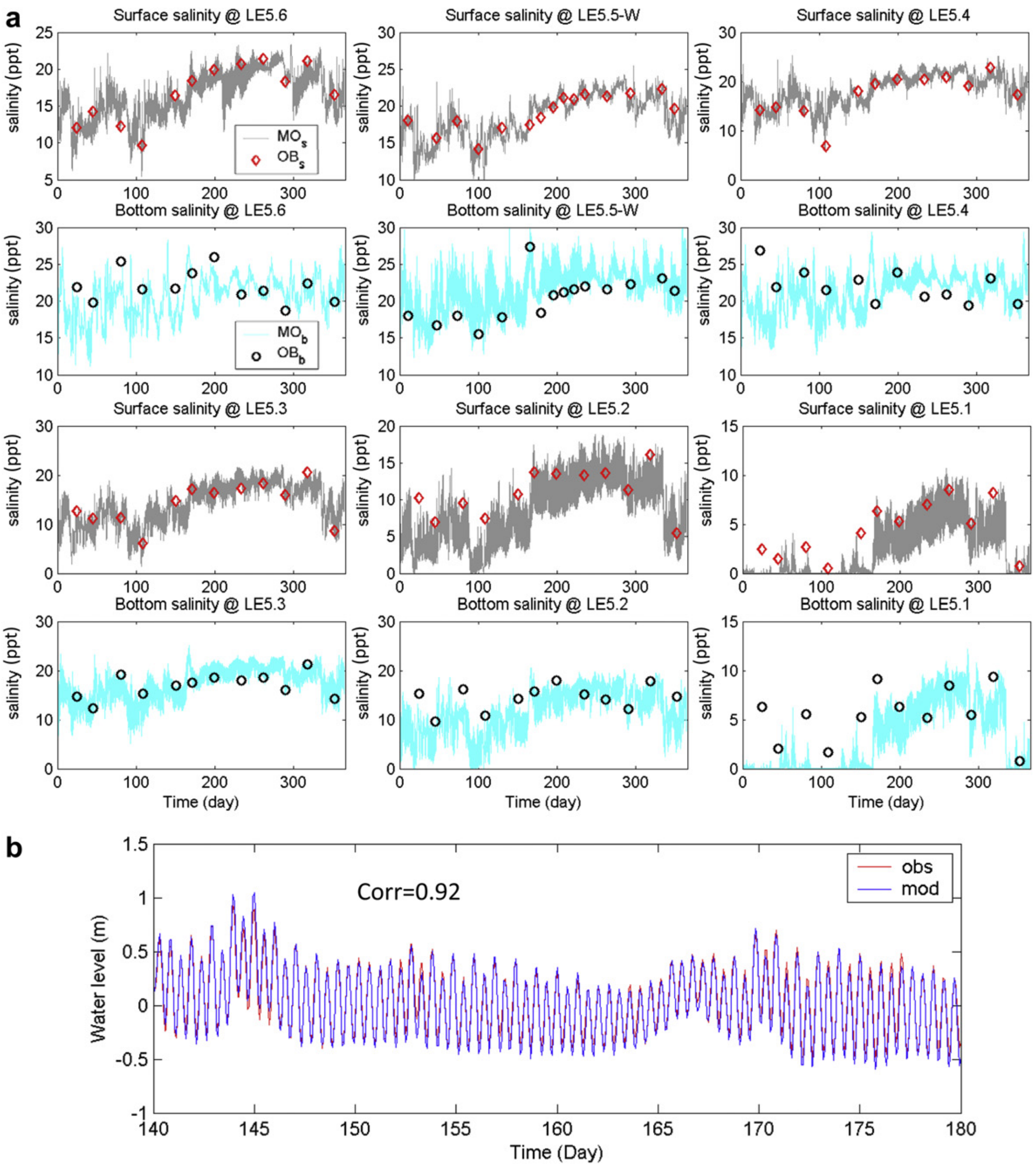

Fig. 3. Model-data comparisons for 2005 for (a) salinity, and (b) water level. The model was run with the actual forcing condition in 2005. The modeled surface and bottom salinities were compared to measured salinities at stations LE5.6, LE5.5-W, LE5.4, LE5.3, LE5.2, and LE5.1. The modeled water level was compared to the observations at the Sewells Point station; the correlation coefficient is 0.92, at the 95% confidence level. Locations of the stations are shown in Fig. 2.

sea-level rise. The effects of sea-level rise on the TFW of the James River tributaries and on the drinking-water intake on the CHK River were assessed. Such information can be useful as decision makers and water managers are forced to adapt to changing conditions.

1.1. *Sea-level rise scenarios*

The U.S. Climate Change Science Program (2009) synthesized an enormous amount of climatic and oceanic modeling and proposed three future sea-level rise scenarios for the 21st century for the mid-Atlantic region of the USA. The scenarios were developed from a combination of the 20th century relative sea-level rise rate in the mid-Atlantic region and either a 2 or 7 mm per year increase in global sea level:

Scenario 1: the 20th century rate, which is generally 3–4 mm per year (30–40 cm total by the year 2100);
Scenario 2: the 20th century rate plus 2 mm per year acceleration (up to 50 cm total by 2100);
Scenario 3: the 20th century rate plus 7 mm per year acceleration (up to 100 cm total by 2100).

Scenario 1 assesses the effects if future sea-level rise occurs at the same rate as was observed over the 20th century at a particular location. Scenarios 1 and 2 are within the range of those reported by the IPCC (2007). Scenario 3 exceeds the IPCC scenario range by up to 40 cm by 2100; such higher estimates have been suggested (e.g., Najjar et al., 2010), although there currently is no consensus on the probable upper bound of global sea-level rise. These three sea-level rise scenarios were selected for use in the numerical model simulations in this study and are referred to as the 30-, 50-, and 100-cm sea-level rise scenarios, respectively. The sea-level values are considered mean values and do not take into account any intertidal effects.

The scenarios do not consider any future changes in freshwater flows in the James and CHK Rivers. Generally it is estimated that the eastern USA will receive more precipitation because of climate change (e.g., Brekke et al., 2009) and that individual storms in the Chesapeake Bay area may become more intense (Najjar et al., 2010). In addition, these scenarios do not consider any future increase in the salinity at the mouth of Chesapeake Bay, which is expected to occur with continued sea-level rise (Hilton et al., 2008).

2. Material and methods

The Three-Dimensional Hydrodynamic-Eutrophication Model (HEM-3D) (Hamrick, 1992), developed by the Virginia Institute of Marine Science, was applied in this study. This model has been used in a wide range of environmental studies (e.g., Park et al., 1995, 2005; Sisson et al., 1997; Shen and Kuo, 1999; Shen et al., 1999; Shen and Lin, 2006; Morse et al., 2011). The hydrodynamic portion of the HEM-3D model resembles the widely used Princeton Ocean Model (Blumberg and Mellor, 1987) in both the physics and the computational scheme utilized. The model uses stretched (or sigma) vertical coordinates and Cartesian (or curvilinear), orthogonal horizontal coordinates. The vertical eddy viscosity/diffusivity coefficient was calculated by the Mellor and Yamada level 2.5 turbulence closure scheme (Mellor and Yamada, 1982; Galperin et al., 1988). The model solves the three-dimensional continuity and free-surface equations of motion. It is capable of simulating density and topographically induced circulation; tidal and wind-driven flows; and spatial and temporal distributions of salinity and temperature.

To obtain salinity boundary conditions due to sea-level rise and reduce the influence of the boundary conditions on the interior-model domain, a large-domain model that encompasses the entire Chesapeake Bay and adjacent shelf area was used (Fig. 2). Because this model has relatively low resolution in the tributaries, the high-resolution small-domain model for the James River was nested in the Chesapeake Bay model, and the high-resolution CHK River model was nested in the James River model. The open boundary of the small-domain models was placed in the main channel of Chesapeake Bay and the James River, respectively, where the bathymetry is identical to the large-domain models. This ensures the resulting open boundary information is capable of modeling accurate flow and salinity in the small-domain models.

The Chesapeake Bay model has 20 vertical layers, while the James and CHK River models have 8 vertical layers. The configuration and forcing fields of the Chesapeake Bay model are described in detail by Hong and Shen (2012). The surface forcing fields for the small-domain models are identical to those used in the large-domain model. The hourly outputs of the large-domain model were used as the boundary conditions for the nested models in the Baseline (present sea level) and each sea-level rise scenario. An 11-year period of simulation (1998–2008) for the Baseline and three sea-level rise scenarios (30, 50, and 100 cm) was conducted for each model.

The salt intrusion distance was calculated as the distance from the river mouth to the location upstream with a cross-section mean salinity of 0.1 ppt. Analysis of the freshwater discharge record (from 1990 to 2009) for the James River near Richmond (USGS gage 02037500) indicates that 2002 was a dry year and 2005 was a typical year (Rice et al., 2011); model results for these years are presented to illustrate the sea-level rise effect in a dry and a typical year. The record also indicates that October has the lowest monthly

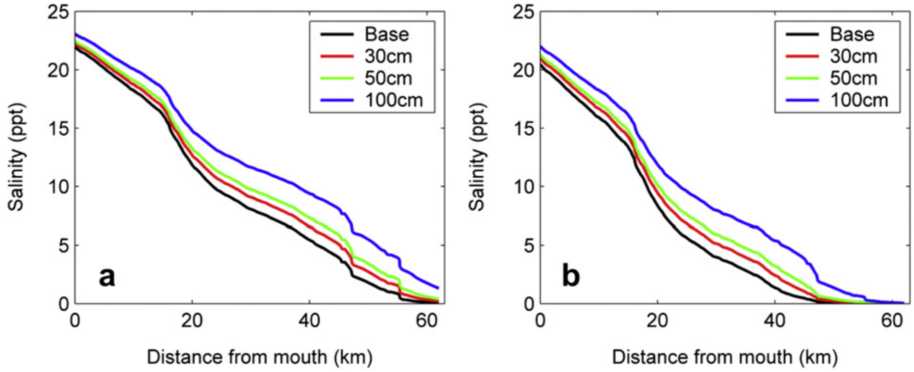

Fig. 4. Effect of simulated sea-level rise scenarios on 31-day mean salinity along the James River during October for (a) 2002 (dry year); and (b) 2005 (typical year). Results from the Baseline and each sea-level rise case are presented.

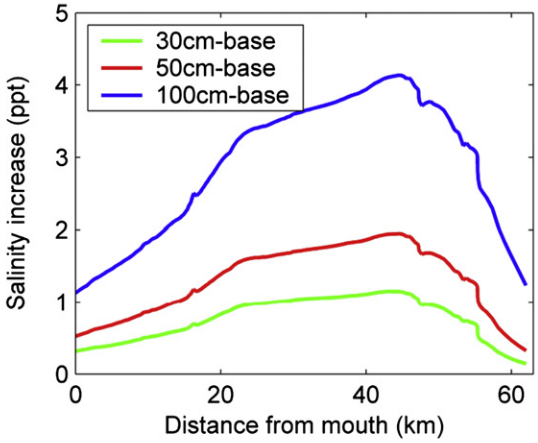

Fig. 5. The increase of mean salinity along the James River for each sea-level rise scenario relative to the Baseline, i.e., the sea-level rise value minus the Baseline value. The results are averaged in October during the dry year, 2002.

mean freshwater discharge of the year, during which the saline water can intrude farther upstream than during other months. Thus, the monthly mean results in October were used to present the effect of sea-level rise on the salinity field.

3. Model calibration

Detailed calibrations of the Chesapeake Bay and the CHK River models can be found in Hong and Shen (2012) and Rice et al. (2011), respectively. For the James River model, model outputs were compared with observed salinity data obtained from the Chesapeake Bay Water Quality Monitoring Program (http://www.chesapeakebay.net/data_waterquality.aspx) (Fig. 3). The modeled salinity field matched the observed seasonal variations very well (Fig. 3a). The stratification–destratification processes also were properly reproduced by the model. Water elevation data at Sewells Point were obtained from NOAA's Center for Operational Oceanographic Products and Services (NOAA, 2010). The correlation coefficient between the modeled and observed water level is 0.92 (at the 95% confidence level), which indicates good performance of the model in simulating the water elevation (Fig. 3b). The model-data comparisons for other years (data not shown) indicated similar model performance. The calibration results indicate that the nested-grid strategy has good performance and is suitable to assess the sea-level rise effect on the salinity field in the James and CHK Rivers.

4. Results

All modeled salinity results were averaged in both the vertical (depth) and the horizontal (cross-sectional) directions.

4.1. James River

Model results for October 2002 (dry) and 2005 (typical) indicate that salinity increases along the entire James River as sea level rises (Fig. 4). The salinity increase in a dry year (Fig. 4a) is greater in magnitude and spatial extent than that in a typical year (Fig. 4b). For example, for a 50-cm sea-level rise, the location of 10 ppt mean salinity moves 8 km upstream in a dry year (Fig. 4a) but moves only 3 km upstream in a typical year (Fig. 4b). With a sea-level rise of 100 cm, the location of 10 ppt mean salinity moves 18 km upstream in a dry year but moves only 9 km upstream in a typical year. Near the head of the river, during a typical year (Fig. 4b), with a 100-cm

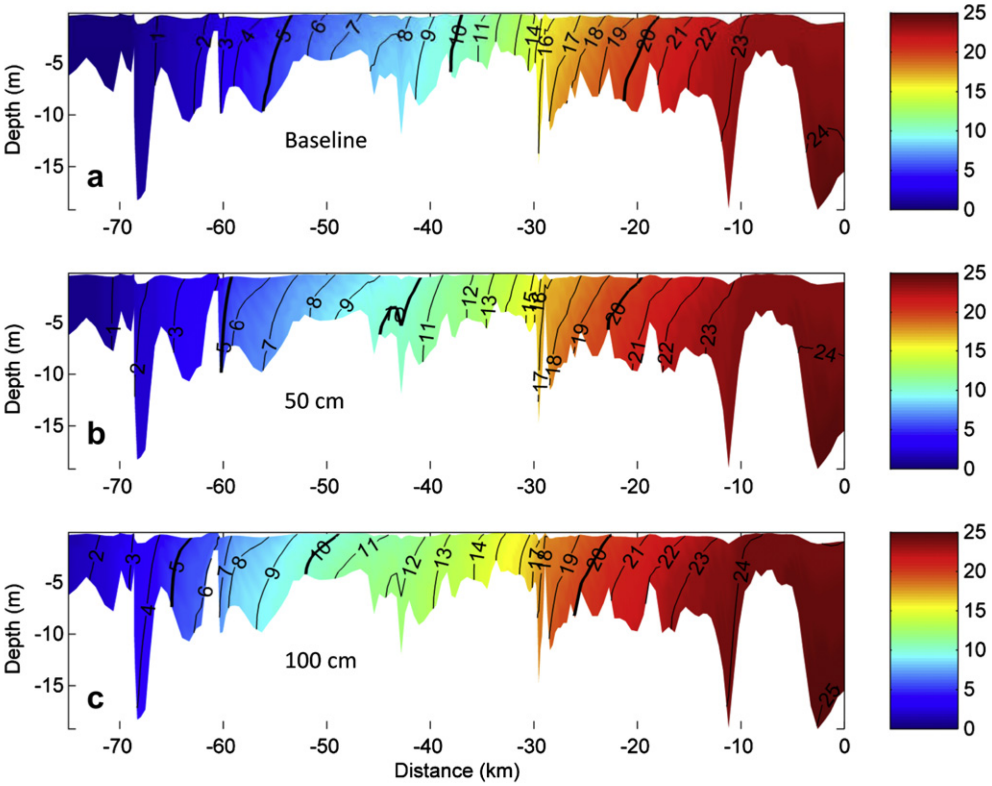

Fig. 6. Distribution of salinity vertical profile along the James River for (a) Baseline; (b) sea-level rise 50 cm; and (c) sea-level rise 100 cm. Isohaline units are ppt.

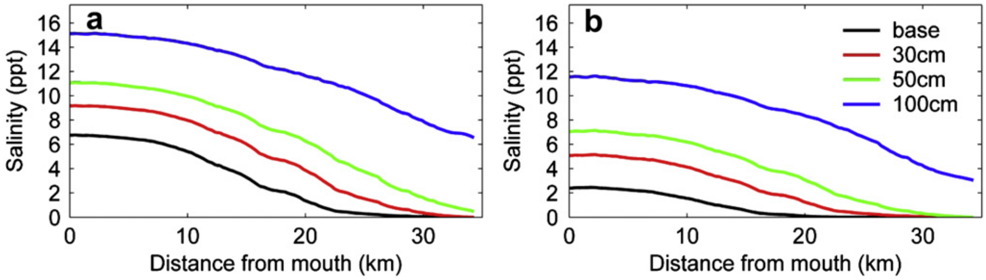

Fig. 7. Effect of simulated sea-level rise scenarios on 31-day mean salinity along the Chickahominy River (from the river mouth to Walkers Dam) during October for (a) 2002 (dry year); and (b) 2005 (typical year). Results from the Baseline and each sea-level rise case are presented.

rise, freshwater still occupies this area, whereas in a dry year, mean salinity at this location is greater than 1 ppt.

In order to quantify the spatial variations in salinity along the river (Fig. 4), the salinity difference between the Baseline and each sea-level rise scenario was calculated (Fig. 5). The monthly mean results for October 2002 indicate that the salinity increase in the middle-to-upper river (from 25 km to 50 km) is greater than that in the lower and upper parts of the river (Fig. 5). For a sea-level rise of 50 cm, the maximum mean salinity increase would be 2 ppt. Should sea-level rise double to 100 cm, the maximum mean salinity increase also would double to 4 ppt.

The vertical salinity profile along the James River shows the detailed change in salinity structure with sea-level rise (Fig. 6). Salinity change can be observed in the entire river. Comparing reference isohalines of 5, 10, and 20 ppt, the upstream movement of the 10 ppt isohaline is much larger than the 5 and 20 ppt isohalines as sea level rises (Fig. 6). The volume of water with salinity between 10 and 20 ppt would increase greatly if sea level rises 100 cm.

4.2. Chickahominy River

Salinity in the CHK River from the mouth to Walkers Dam (34 km from the river mouth) also increases as sea level rises (Fig. 7). The effect of sea-level rise at Walkers Dam is greater in a dry year (Fig. 7a) than a typical year (Fig. 7b). For example, for a 100-cm sea-level rise, the mean salinity at Walkers Dam would be about 3 ppt in a typical year vs. 6 ppt in a dry year. The mean salinity increase at Walkers Dam is relatively small for the 30- and 50-cm rises, compared to the 100-cm rise. Salinity at the CHK River mouth is 4 ppt higher in a dry year than in a typical year for the Baseline case and the three sea-level rise scenarios, because of the difference in freshwater discharge. If sea level rises 50 cm, a mean salinity of 5 ppt could reach 23 km upstream of the river mouth in a dry year, whereas 5 ppt would extend only 14 km upstream in a typical year.

Table 1
Number of days that salinity is predicted to exceed 0.1 psu at Walkers Dam and number of days that water is predicted to overtop Walkers Dam in the Chickahominy River from June 1 through December 31 (total 214 days) of a typical year (2005) and a dry year (2002) for the Base case and three sea-level rise scenarios.

Model scenario	Typical year 2005	Dry year 2002
Number of days salinity exceeds 0.1 psu		
Base case	2	69
30-cm rise	11	106
50-cm rise	20	131
100-cm rise	71	194
Number of days water overtops Walkers Dam		
Base case	17	1
30-cm rise	120	44
50-cm rise	195	138
100-cm rise	214	214

From a drinking-water perspective, it is useful to predict the number of days that salinity at Walkers Dam would exceed 0.1 ppt (100 mg/L total dissolved solids). The results from June 1 through December 31 (214 days) were used for this analysis, because this is usually when river discharge is the lowest and when upstream salinity migration is most likely. During a typical year, salinity may exceed 0.1 ppt for two days in the Baseline and for fewer than 100 days in all the sea-level rise scenarios (Table 1). In contrast, during a dry year when river discharge is low, salinity would exceed 0.1 ppt for 69 days in the Baseline and for more than 100 days in all the sea-level rise scenarios. The number of days when salinity would exceed 0.1 ppt increases with increasing sea-level rise. Overtopping of the dam, which has a height of 1.6 feet (NAVD88), by increased tide level also is a water-supply concern as sea level rises. The likelihood of water overtopping the dam also increases with sea-level rise and is more likely to occur in a typical year than in a dry year for the 30- and 50-cm rise scenarios (Table 1). Should sea level rise 100 cm, water would overtop the dam every day from June 1-December 31, whether it is a typical or a dry year (Table 1).

5. Discussion

With sea-level rise, salinity in the James River would increase almost linearly from the river mouth to 28 km upstream, remain nearly constant from 28 to 50 km, then decrease farther upstream (Fig. 5). Such variation in the magnitude of salinity increase over distance is caused by changes in the stratification of the estuary. As sea level rises, the channel depth increases and the horizontal gradient of salinity changes, resulting in increased estuarine circulation. The stratification increase between 28 and 50 km could have a profound effect on TFW in the tributaries. The model

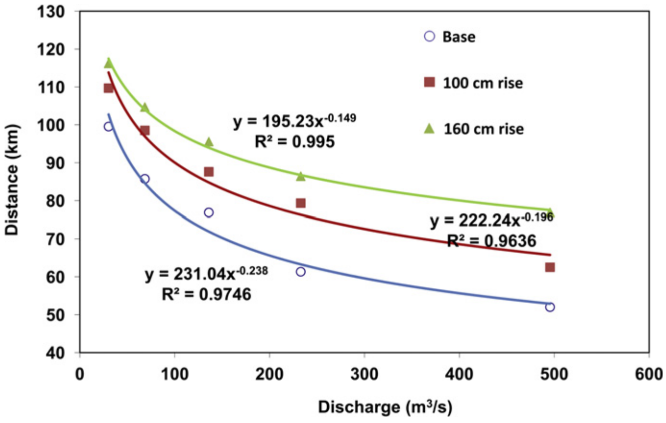

Fig. 8. Relations between salt intrusion distance and discharge on the James River for Baseline (circles), 100-cm sea-level rise (squares), and 160-cm sea-level rise (triangles). Lines are drawn by regression for each case.

simulations indicate that the location of 10 ppt salinity would migrate up to 10 km upstream if sea level rises 100 cm, affecting the current distribution of TFW.

A consequence of reduced river discharge is increased salinity in the estuary. Historical data confirm that when river discharge is diminished in the James and CHK Rivers, saline water moves upstream to Walkers Dam (Ron Harris, Newport News Waterworks, personal commun., 2010). Any increase in the occurrence or duration of salinity at the location of the intake could affect the safe yield and sustainability of the drinking-water supply. The model simulations conducted here indicate that the water-supply intake would be affected (Table 1). For example, for a 100-cm sea-level rise during a dry year, salinity at Walkers Dam would be greater than 5 ppt, an order of magnitude in excess of the U.S. Environmental Protection Agency's secondary standard for drinking water for total dissolved solids of 500 mg/L (equivalent to 0.5 ppt) (http://water.epa.gov/drink/contaminants/index.cfm; accessed 7/21/2011).

5.1. Relation of discharge and salinity intrusion

To examine the effect of discharge on salinity migration in the James River, model simulations of sea-level rise in excess of those indicated by the U.S. Climate Change Science Program (2009) with varying discharges were conducted. Najjar et al. (2010) indicate that 160 cm is the upper bound of sea-level rise in Chesapeake Bay. The salt intrusion distance was calculated for present sea level and for sea-level rises of 100 cm and 160 cm (Fig. 8). For a given discharge, any sea-level rise causes salinity to migrate farther upstream (Fig. 8). With increasing sea level, the exponent in the regression relation decreases, indicating that salinity deceases with flow but migrates farther upstream. As freshwater discharge increases from 50 to 500 m^3/s with present sea level, the salt intrusion distance decreases by 50 km (from river km 100 to river km 50). For a typical mean annual flow of the James River, 200 m^3/s, a 100-cm and 160-cm rise in sea level would cause the salt intrusion distance to

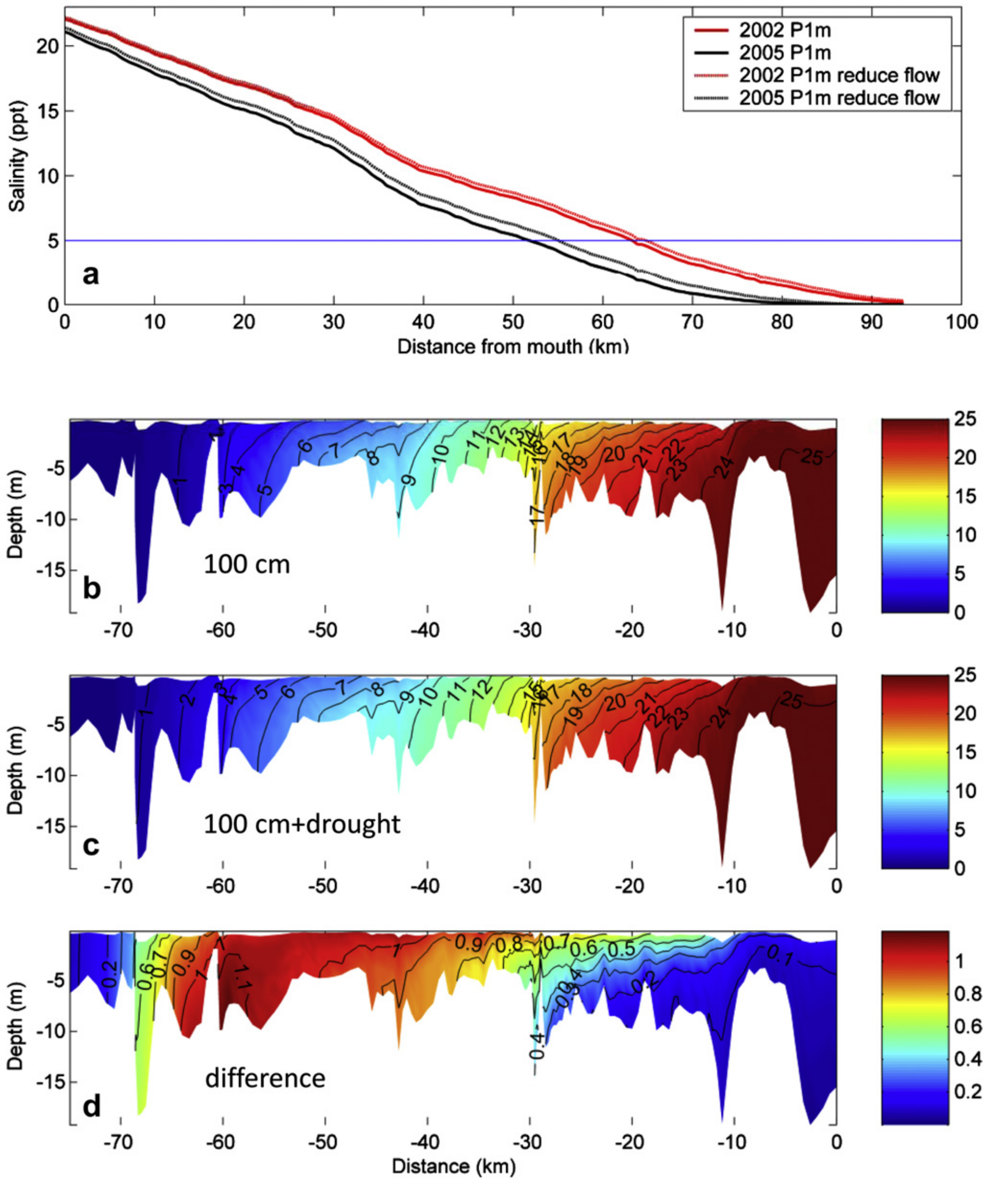

Fig. 9. (a) Change of mean salinity distribution in August 2002 and 2005 with and without flow reduction in the James River for the 100-cm sea-level rise case; salinity vertical profile along the James River for (b) 100-cm sea-level rise with typical flow; (c) 100-cm sea-level rise with 30% reduction of flow in summer; and (d) the salinity difference between (b) and (c), indicating the change of salinity with the extreme conditions. Isohaline units are ppt.

increase about 15 km and 25 km, respectively, relative to the current condition. The salt intrusion distance is a power function of the freshwater discharge, which explains at least 96% of the variance of the salinity intrusion (Fig. 8). Based on the Hansen and Rattray (1965) steady-state estuarine model, the salt intrusion distance is proportional to river flow with an exponent of about −0.33 (Monismith et al., 2002). The exponent varies for different estuaries depending on the localized bathymetry and hydrology (Gong and Shen, 2011; Gibson and Najjar, 2000). The exponent for the James River ranges from −0.149 to −0.238, which is lower than the theoretical value of −0.33, suggesting that salinity can migrate farther upstream for a given discharge of the James River. The model results indicate that the salinity increase in the James River from sea-level rise would be larger than the maximum 3.2 ppt estimated for Chesapeake Bay by Hilton et al. (2008).

5.2. *Synergistic effect of drought and sea-level rise*

Studies in the Chesapeake Bay region suggest that freshwater discharge may be altered as a result of climate change, including an increase in short-term droughts. Model simulations of an extreme condition were conducted by reducing summer (June through August) freshwater discharge by 30% to mimic a short-term drought, combined with a 100-cm sea-level rise. Cross-sectional averaged salinity distributions along the James River in August for a 100-cm sea-level rise with and without summer flow reduction are shown (Fig. 9a). A summer drought would allow salinity to migrate farther upstream during August of a typical year (2005; 3.2 km) than of a dry year (2002; 1.6 km). Because the discharge during August 2002 was very low, any reduction of flow during this period has less effect on salinity migration than during a typical year. The monthly mean vertical salinity profiles along the James River in August 2005 for a 100-cm sea-level rise without (Fig. 9b) and with (Fig. 9c) a summer drought are shown. A marked change of salinity would occur in the upstream area, where the zone with salinity change greater than 1 ppt could be as long as 15 river km (Fig. 9d). The maximum salinity change would occur around river km 60.

The model simulations indicate that extreme conditions (sea-level rise combined with a summer drought) would result in a large change of salinity in the mesohaline region of the James River. Such a change in the main channel would greatly strengthen the gravitational circulation in its tributaries, including the CHK, which would affect TFW and limit the availability of water of suitable quality for municipal and industrial uses.

6. Conclusions

Model simulations of sea-level rise indicate that effects on the salinity field of the James and CHK Rivers would affect floral and faunal habitats and a drinking-water supply. On the basis of model simulations, if sea level continues to rise, salinity structure of the James River would be changed, which could alter the distribution of tidal freshwater wetlands. The part of the James River that would be most affected by an increase in salinity is from 25 to 50 km upstream of the river mouth. If sea level rises by 100 cm, a salinity of 10 ppt would migrate as much as 10 km upstream. With a river discharge of 200 m^3/s in the James River, the salt intrusion distance would increase about 20 km if sea level rises 160 cm compared to the Baseline condition. If a short-term drought occurs during the summer low flow period, a salinity increase would be observed, especially in a typical year.

Increases in mean salinity will greatly alter the existing water-quality gradients between saltwater and freshwater, affecting tidal freshwater wetlands along the tributaries of the James River. An increase in mean salinity is particularly important for the CHK River, where extensive tidal freshwater wetlands occur and a drinking-water-supply intake for the City of Newport News is located. For a 100-cm rise in sea level during a dry year, salinity at the drinking-water intake would be greater than 5 ppt, far in excess of the U.S. Environmental Protection Agency's secondary standard for drinking water.

Acknowledgments

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