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Modeling Groundwater Rise Caused by Sea-Level Rise in Coastal New Hampshire

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ABSTRACT

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Coastal communities with low topography are vulnerable from sea-level rise (SLR) caused by climate change and glacial isostasy. Coastal groundwater will rise with sea level, affecting water quality, the structural integrity of infrastructure, and natural ecosystem health. SLR-induced groundwater rise has been studied in coastal areas of high aquifer transmissivity. In this regional study, SLR-induced groundwater rise is investigated in a coastal area characterized by shallow unconsolidated deposits overlying fractured bedrock, typical of the glaciated NE. A numerical groundwater-flow model is used with groundwater observations and withdrawals, LIDAR topography, and surface-water hydrology to investigate SLR-induced changes in groundwater levels in New Hampshire's coastal region. The SLR groundwater signal is detected more than three times farther inland than projected tidal flooding from SLR. The projected mean groundwater rise relative to SLR is 66% between 0 and 1 km, 34% between 1 and 2 km, 18% between 2 and 3 km, 7% between 3 and 4 km, and 3% between 4 and 5 km of the coastline, with large variability around the mean. The largest magnitude of SLR-induced groundwater rise occurs in the marine and estuarine deposits and peninsulas with tidal water bodies on three sides. Groundwater rise is dampened near streams. Groundwater inundation is projected to contribute 48% of the total inundated area from both SLR-induced groundwater rise and marine tidal flooding in the city of Portsmouth, with consequences for built and natural resources. Freshwater wetlands are projected to expand 3% by the year 2030, increasing to 25% by the end of the century, coupled with water-depth increases.

ADDITIONAL INDEX WORDS: *Inundation, tidal flooding, wetlands, groundwater modeling, climate change, coastal impacts, groundwater-rise zone.*

INTRODUCTION

The northeastern United States is expected to experience sea-level rise (SLR) greater than the global average because of factors such as changing ocean circulation patterns in the NW Atlantic Ocean and land subsidence from glacial isostatic adjustment (Ezer and Atkinson, 2014; Kopp *et al.*, 2014; Sweet *et al.*, 2017). The National Oceanic and Atmospheric Administration (NOAA) assessed a large body of SLR studies and produced scenarios of global mean SLR from 1992 ranging from 0.2 to 2 m by the end of the century (Parris *et al.*, 2012). The low scenario is based on an extrapolation of the historical record. The high scenario is based on a combination of estimated thermal water expansion from the Intergovernmental Panel on Climate Change AR4 global SLR projections (IPCC, 2007) and an estimate of the maximum amount of glacial and ice sheet loss by the end of the century. NOAA recommends that the highest scenario be used to plan for infrastructure where there is little tolerance for risk (Parris *et al.*, 2012).

Whereas increased surface-water flooding due to storm surge and tides is commonly recognized as a significant consequence of SLR, modeling studies have shown that groundwater will also rise with SLR in coastal areas (Cooper, Zhang, and Selch, 2015; Habel *et al.*, 2017; Hoover *et al.*, 2017; Manda *et al.*, 2015; Masterson, 2004; Masterson *et al.*, 2014; Masterson and Garabedian, 2007; Oude Essink, van Baaren, and de Louw, 2010; Rotzoll and Fletcher, 2013; Walter *et al.*, 2016). The historical SLR signal has also been detected in groundwater. Groundwater rose by 2.1 mm/y from 1950 to 2001 in a monitoring well 300 m from the coast on Cape Cod, which is slightly less than the 2.6 mm/y SLR recorded at the Boston tide gauge (1921 to 2000) (McCobb and Weiskel, 2003).

In the northeastern United States, groundwater rise from SLR is anticipated to occur farther inland than tidal flooding on Cape Cod (Masterson and Garabedian, 2007; Walter *et al.*, 2016) and in New Haven, Connecticut (Bjerklie *et al.*, 2012). In Honolulu, Hawaii, the combined area of inundation from tidal water and groundwater rise caused by SLR was twice that of tidal water alone (Rotzoll and Fletcher, 2013). Flooding associated with SLR-induced groundwater rise is expected to cause problems at the Homestead Air Reserve Base in Miami–Dade County, Florida. (Cooper, Zhang, and Selch, 2015). Rising groundwater is predicted to have serious consequences for ecology and water quality in the barrier islands off the Maryland and North Carolina coasts (Manda *et al.*, 2015; Masterson *et al.*, 2014).

Several SLR-induced groundwater rise studies have investigated coastal aquifers where the bedrock is more than 100 m deep (Masterson and Garabedian, 2007; Walter *et al.*, 2016) or porous (Cooper, Zhang, and Selch, 2015; Habel *et al.*, 2017; Rotzoll and Fletcher, 2013) and the transmissivity, or the rate of groundwater flow through the geologic materials, is high. New Hampshire's coastal region was chosen for this study for its complex hydrogeology, extensive rivers and stream net-

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work, fresh and saltwater wetlands, estuaries, and marine environments. Its geology is representative of the glaciated NE with variations in topography and relatively thin unconsolidated glacial deposits overlying fractured metamorphic and igneous bedrock (Ayotte and Toppin, 1995; Lyons *et al*., 1998; Mack, 2009; Medalie and Moore, 1995; Stekl and Flanagan, 1992). Although heterogeneous glacial deposits were also simulated in New Haven, Connecticut, the coastal New Hampshire deposits are thinner than the 75-m-thick glacial meltwater and glaciolacustrine deposits found in New Haven (Bjerklie *et al*., 2012).

Groundwater rise characterization is important because it has the potential to affect both natural and built systems in coastal regions. Rising groundwater has been shown to reduce pavement life in coastal-road infrastructure (Knott *et al*., 2017), reduce the effectiveness of onsite wastewater treatment systems (Habel *et al*. 2017; Manda *et al*., 2015), and infiltrate wastewater collection systems (Flood and Cahoon, 2011). Freshwater wetlands and salt marshes occur where groundwater is near or above the ground surface and are highly vulnerable to changing groundwater levels (Lorah and Olsen, 1999; Masterson *et al*., 2014; Wilson *et al*., 2012). Salt-marsh ecology is dependent on the interaction between fresh groundwater and tidal surface water (Harvey and Odum, 1990; Hemond and Fifield, 1982). Rising groundwater from SLR can expand or drown wetland ecosystems, change salinity within salt marshes, and change the type and distribution of wetland vegetation (Moffett *et al*., 2012).

Objectives

The objectives of this study are to (1) determine the magnitude and inland extent of groundwater rise from SLR, (2) define the groundwater-rise zone (GWRZ), the area where groundwater is predicted to rise with SLR, (3) investigate the variability of projected groundwater rise with distance from the coast, (4) explore relationships between groundwater rise and depositional environments, and (5) demonstrate how this methodology can be used to identify potential impacts to freshwater and saltwater wetlands.

Study Area

The focus of this study is the New Hampshire coastal region (Figure 1). A regional groundwater-flow model (Mack, 2009) is used to simulate SLR-induced groundwater rise in coastal New Hamphsire. The model boundaries simulate natural hydrologic boundaries and, consequently, a small section of Massachusetts is simulated to include the Merrimack Estuary as the southernmost boundary. The geography, hydrogeology, and depositional environments of coastal New Hampshire are described below.

Geography

The modeled area encompasses approximately 488 km^2 of a coastal region with 410 km^2 in New Hampshire and 78 km^2 in Massachusetts. The New Hampshire coastal region consists of all or a part of 13 New Hampshire towns. The region includes coastal and freshwater wetlands, rivers and streams, estuaries, and beaches (Mack, 2009). It is bounded by the Piscataqua Estuary and the Maine border to the north, Great Bay and the Squamscott River to the west, the Merrimack Estuary in Massachusetts to the south, and the Gulf of Maine to the east (Figure 1). There are approximately 64 km of shoreline including the Gulf of Maine, Piscataqua Estuary, and Great Bay within the study area. Land surface altitude is greater than 90 m above the North American Vertical Datum of 1988 (NAVD88) in the southwestern part of the coastal region, less than 15 m over areas in the south-central and northeastern parts of the region, and at sea level along the coast (NH Coastal Lidar, 2011).

Hydrogeology

New Hampshire's coastal region is characterized by thin glacial and marine sediments with topography that generally follows the bedrock surface (Mack, 2009). Fine-grained till and marine silts and clays and coarse-grained stratified drift make up the surficial geology overlying crystalline metamorphic rock of sedimentary origin and igneous bedrock (Lyons *et al*., 1998; NH State Geologist, 2004). The surficial deposits, mapped by the U.S. Geological Survey (USGS) (Moore, 1990; Stekl and Flanagan, 1992), are typically less than 12 m thick in the region, with deposits of up to 21 m thick beneath Pease International Airport in the northern portion of the study area (Mack, 2009). The coarse stratified-drift sediments, consisting of sands and gravels, are the most permeable, with hydraulic conductivities ranging from 15 to more than 61 m/d. Lower values ranging from 0.6 to 4.6 m/d are found in the fine-grained sands (Ayotte and Toppin, 1995; Mack, 2009; Medalie and Moore, 1995). These sediments form unconfined aquifers bounded above by the water table and below by bedrock. Groundwater flows from areas of high groundwater altitude toward the natural discharge areas in streams, Great Bay, and the Piscataqua Estuary to the north, the Gulf of Maine to the east, and the Merrimack River to the south (Figure 1). Streams and wetlands are typically hydraulically connected to the groundwater and affect local groundwater-flow patterns (Mack, 2009).

Depositional Environment

Seven depositional environments are identified in the surficial geology (MassGIS, 2004; NH State Geologist, 2004): (1) Beach deposits consist of well-sorted sand and are located on the eastern shoreline bordering the Gulf of Maine. (2) Estuarine deposits are primarily salt marshes bordering the Gulf of Maine, Piscataqua Estuary, and Great Bay. (3) Anthropogenic deposits are coarse-grained fill materials used in landfills and the base layers of roads. (4) Glaciomarine deposits consist of deltaic, wave-formed, and wave-modified marine delta deposits. Fine-grained clayey-silt and sand deposits are found adjacent to protected water bodies such as Great Bay and wetland areas, whereas the coarse-grained materials are found farther inland. Undifferentiated facies are found in the northern part of the study area. (5) Glacial till is poorly sorted material consisting of fine-grained silts and clays and coarse sands and gravels with low hydraulic conductivities (Ayotte and Toppin, 1995; Moore, 1990). (6) Palustrine are the freshwater wetland deposits. (7) Alluvial deposits consist of alluvium and stream terrace deposits (NH State Geologist, 2004).

New Hampshire Wetlands

In the New Hampshire coastal region, 25% of the land area is wetland, with 15% freshwater and 10% saltwater wetlands.

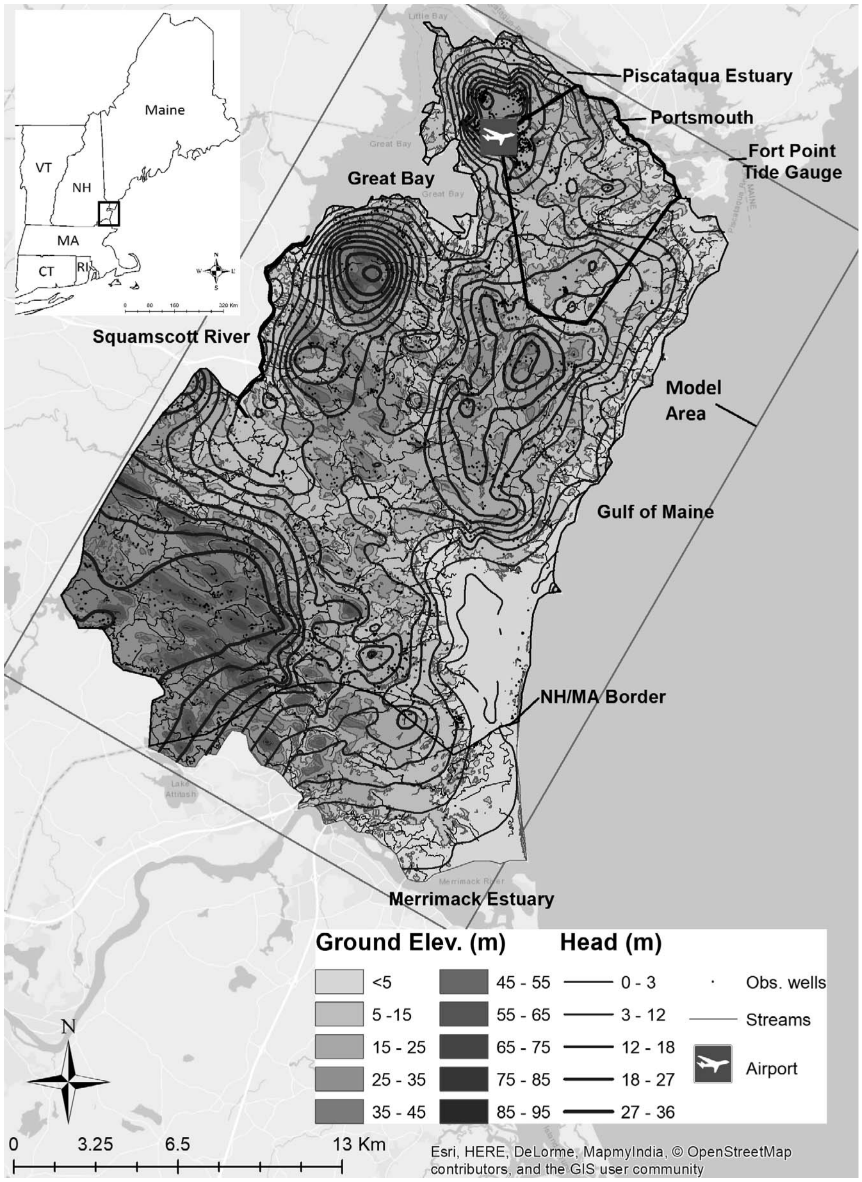

Figure 1. Study area in New Hampshire's coastal region. The rectangular area is the groundwater model domain and the coastal boundaries are shown. Shading illustrates the land-surface elevation and observation wells are indicated. Groundwater piezometric head contour lines are illustrated with thick to thin lines indication high to low head. The inset shows the location within the New England region of the United States.

Saltwater wetlands are classified at estuarine and marine wetlands and freshwater wetlands are classified as freshwater emergent wetland, freshwater forested/shrub wetland, and freshwater pond (U.S. Fish and Wildlife Service, 2001). Forested/shrub wetlands, emergent wetlands, ponds, lakes, and riverine wetlands are the primary freshwater wetland types in the region, with freshwater forested/shrub wetlands dominating at 72% of all freshwater wetlands (U.S. Fish and Wildlife Service, 2001). Wetlands in Portsmouth are representative of the larger New Hampshire coastal region. Wetlands make up 30% (12.5 km^2) of the land area in Portsmouth, with 21% (8.8 km^2) freshwater wetlands and 9% (3.7 km^2) estuarine and marine wetlands. Forested/shrub dominate the freshwater wetlands at 73% (6.4 km^2) and the remainder consists of emergent wetlands and freshwater ponds at 24% (2.1 km^2) and 3% (0.2 km^2), respectively (U.S. Fish and Wildlife Service, 2001).

METHODS

A numerical groundwater-flow model was used to investigate the effect of rising sea level on groundwater levels in the study area. The output from the groundwater model was analyzed to determine the areal extent and variation of groundwater rise within the GWRZ. The assumptions and limitations of this analysis are also presented.

Groundwater Model

Groundwater modeling is used to simulate SLR effects on groundwater levels, changing groundwater flow patterns, and saltwater intrusion (Masterson, 2004; Masterson and Garabedian, 2007; Oude Essink, van Baaren, and de Louw, 2010; Pitz, 2016; Walter *et al.*, 2016). In this study, an existing USGS regional groundwater flow model of the New Hampshire coastal region was updated and modified to investigate SLR-induced changes in groundwater levels. A portion of NE Massachusetts is also included in the model area to allow for the use of a natural hydrologic boundary, the Merrimack River, as a model boundary. A complete description of the model is presented in Mack (2009) and only a brief description of the updates to the model is presented here.

MODFLOW2005 (Harbaugh, 2005), a three-dimensional finite-difference model, was used to solve the groundwater-flow equation for various sea levels. The model grid consists of 535 rows, 350 columns, and five layers with a uniform horizontal discretization of 61 m (Mack, 2009). The top of the model is defined by land-surface topography derived from LIDAR digital elevation models (DEMs) (NH Coastal Lidar, 2011) and the top two layers simulate unconsolidated geologic deposits consisting of stratified drift, till, beach, and wetland sediments. Differentiation between these sediments in the model was achieved by creating zones of aquifer properties (Mack, 2009). This study focuses on layer 1, as the groundwater table primarily resides in this layer throughout the model. Layer 1 simulates surficial deposits ranging in thickness from 3 to 21 m consisting of fine-grained marine silts and clays, coarse-grained stratified drift, and wetland deposits. Layer 2 is a thin layer simulating till above the bedrock and layers 3 through 5 represent bedrock. The three bedrock layers are used to simulate bedrock well withdrawals from multiple depths. The grid is oriented with the NE-SW structural pattern of the bedrock and aligns with the coastline (Mack, 2009).

Model Input

Climate-sensitive parameters include aquifer recharge, streamflow, and sea level (Kopp *et al.*, 2014). Aquifer recharge is the infiltration of precipitation and/or surface water and its percolation through the unsaturated zone to the saturated zone of the soil profile (Heath, 1983). Areal recharge rates used in the groundwater model were determined by the New Hampshire Geological Survey (NHGS) using the Dripps water balance model (Dripps and Bradbury, 2007). This is a soil-water model that accounts for interception, evapotranspiration (ET), partitioning of runoff, soil infiltration or snow-pack storage, and soil-moisture partitioning. The input parameters, compiled by NHGS, include the following GIS-gridded data: flow direction, land cover/land use, Natural Resource Conservation Service (NRCS) soil groups, NRCS available soil-water capacity, snow cover, and initial soil moisture. The recharge model is run with daily time steps and allows runoff to move from one cell to another. The output is a GIS map of gridded (28 m $\times$ 28 m) annual recharge rates (Dripps and Bradbury, 2007). The areal recharge values used in the model range from 0 to 0.96 m/y with an average of 0.21 m/y and a standard deviation (SD) of 0.14 m/y.

Rivers, streams, and wetlands connected to streams are represented as head-dependent flux boundaries using the stream package in MODFLOW2005 (Harbaugh, 2005). There are over 14,000 stream reaches in the model ranging in length from 3 to 150 m (NH Hydrography, 2006). The width of each stream reach was estimated using high-resolution aerial photographs in GIS (Aerial Photos, 2011; Coastal NH, 2013; NH Hydrography, 2006). Stream stage at the beginning and end of each stream reach was determined from bare-earth LIDAR DEMs (NH Coastal Lidar, 2011). The streambed hydraulic conductivity was initially estimated using typical values for the area (Mack, 2009) and refined using Groundwater Vistas parameter estimation techniques (Rumbaugh and Rumbaugh, 2011). The focus of this study is the effect of SLR on groundwater levels, and climate change-induced changes in recharge and streamflow were not simulated in this analysis.

Model cells inundated at mean sea level (MSL) were designated as constant-head boundary cells (Harbaugh *et al.*, 2000; Rumbaugh and Rumbaugh, 2011) for each steady-state model run. For the current condition, these cells were assigned a constant head of 0.09 m below NAVD88, the altitude of MSL recorded at the Fort Point tidal station (Station identification: 8423898) located in New Castle, New Hampshire in the northeastern corner of the study area (NOAA, 2016). Freshwater equivalent heads were used to simulate the freshwater/saltwater density effects (Rumbaugh and Rumbaugh, 2011).

Climate-insensitive parameters include ground-surface topography from LIDAR, hydraulic conductivity, and aquifer layer thickness. LIDAR DEMs collected over approximately 2336 km^2 covering all coastal New Hampshire in 2011 were used to map the ground-surface topography. The DEM resolution is 2 m and the vertical accuracy is 30 cm at the 95% confidence level per the National Standard for Spatial Data Accuracy on the basis of a root mean square error (RMSE) of 15 cm (NH Coastal Lidar, 2011). Hydraulic conductivity and aquifer thickness were regional values based on the surficial and bedrock geology (Mack, 2009). Hydraulic conductivity was refined using MODFLOW parameter estimation techniques during the calibration phase. A summary of the model input parameters is presented in Table 1.

Permitted drinking-water withdrawals from the New Hampshire Department of Environmental Service (NHDES) were included in the model and were kept constant through all the simulations. Active production wells, 219 in total, were simulated: 36 withdrawing water from the unconsolidated deposits and 183 withdrawing water from the fractured bedrock. Production-well withdrawal volumes were based on reported well yields, permitted volumes, or wellhead protection maximum rates depending on the availability of data. These withdrawal volumes were reduced to represent actual withdrawal volumes based on communication with NHDES. Water withdrawals used in the model ranged from 0.2 m^3/d from the bedrock to approximately 309 m^3/d from the unconsolidated deposits in the eastern portion of the study area, with an average of 47 m^3/d and a SD of 78 m^3/d. Domestic withdrawals were simulated in layers 3 and 4 using the flow and head boundary condition in MODFLOW and withdrawal returns in

Table 1. *Summary and comparison of groundwater model input parameters between Mack (2009) and this study. The hydraulic conductivity (*K*) shown is horizontal* K. *In both studies, vertical* K *is typically one-tenth of the overburden horizontal* K *and equal to the bedrock horizontal* K.

Description	Units	Mack (2009)	Current Study
Overburden Hydraulic Conductivity			
Fine-grained sediments	m/d	0.03	0.02
Sand and coarse-grained sediments	m/d	3.05	0.12–7.86
Wetlands	m/d	3.05	7.86
Till	m/d	0.30	0.3–0.5
Bedrock Hydraulic Conductivity			
Rx1–Rye Complex, Breakfast Hill Granite	m/d	0.15	0.15
Rx2–Kittery Formation	m/d	0.30	0.24
Rx3–Eliot and Berwick Formations	m/d	0.03	0.03
Rx4–Exeter Diorite	m/d	0.06	0.06
Stream Parameters			
Streambed hydraulic conductivity	m/d	0.76	0.02–1.52
Streambed thickness	m	0.30	0.30
Stream width	m	1.52	1.52–305
Areal recharge	m/yr	0.3	0–0.96
Sea Level (relative to NAV88)			
Mean Sea Level (MSL)	m	−0.09	−0.09
0.3 m SLR	m	—	0.21
0.8 m SLR	m	—	0.71
1.6 m SLR	m	—	1.51
2.0 m SLR	m	—	1.91

Note: Bedrock formations are from Mack (2009).

nonsewered areas were distributed back into model layer 2 (Mack, 2009).

Groundwater Measurements and Contour Mapping

Groundwater piezometric heads were compiled from the NHDES, NHGS, U.S. Air Force, USGS, and New Hampshire Department of Transportation (NHDOT). Data from 2919 wells, 1645 installed in unconsolidated deposits above the bedrock (overburden) and 1274 in the bedrock, were used in this study. Piezometric heads, measured monthly or quarterly from 2011 to 2015, in 901 wells (827 in the overburden and 74 in the bedrock) were available from the Pease International Airport (Figure 1). These wells had been surveyed to the National Geodetic Vertical Datum of 1929 (NGVD29) and groundwater heads were measured with an accuracy of 0.03 m (Forbes, 2015; Holmes *et al.*, 2001). Groundwater heads measured over the remainder of the study area from 1970 through the present were acquired from 652 wells in the GEOLOGs (NHGS) database (622 in the overburden and 30 in the bedrock) and 1366 wells (196 in the overburden and 1170 in the bedrock) from the water-well inventory (NHDES).

GEOLOGs are a compilation of boring and well information from NHDES, NHDOT, and USGS. Groundwater heads in many wells were measured only one time, whereas others were monitored over time through 2009 (Barker, 2016). Approximately 37% of the GEOLOG wells had been surveyed to NGVD29 or NAVD88 and the accuracy of the measured heads is 0.03 m. The remaining wells were either surveyed to a local datum or were not surveyed for elevation. The water-well inventory contains boring and well information compiled by the NHDES from wells installed between 1984 and 2015 for domestic and industrial water supply, exploration, and testing. Depths to groundwater were recorded by drillers during installation, but the wells were not surveyed. The location of these wells is typically sketched on property maps. The piezometric heads in the saline coastal water bodies were assumed to be MSL as recorded at the NOAA tidal gauge at Fort Point, Newcastle, New Hampshire (NOAA, 2016) and were adjusted for density using freshwater equivalent heads (Rumbaugh and Rumbaugh, 2011).

A new regional database of groundwater information referenced to the common datum, NAVD88, was created from the compiled groundwater information. This database includes the station number, well location in New Hampshire State Plane coordinates, well depth, ground-surface elevation, screened interval, groundwater piezometric heads, and measurement date. Heads referenced to NGVD29 in the source data were converted to NAVD88 using VERTCON (National Geodetic Survey, 2016). Piezometric heads from the wells that were not surveyed to NGVD29 or NAVD88 were estimated from LIDAR ground-surface elevation and the measured water depth in the well. The vertical accuracies of the heads estimated from GEOLOGs and the water-well inventory are 0.6 m and 1.0 m, respectively. A groundwater piezometric head contour map was constructed from groundwater observations in the overburden to examine the existing groundwater flow regime. These contours are shown on Figure 1.

Calibration

The model was calibrated to average groundwater levels from 1970 to 2014 in 3156 wells (target observations). Groundwater levels representative of the low recharge condition were used from wells with seasonal observations. The automated calibration procedure from Groundwater Vistas (Rumbaugh and Rumbaugh, 2011) was used. This procedure determines the model parameters that produce the best fit to these target observations using inverse calibration methods. It uses Marquardt's modification to the Gauss–Newton nonlinear least-squares parameter estimation technique (Levenberg, 1944; Marquardt, 1963). Plots of the observed groundwater heads and the residual (the difference between observed and computed values) *vs.* the computed heads are presented in Figure 2.

For layer 1 of the model, the range of observed piezometric heads over the entire modeled region is 53.6 m. The RMSE of the fit is 2.4 m, or 4.5% of the observed range (scaled RMSE). Typically, the scaled RMSE should be less than 10% for a good calibration (Rumbaugh and Rumbaugh, 2011). The residual mean is –0.4 m and the absolute residual mean, a measure of the average error in the model, is 1.8 m. Differences between the computed and observed groundwater heads are due to groundwater measurement errors and uncertainties in the hydrogeologic properties of the heterogeneous geologic materials and fractured bedrock. In the northern part of the study area near the Pease International Airport where the groundwater measurements are the most accurate, the range of observed piezometric heads is 24.9 m. The RMSE is 1.7 m, or 6.7% of the observed range, the residual mean is –0.1 m, and the absolute residual mean is 1.3 m.

Streamflow, measured in 14 streams during a period of streamflow recession (Mack, 2009), were compared with the calculated base flow to streams. Groundwater flux from the

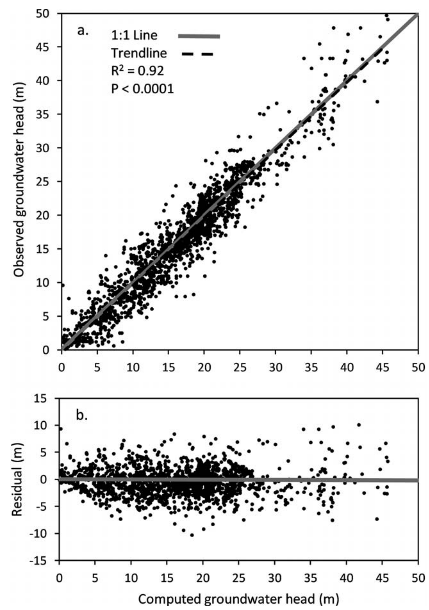

Figure 2. Model calibration results: (a) observed groundwater piezometric heads in unconsolidated deposits *vs*. computed groundwater heads, and (b) groundwater-head residuals (observed minus computed heads) *vs*. computed groundwater heads.

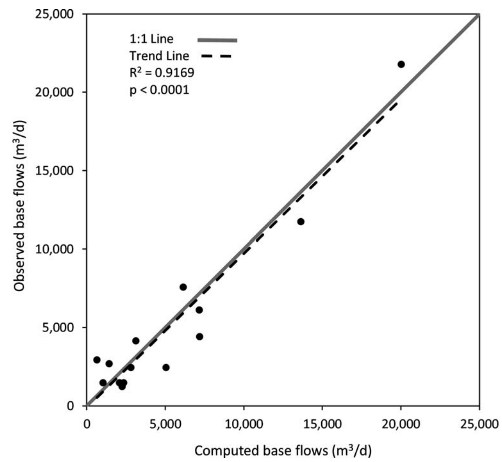

Figure 3. Measured stream base flow *vs*. computed groundwater discharge to streams in the model area. The base flow for the Winnicut River is the September mean flow from 2001 through 2016. All other base flows were measured in October 2004.

aquifer to the stream at each reach upstream of the USGS gaging station is summed to determine the simulated base flow at each gaging station. The comparison between observed and simulated base flows is presented in Figure 3. Observed base flows range from 0.014 to 0.252 m^3/s and the RMSE of the simulated flows is 0.018 m^3/s.

Although the accuracy of the model is not sufficient to predict the groundwater head at any individual well or location, the simulations are useful in identifying future changes in regional groundwater-flow patterns and relative groundwater response to SLR. A comparison of the baseline simulated head contours and the average observed head contours demonstrates that the groundwater model provides an accurate representation of the regional groundwater flow patterns and discharge areas. The regional model is useful for identifying the GWRZ, as well as trends and uncertainties in SLR-induced groundwater rise. Coupled with LIDAR DEMs, areas with shallow groundwater that are at risk from groundwater rise can be identified for detailed vulnerability studies and adaptation planning.

SLR Scenarios

The New Hampshire Hazards and Risks Commission's NOAA-derived SLR scenarios for coastal adaptation planning (Kirshen *et al*., 2014; Parris *et al*., 2012) were used in this research. SLRs of 0.3, 0.8, 1.6, and 2 m corresponding to the high-emission scenario in early century (2030), mid-century (2060), and the end of the century (2090 and 2100), respectively, were simulated using the groundwater model. Each projected rise in sea level was added to the current MSL and then used as the coastal boundary condition for the steady-state simulations (Table 1). The model was run to calculate groundwater heads for the current condition and the four SLR scenarios. This is a conservative analysis of SLR-induced groundwater rise as it considers only the change in hydraulic head at the coast. It does not include the inland migration of the shoreline.

Analysis Methods

The model output utilized in this analysis is piezometric head corresponding to the phreatic surface (or water table) in the surficial layer and groundwater flow to discharge areas. Groundwater rise was calculated by subtracting the computed groundwater heads at MSL from the computed heads for each SLR scenario. Distributions of simulated groundwater rise within 1-km intervals from the coast were generated. The 1-km interval is a commonly used distance metric and encompasses a large-enough sample of modeling results (61 × 61 m grid cell size) for statistical analysis. In addition, groundwater discharge to streams and coastal discharge areas was calculated and compared between the MSL condition and the SLR scenarios.

The transmissivity of the unconsolidated deposits, or the groundwater rate of flow per unit width, depends on the hydraulic conductivity of the materials and thickness of the deposits (Bear, 1979). The depositional environment, identified in the commonly available surficial geology data layer (NH State Geologist, 2004), is one way to categorize these properties. Distributions of simulated groundwater rise within each depositional environment were calculated.

Wetland-area expansion and water depth increases were investigated and compared with projected seawater (marine surface water) inundation in the city of Portsmouth (Figure 1). This was a simple mapping analysis and was not intended to be a detailed investigation of these complex ecosystems. Wetland-area expansion was investigated by mapping the difference between the simulated wetland area at MSL and the predicted groundwater inundation (GWI) area (land inundated by groundwater rise) with SLR. The simulated wetland areas at

MSL were determined by subtracting the computed groundwater heads at MSL from the LIDAR DEMs, resulting in a depth to groundwater. Areas with groundwater at or above the ground surface were identified as wetland areas. Model findings were analyzed relative to the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2001). SLR-induced groundwater rise was mapped within existing wetland areas identified in the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2001) to estimate the water-depth change that may occur in these ecosystems. Distributions of groundwater rise were compared among the following wetland types: estuarine and marine wetland, freshwater emergent wetland, freshwater forested/shrub wetland, and freshwater pond.

Assumptions and Limitations

The model is a regional groundwater-flow model in an area where the surficial geology is heterogeneous and typically thin (less than 30 m). Fractured bedrock is modeled as part of the flow regime. Ground-surface topography, areal recharge, water withdrawals, hydrogeologic properties, surface water, and SLR were used as inputs and the model was run in steady state. These inputs have uncertainties including errors associated with measuring the parameter, parameter variability in space and time, complex interactions between surface water and groundwater, insufficient data density, and an uncertain climate future. Consequently, the model should not be used to predict groundwater piezometric head at individual wells or locations but can be used to investigate regional groundwater flow patterns and relative trends with projected SLR.

The density effects of saltwater were included in this analysis using equivalent freshwater heads, but salt transport was not explicitly modeled. The location of the freshwater/saltwater interface in the bedrock is not well known, but is believed to be close to the coastline on the basis of salinity measurements in a small number of domestic water-supply wells (Mack, 2009). Regional inland migration of the freshwater/saltwater interface in the bedrock is not expected to be extensive with SLR because of low bedrock hydraulic conductivity and bedrock structure orientation parallel to the coast (Mack, 2004). Equivalent freshwater heads provide a good approximation of the density effects on piezometric heads in the shallow aquifer near the coast (Mack, 2004; Rumbaugh and Rumbaugh, 2011).

Steady-state simulations were used to assess the long-term effect of SLR on average groundwater levels. Seasonal or annual variation in recharge rates caused by climate change were not considered. In the NE, the groundwater is typically highest in the early spring when the aquifer recharge from rainfall and snowmelt is maximum and ET is small (Mack, 2009). Precipitation and temperature are expected to increase in the NE with climate change (Hayhoe *et al*., 2015), affecting groundwater levels through changes in aquifer recharge (Bjerklie *et al*., 2012; Mack, 2009). Groundwater withdrawals were also assumed to be constant throughout the study period. Mack (2009) investigated the effect of increased drinking-water demands and found minor lowering of groundwater levels, most apparent near the water supply wells. This study's objective is to investigate the effect of SLR on groundwater levels and all other input parameters were held constant in the simulations. Long-term changes in recharge and groundwater withdrawals will affect long-term groundwater levels in the region.

The model calibration uses data from multiple years, but primarily represents periods of low recharge. Additional data collection and model calibration will be needed to generate higher resolution and transient groundwater-rise projections required for adaptation planning in individual towns or municipalities within the study area.

RESULTS

This research demonstrates that groundwater will rise with SLR in coastal geologic environments typical of the glaciated NE. The distribution of groundwater rise with distance from the coast and within different depositional environments is presented. GWI areas are compared with tidal-water inundation areas in Portsmouth, New Hampshire and consequential changes in freshwater and saltwater wetland hydrology are discussed. The results presented here represent groundwater rise caused by SLR only. Future groundwater levels will also be affected by changes in annual and seasonal recharge rates, influenced by precipitation and ET changes, and future groundwater withdrawals in the region.

SLR Effects on Groundwater

In the New Hampshire coastal region, groundwater rise caused by 2 m of SLR is projected to extend farther inland than projected mean higher high water (MHHW) inundation (Figure 4). The farthest extent of projected MHHW inundation is approximately 1 to 1.5 km, whereas groundwater rise up to 0.2 m is predicted to occur more than 4 km inland in some locations. The magnitude of groundwater rise and inland extent varies along the coastline. The analysis predicts 0.75- to 1.25-m groundwater rise 2 to 3 km from the shoreline (with 2 m of SLR) primarily in the northern part of the study area where groundwater rise is controlled by tidal surface water bodies on three sides (Figure 4). Projected MHHW with 2 m of SLR is predicted to extend inland from the coast less than 0.8 km in this region.

SLR-induced rising groundwater is projected to inundate the land surface in some areas. Where the vadose-zone thickness is currently less than the projected groundwater rise, GWI may occur. Tidal surface water and groundwater are projected to inundate approximately 3.7 km^2 or 9% of Portsmouth land area with 2 m of SLR. GWI contributes 48% of the total inundation (1.8 km^2) and is projected to flood areas up to 3.5 km inland from the Portsmouth coast.

Groundwater rise is dampened near streams (Figure 4) as increased gradients between the two systems drive more groundwater discharge to streams. The net groundwater discharge to surface water in the study area is approximately 3.1 m^3/s with 73% of the net groundwater discharge going to streams and 27% to coastal discharge areas (lands flooded with tidal waters at MSL). For all scenarios, SLR was found to increase gradients between groundwater piezometric head and stream stage, increasing groundwater discharge to streams. However, increased tidal-water piezometric head at the coast reduces groundwater discharge to coastal wetlands. In addition, inflow from marine surface water to coastal groundwater is projected to increase. For example,

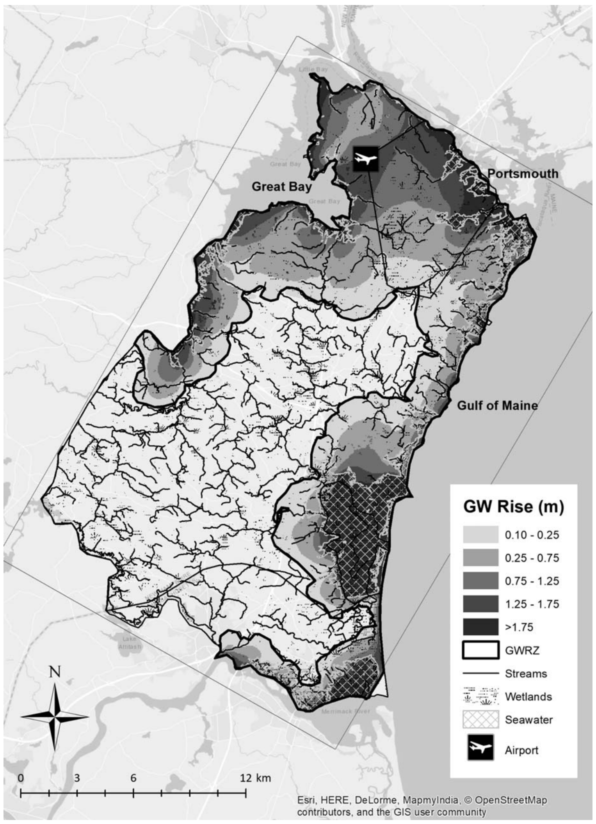

Figure 4. Groundwater-rise zone (GWRZ) and mean higher high water (MHHW) seawater inundation simulated with 2 m of sea-level rise. The shading indicates the magnitude of projected groundwater rise.

with 2 m of SLR, the net groundwater discharge to streams increases from 73 to 83% of the total discharge with a corresponding decrease in groundwater discharge to coastal discharge areas. This represents a 0.3 m^3/s increase in net groundwater discharge to streams compared with the MSL condition. Inflow from marine surface water to coastal groundwater is projected to increase approximately 0.1 m^3/s or 52% relative to the MSL inflow.

Groundwater Rise with Distance from the Coast

Groundwater rise, simulated for the four SLR scenarios, was evaluated at 1-km intervals from the shoreline and the results are presented in Figure 5. The ratio of mean groundwater rise to SLR is consistent across the SLR scenarios analyzed and is projected to be approximately 66% between 0 and 1 km, 34% between 1 and 2 km, 18% between 2 and 3 km, 7% between 3 and 4 km, and 3% between 4 and 5 km of the coast (Figure 5). By the end of the century, the mean groundwater rise ranges from more than 1.3 m between 0 and 1 km to less than 0.1 m between 4 and 5 km from the coast (Figure 5d).

Distance from the coast explains approximately 50% of the variability in groundwater rise ($R^2 = 0.51$ to 0.52). Although groundwater rise decreases with distance from the coast ($p <$ 0.0001), the remaining variability due to other factors is as important. Maximum groundwater rise at the coast equals the SLR magnitude and exceeds 1.8 m as far as 2 to 3 km inland with 2 m of SLR in some locations. In contrast, 25% of the area within 0 to 1 km of the coast is projected to experience groundwater rise less than 0.8 m.

The probability of finding various levels of groundwater rise within each distance interval was determined. With 2 m SLR, approximately 85% of land area within 1 km of the coast is projected to experience more than 0.5 m of groundwater rise and 50% is projected to experience more than 1.5-m rise. Within 2 km of the shoreline, there is a 50% chance of groundwater rise greater than 0.1 m by year 2030, 0.4 m by mid-century, and 0.9 m by the end of the century. With 2-m SLR, 25% of the land area between 2 and 3 km from the coast is predicted to experience more than 0.5-m groundwater rise. Projected groundwater rise greater than 0.5 m drops to 5% between 3 and 4 km of the coast and zero beyond 4 km. On the basis of this information and the results presented in Figure 5, the landward boundary of the SLR-induced GWRZ occurs between 4 and 5 km from the coast.

Groundwater Rise and Surficial Geology

The depositional environment controls on groundwater rise within 4 km of the coast for the 0.8- and 2-m SLR scenarios are quantified in Table 2. The mean groundwater rise is significantly different among all the depositional environments except between the palustrine and alluvial deposits according to the Tukey-Kramer HSD test ($p <$ 0.0001). The relationship is also characterized by large variability around the mean as indicated by the SD and coefficient of variance (CV) (Table 2). As with distance from the coast, the mean groundwater rise-to-SLR ratio for each depositional environment is consistent regardless of the absolute magnitude of SLR, but large variations exist within the depositional environments.

The largest magnitude of groundwater rise occurs in the beach and estuarine depositional environments, with mean groundwater rise relative to SLR of 81 and 54%, respectively. These deposits make up approximately 15% of the area within 4 km of the shoreline, are close to the coast, and experience direct marine surface-water influence on groundwater in beaches and dunes and coastal wetlands (estuarine). The interquartile range of relative groundwater rise in the beach sediments falls between 66 and 100% of SLR, whereas the estuarine depositional environment exhibits a large interquartile range of 12 to 100%.

Anthropogenic deposits make up slightly over 1% of the area and include fill used in coastal roadway construction and disposal sites. These deposits are predicted to experience a mean relative groundwater rise of just under 50% with an interquartile range of 24 to 62% of SLR. Glaciomarine and glacial till deposits dominate the surficial geology of the region, making up approximately 53 and 27% of the area within 4 km of the coast, respectively. The mean glaciomarine and glacial till groundwater responses are essentially the same, 35 *vs.* 32% of SLR with SDs of 28 and 31% of SLR, respectively. The groundwater-rise differentiation between the major depositional environments (estuarine, glacial till, glaciomarine, and

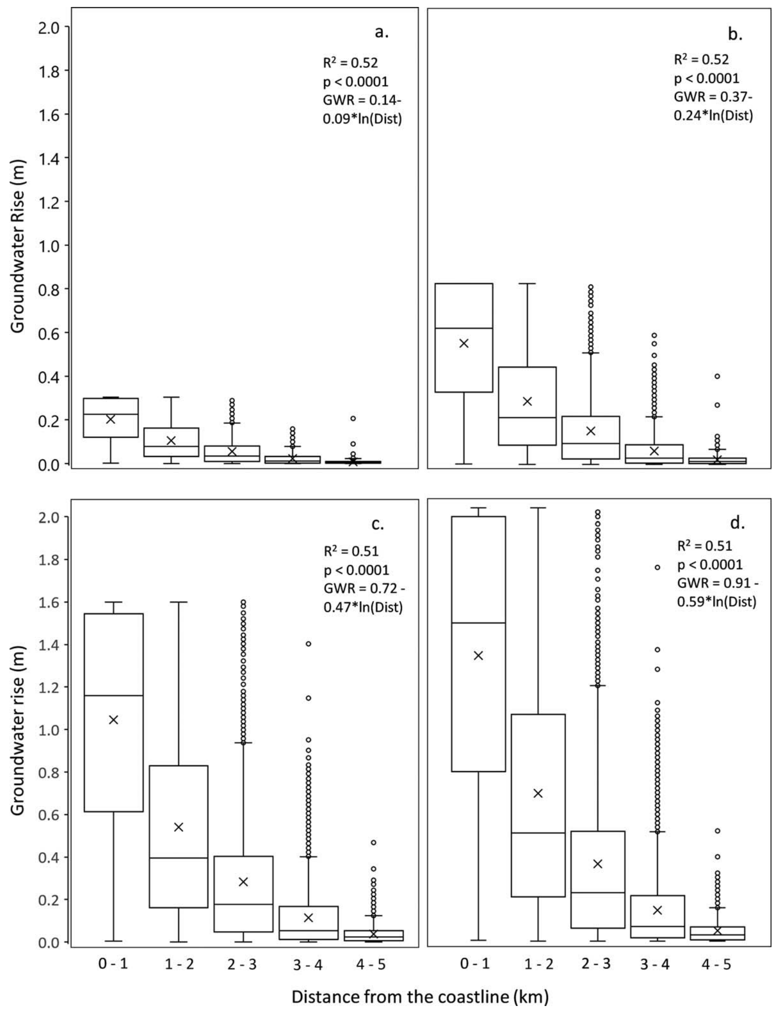

Figure 5. Simulated groundwater rise *vs*. distance from the coast for the four sea-level rise scenarios: (a) 0.3 m, (b) 0.8 m, (c) 1.6 m, and (d) 2 m. Each box shows the mean ($\bar{x}$), median, interquartile range, and outliers for each 1.0-km distance interval from the coast. The R^2 and *p*- values are from a linear fit of groundwater rise and the natural logarithm of the distance.

anthropogenic) increases from 0.2 m by mid-century to 0.4 m by the end of the century (Table 2). Palustrine deposits (freshwater wetlands) and alluvial deposits exhibit the lowest predicted mean groundwater rise.

Impacts of Rising Groundwater on Wetlands

Wetlands are areas where groundwater is near or above the ground surface and are, consequently, highly susceptible to changes in groundwater levels. The city of Portsmouth was

Table 2. *Summary of groundwater-rise statistics in the study area depositional environments at mid-century and end of century. The relative groundwater rise is the same for 0.8-m and 2-m sea-level rise.*

	Mid-Century (0.8 m SLR)			End of Century (2 m SLR)			Relative GW Rise
Depositional Environment (% of area within 4 km of the coast)	Mean GW Rise (m)	SD (m)	CV (%)	Mean GW Rise (m)	SD (m)	CV (%)	Mean GW Rise (% of SLR)
Marine (2)	0.67	0.19	28	1.62	0.46	28	81
Estuarine (13)	0.45	0.33	74	1.08	0.81	75	54
Anthropogenic (1)	0.37	0.24	65	0.90	0.59	65	45
Glaciomarine (53)	0.28	0.23	82	0.69	0.57	83	35
Glacial till (27)	0.26	0.25	97	0.63	0.62	99	32
Palustrine (4)	0.10	0.08	73	0.25	0.19	77	13
Alluvial (<1)	0.05	0.04	98	0.11	0.11	98	6

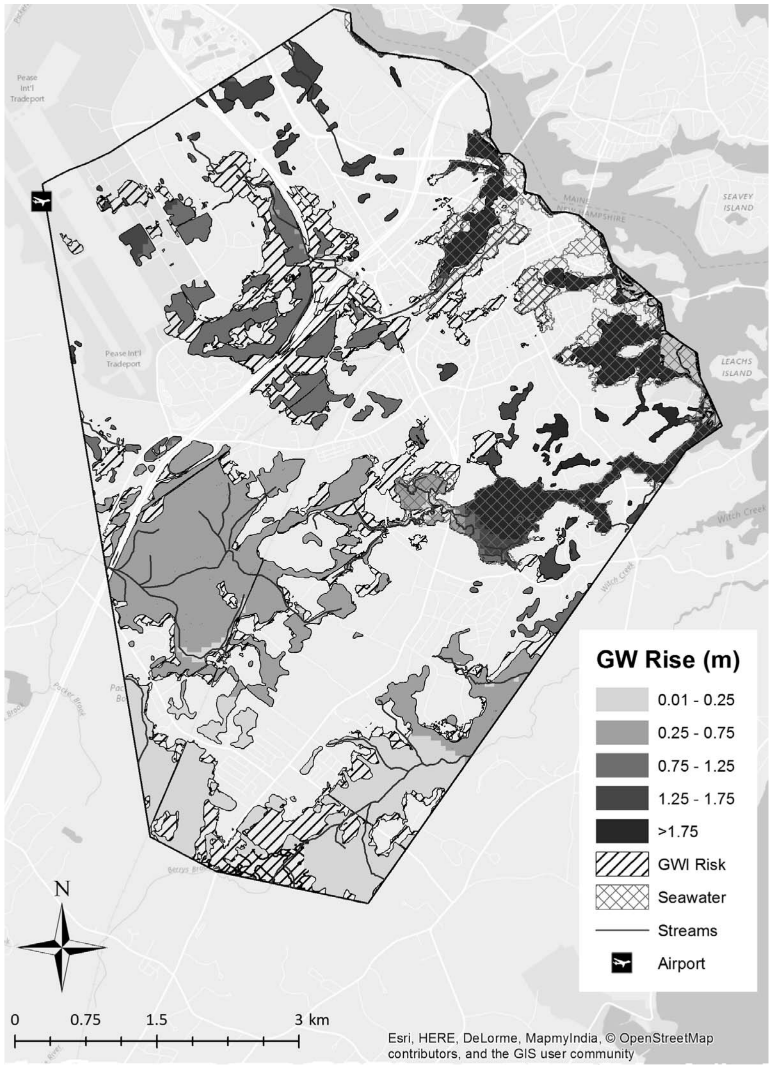

Figure 6. Simulated groundwater rise in Portsmouth's marine and freshwater wetlands caused by 2 m of sea-level rise. The shading indicates projected groundwater rise within existing wetlands defined by the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2001). Areas of GWI risk (groundwater table $<$ 1 m deep) are shown with black diagonal lines and projected MHHW seawater inundation is delineated with cross-hatch.

chosen as a focus area to examine potential impacts of rising groundwater on wetlands. It occupies an area of 42.3 km^2 in the GWRZ and has freshwater and coastal wetlands representative of the coastal region (Figure 6). Freshwater and coastal wetlands currently occupy 8.8 km^2 and 3.7 km^2, respectively, in Portsmouth and both are projected to be affected by SLR either from marine surface-water inundation, GWI, or both. Projected MHHW seawater inundation and GWI-risk areas, where the groundwater-table depth below land surface is less than 1 m, with 2-m SLR are presented in Figure 6. These vulnerable areas are typically low-lying lands located adjacent to existing wetlands. Freshwater wetland expansion from GWI is projected to begin slowly, with a 3% increase by 2030, a 10% increase by mid-century, and a 19 to 25% increase by the end of century.

The magnitude of SLR-induced groundwater rise, distance from the coast, land-surface topography, and wetland types are all important in determining the impact of SLR on wetlands. By the end of the century, land projected to be flooded by marine surface water is 1.9 km^2 or 4.5% of Portsmouth, with approximately 3.6% of the freshwater wetlands near the shoreline projected to be inundated with seawater. GWI will more than double the inundated land, affecting 2.2 km^2 (5.2%) of the city. Approximately 1.8 km^2 (82% of the GWI area) will occur inland of the projected MHHW tidal inundation zone. The remaining 0.4 km^2 (18% of the GWI area) will occur beneath areas inundated by marine waters as possible new groundwater seeps into coastal wetlands.

Groundwater rise *vs*. wetland type is presented in Figure 7. The projected mean groundwater rise is significantly different among all the wetland types analyzed except between the two

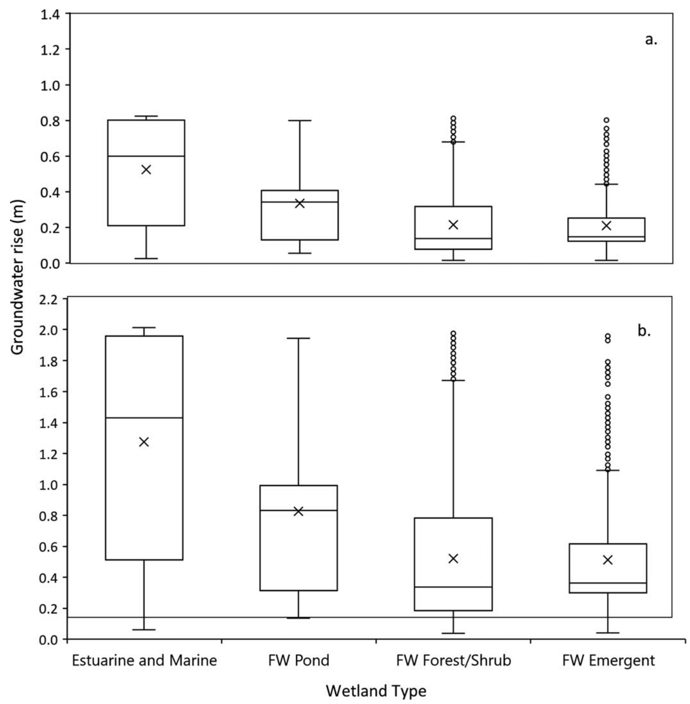

Figure 7. Simulated groundwater rise caused by (a) 0.8 m and (b) 2 m of sea-level rise *vs.* wetland type: estuarine and marine wetlands, freshwater emergent wetlands, freshwater forest/shrub wetlands, and freshwater ponds in Portsmouth.

dominant freshwater wetland types in the study area: forested/shrub and emergent wetlands. The marine and estuarine wetlands are projected to experience groundwater rise ranging from 0.2 to 0.8 m by mid-century and 0.5 to 2 m by end of century, with a mean relative groundwater rise approximately 65% of SLR. The projected mean groundwater rise for the forested/shrub and emergent wetlands is 0.2 m by mid-century and 0.5 m by the end of the century (26% of SLR). The forested/shrub wetland distribution is skewed toward greater groundwater rise and exhibits more variation than the emergent wetlands. Freshwater pond wetlands make up less than 1% of Portsmouth but have the highest projected mean groundwater rise of the freshwater wetlands, 0.3 m by mid-century and 0.8 m by the end of the century (41% of SLR).

DISCUSSION

Many coastal vulnerability studies, used for adaptation planning, have used SLR mapping to show areas that will be flooded in the future (Batouli and Mostafavi, 2016; Johnston, Slovinsky, and Yates, 2014; Wu, Najjar, and Siewert, 2009), and a few have included groundwater. Groundwater rise is predicted to be approximately 50% of SLR 3 km from the shoreline in New Haven, Connecticut (Bjerklie *et al.*, 2012) and 6 km from the shoreline on Cape Cod (Walter *et al.*, 2016). This study shows, in the northern part of the study area, that relative groundwater rise equal to 50% of SLR is projected to occur within 2 to 3 km of the coast. This is more than twice the distance inland than MHHW surface-water flooding projections (0.5 to 1 km) in this area. In addition, groundwater is predicted to rise in areas where no tidal inundation is anticipated, including the northwestern portion of the study area, because of tidal influences on the Great Bay and its contributing rivers as well as the tidally influenced section of the Merrimack River at the study area's southern boundary.

Many of the previous studies used MODFLOW for three-dimensional numerical modeling of the groundwater flow regime with SLR (Bjerklie *et al.*, 2012; Habel *et al.*, 2017; Masterson *et al.*, 2014; Masterson and Garabedian, 2007; Oude Essink, van Baaren, and B de Louw, 2010; Walter *et al.*, 2016), and others used a simpler approach to groundwater-elevation modeling assuming a linear groundwater response to SLR (Cooper, Zhang, and Zelch, 2015; Hoover *et al.*, 2017, Manda *et al.*, 2015; Rotzoll and Fletcher, 2013). Among the studies using MODFLOW, there are differences in approaches. In the study on Cape Cod, a migrating coastline and the freshwater/saltwater interface were both simulated (Walter *et al.*, 2016), whereas in Honolulu, a migrating coastline was simulated, but not the freshwater/saltwater interface (Habel *et al.*, 2017). In New Haven, neither a migrating coastline nor the freshwater/saltwater interface were simulated (Bjerklie *et al.*, 2012). Here, a similar approach to the New Haven study is used, representing SLR as a rising piezometric head at the coast without incorporating a migrating coastline. This results in a conservative estimate of the SLR-induced GWRZ. Freshwater/saltwater density effects at the coast were included as equivalent freshwater heads, but a moving freshwater/saltwater interface (salt transport) was not simulated. Recharge and drinking-water withdrawals were assumed to be stationary.

Modeling a migrating coastline with SLR will move the groundwater signal farther inland, especially in low, flat areas where surface tidal-water migration is projected to be large. Saltwater-intrusion modeling in the New Hampshire coastal region will improve estimates of groundwater rise in areas where the unconsolidated deposits are thick or where bedrock fractures allow for the landward migration of the freshwater/saltwater interface. Saltwater-intrusion modeling also provides useful information on changing salinity distributions in coastal groundwater. Seasonal and annual recharge rates will change with rising temperatures, affecting ET and changing precipitation patterns (Bjerklie *et al.*, 2012; Mack, 2009). In New Haven, a projected 12% increase in recharge was found to increase groundwater levels up to 0.3 m on top of SLR-induced groundwater rise (Bjerklie *et al.*, 2012). In coastal New Hampshire, simulated changes in seasonal precipitation and temperature patterns without SLR resulted in an earlier peak recharge in late winter with a longer low recharge period. This could lower base flows in streams and reduce freshwater discharge to the ocean. SLR coupled with decreased freshwater discharge to the sea could potentially result in saltwater intrusion into coastal aquifers (Mack, 2009).

SLR-induced groundwater rise is not spatially uniform. Although this study shows a significant negative trend between groundwater rise and distance from the coast (low p-value), only half of the variation around the mean is due to distance from the coast. This variation results in low precision when using distance from the coast to predict SLR-induced groundwater rise at specific locations, and mean values should be used with caution. Some generalizations can be made, however. Larger magnitudes of groundwater rise occur where groundwater is influenced by tidal waters on three sides and the unconsolidated deposits are the thickest (Figure 4), as in the northern part of the study area. In this area, the median relative groundwater rise is 62% of SLR (with an interquartile range of 42 to 82%) as opposed to areas with a linear coastline where the median relative groundwater rise is 19% of SLR (with an interquartile range of 11 to 40%). On Cape Cod, the median relative groundwater rise was found to range from 25 to 29% in the wider portion of the peninsula, increasing to 46 to 50% farther out on the peninsula where the land mass between the two tidal water bodies thins (Walter *et al.*, 2016). This suggests that the potential impact of SLR-induced groundwater rise may be greater on peninsulas and islands than on straight coastlines.

In contrast, small magnitudes of groundwater rise are found in all distance intervals including very near the coast, suggesting that distance from the coast, although important, is not the only factor dampening SLR-induced groundwater rise. Increased groundwater flow to surface-water discharge areas (palustrine and alluvial deposits) also dampens groundwater rise and may result in more stream base flow, freshwater wetland expansion, or greater water depth in wetlands. Net groundwater discharge to streams with 2 m of SLR increased from 73 to 83% of the total outflow, resulting in a 14% increase in net discharge to streams and a 32% decrease in net outflow to coastal discharge areas. This is consistent with the findings of others (Bjerklie *et al.*, 2012; Masterson and Garabedian, 2007; Walter *et al.*, 2016). On Cape Cod, the groundwater discharge to freshwater streams and wetlands increased from 49 to 61% of the total outflow with 1.8-m SLR (Walter *et al.*, 2016). In New Haven, groundwater rise caused by 0.9-m SLR was lower near a stream with a corresponding 34% increase in streamflow (Bjerklie *et al.*, 2012).

A relationship may exist between groundwater rise and depositional environments. Differences in the mean groundwater rise among the depositional environments investigated were found to be significant, except between palustrine and alluvial deposits, but the variation around the means is large. This limits the use of depositional environment as a precise predictor of SLR-induced groundwater rise, but some general observations can be made. The highest mean groundwater rise occurs in the beach and estuarine environments. The beach sediments consist of well-sorted beach sands with hydraulic conductivities that enable groundwater to respond uniformly to changes in sea level. The estuarine environment consists of a variety of organic and inorganic sediments with wide-ranging hydraulic conductivities and complex hydrology, including tidal inflows and outflows coupled with groundwater discharge. These characteristics most likely contribute to the large variability of projected groundwater rise. The next highest mean groundwater rise is predicted to occur in the anthropogenic sediments, with the highest groundwater rise occurring along roads crossing the estuarine and beach sediments.

The hydraulic properties and thickness of the geologic materials may affect the propagation of groundwater rise. In coastal New Hampshire, the unconsolidated deposits are on average 12 m thick, with the thickest deposits, 21 m, occurring in the northern part of the site. SLR-induced groundwater rise is projected to propagate the farthest inland in this area where the depositional environment is dominated by coarse-grained glaciomarine sediments. With hydraulic conductivities ranging from 0.1 to 61 m/d, the transmissivities range from 2.1 to 1300 m^2/d. Transmissivity was found to be a dominant factor in determining the GWRZ in the Dutch delta region of The Netherlands where groundwater rise is projected to propagate 10 km from the coast in thick (210 to 300 m) unconsolidated deposits (Oude Essink, van Baaren, and de Louw, 2010). More study is needed to quantify the relationship between aquifer transmissivity and SLR-induced groundwater rise.

Rising groundwater impacts on natural and built surface features depend on the vadose-zone thickness. Areas in the GWRZ where the current groundwater depth is less than the expected groundwater rise have the potential for GWI and performance reduction in subsurface or surface infrastructure. In coastal New Hampshire, the mean vadose-zone thickness is 3.6 m with an interquartile range of 0 to 4.9 m. In the GWRZ, the mean vadose-zone thickness is 2.8 m with an interquartile range from 0 to 4.1 m. On Cape Cod, the vadose zone is thick, approximately 11 m on average (Walter *et al.*, 2016), whereas on Maryland barrier islands the vadose zone is thin, typically less than 1 m (Masterson *et al.*, 2014). Rising groundwater can have an impact in places like the Waikiki area in Honolulu or Miami/Dade County, Florida, where the vadose zone is thin, and a high population density exists near the coast (Cooper *et al.*, 2013; Habel *et al.*, 2017). In Waikiki, 42% of the study area (13 km^2) has a vadose zone thickness less than 1.3 m. Habel *et al.* (2017) projected that 1.0 m of SLR will cause GWI in 23% of the study area within 2.5 km of the coast, possibly affecting 86% of the active cesspool sites (Habel *et al.*, 2017). An earlier study in urban Honolulu found that 1.0 m of SLR inundated 10% of a 1-km-wide coastal zone, with GWI contributing more than half (58%) of the total inundation (surface water and groundwater) (Rotzoll and Fletcher, 2013). By comparison, in Portsmouth, where the mean vadose-zone thickness is 2.8 m, GWI is projected to occur in 7% of the area within 3.5 km of the coast (25 km^2) with 2 m of SLR. Surface water and groundwater are projected to inundate approximately 9% of Portsmouth (42.3 km^2), with GWI contributing 48% of the total inundation.

The current study projects that freshwater wetlands will expand from rising groundwater and, in some cases, be flooded by seawater because of SLR. Studies that considered wetland impacts from SLR and SLR-induced groundwater rise (Cooper, Zhang, and Zelch, 2015; Masterson *et al.*, 2014) indicate that expansion as well as transitions between wetland types can be expected. Whereas not all wetlands in Portsmouth are expected to expand, all are expected to experience groundwater rise. Freshwater and saltwater wetland vegetation are sensitive to the duration of root-zone saturation, directly related to groundwater levels and vadose-zone thickness, influencing the ecohydrological zonation (Moffett *et al.*, 2012; Rheinhardt and Fraser, 2001). In addition, salinity changes can affect wetland ecosystem health. Masterson *et al.* (2014) found that the freshwater lens above the saltwater shrinks and the vadose zone thins with SLR-induced groundwater rise, increasing both the salinity and duration of root-zone saturation. These groundwater changes have serious consequences for ecosystem extent and function (Masterson *et al.,* 2014). Overall, changes in wetland structure will likely change their function in flood control, nutrient attenuation, biodiversity, fisheries production, and recreation (Barbier *et al.,* 2011; Birol *et al.,* 2009; Linhoss *et al.,* 2015; Walters and Babbar-Sebens, 2016). Wetland expansion also has implications for wetlands-protection policy, surface and groundwater quality, and infrastructure. Regional models such as the one used in the study are not adequate to investigate detailed changes in specific wetland hydrology. They can, however, identify potentially vulnerable freshwater and marine wetlands for more detailed study.

CONCLUSIONS

This study combined groundwater modeling, marine surface-water mapping, groundwater and surface-water observations, LIDAR DEMs, and SLR scenarios to quantify SLR-induced groundwater rise in coastal New Hampshire. The modeling demonstrates that groundwater rise solely due to increased piezometric head at the coast will extend more than three to four times farther inland than projected tidal (MHHW) impacts. In much of the area within 2 km of the coast, SLR-induced groundwater rise will be at least half of the SLR. The ground-surface inundation from SLR-induced groundwater rise will double the projected inundation areas from tidal surface water alone.

The groundwater-rise magnitude and areal extent are influenced by the geometry of the coastline, distance from the coast, geologic depositional environments, and the regional stream network. Groundwater underlying peninsulas, islands, and coastlines with extensive inlets will be the most affected by SLR. Marine and estuarine depositional environments are projected to have the highest groundwater rise, and anthropogenic fill deposits are also at risk. In contrast, groundwater rise near streams is dampened where increased gradients between groundwater and surface water result in more groundwater discharge to streams.

SLR-induced groundwater rise will increase the surface area of some coastal and freshwater wetlands and increase the water depth within existing wetlands in the GWRZ. Some freshwater wetlands will be inundated with rising marine surface water, whereas others, farther inland, may expand. All wetlands in Portsmouth are in the GWRZ and are projected to experience groundwater rise; however, not all will expand. Wetland expansion will occur where adjacent lands have vadose-zone thicknesses less than the magnitude of projected groundwater rise. Information on groundwater rise can be used by wetland protection professionals and land-use planners to establish new wetland buffer zones, possibly elevation-based, to accommodate future changes in wetland area and location.

In areas within the GWRZ where the current groundwater depth is within the range of projected groundwater rise, underground assets will be vulnerable to damage or reduced performance. Coastal-road pavements will weaken when rising groundwater moves into the supporting base layers (Knott *et al.*, 2017). On-site wastewater treatment system performance will be reduced when rising groundwater intersects the treatment trenches (Manda *et al.*, 2015). Basements of historic structures may flood regularly with groundwater, compromising their structural integrity. Groundwater infiltration of wastewater collection systems with rising groundwater can damage or reduce the efficiency of wastewater treatment systems (Flood and Cahoon, 2011). In addition, long-term groundwater rise should be considered when remediating contaminated sites. The methodology and insights presented in this study can be used by land-use managers, transportation departments, and environmental protection professionals to identify coastal infrastructure and natural resources vulnerable from SLR-induced groundwater rise for detailed adaptation planning.

Future work may include incorporating a migrating coastline with SLR, modeling saltwater intrusion, and investigating the combined effects of SLR and seasonal fluctuations of groundwater levels. Climate change is projected to produce long-term changes in temperature and precipitation, both important factors affecting groundwater recharge. A study of the combined effects of SLR and long-term changes in recharge and groundwater withdrawal rates should also be investigated to improve the accuracy of future groundwater-level predictions.

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