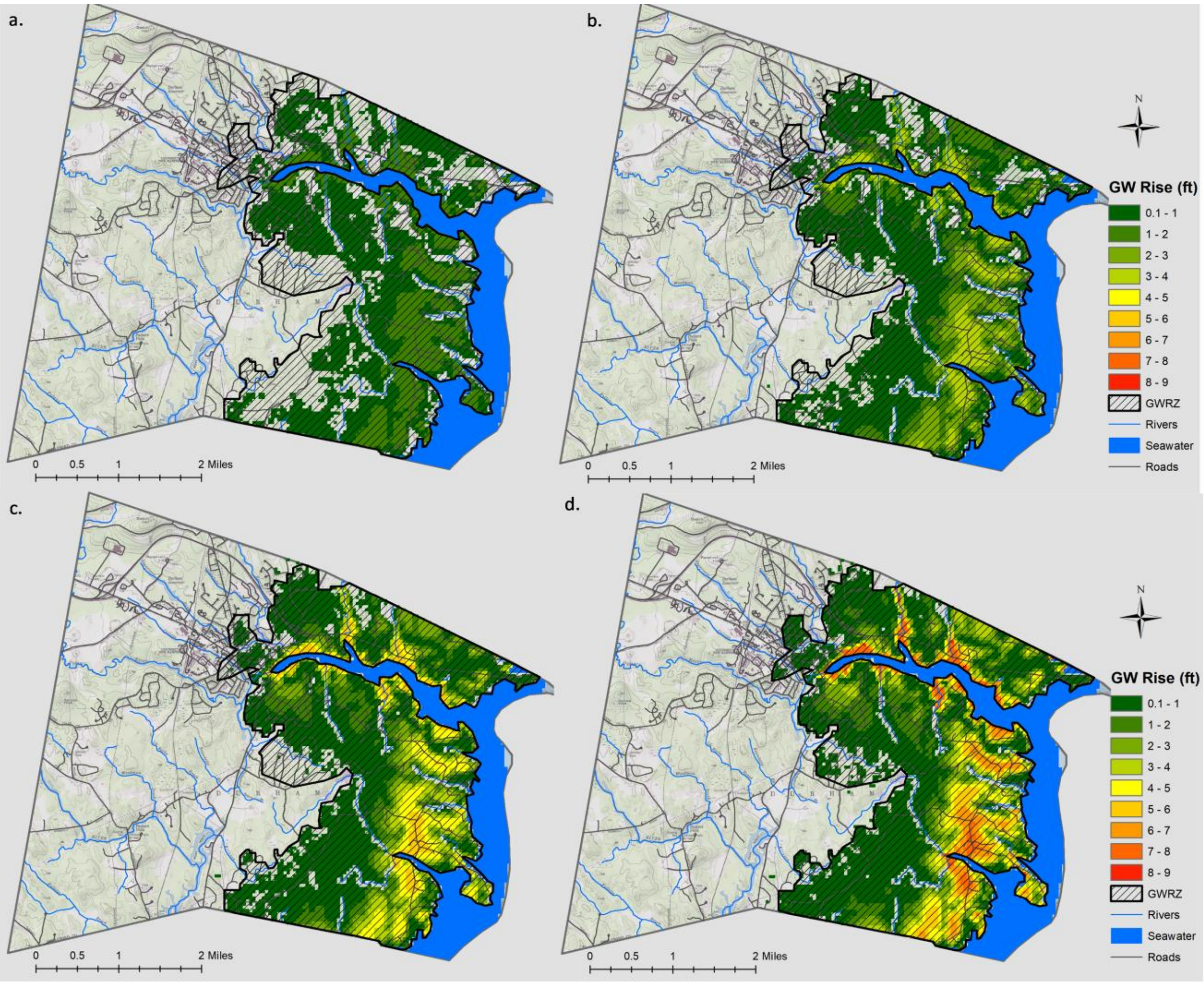
Sea Level Rise Impacts on Groundwater Levels and Water Quality: A Vulnerability and Planning Study in Durham, New Hampshire

FINAL TECHNICAL REPORT

February 2022



Prepared by JFK Environmental LLC

for the

Town of Durham

Glossary

Bedrock – solid rock underlying loose deposits such as sand, gravel, silt and clay

Cubic Feet per Second (CFS) – a measure of flow; commonly used to describe the flow of water in a river

Confined aquifer – an aquifer below the land surface that is saturated with water that is under pressure due to the existence of impermeable layers of geologic material above and below the aquifer.

Glacial till – unsorted glacial sediment

Hydraulic conductivity (K) – a property of geologic materials that describes the ease with which a fluid (usually water) can move through pore spaces or fractures.

LiDAR – a remote sensing method that uses light in the form of a pulsed laser to measure variable distances (ranges) to the Earth.

Overburden – unconsolidated deposits such as sand, sand and gravel, silt, or clay overlying bedrock.

Piezometric head (head) – a specific measurement of liquid pressure above a vertical datum. It can be determined by measuring the height of the water surface in a standpipe piezometer or well relative to a common datum.

Quasi-steady state – a situation that is changing slowly enough that it can be considered to be constant

Recharge - the process by which water is added to an aquifer. It may occur naturally by the percolation (infiltration) of surface water, precipitation, or snowmelt from the ground surface through the unsaturated earth materials to a depth where the earth materials are saturated with water (the water table).

Relative Sea Level Rise (RSLR) – how the height of the ocean rises or falls relative to the land at a particular location

Stratified drift – predominantly unconsolidated, sorted sediment composed of layers of sand, gravel, silt, or clay deposited by meltwaters of glaciers

Stream order – the level of branching in a stream

Stream stage – the average water level of a stream relative to a common datum (in this case, NAVD88)

Unconfined aquifer (water-table aquifer) – an aquifer whose upper water surface (water table) is at atmospheric pressure and thus can rise and fall.

Abbreviations

cfs – Cubic Feet per Second

ft – Feet

in – Inches

K – Hydraulic conductivity

LiDAR – Light Detection and Ranging

MSL – Mean Sea Level

NAVD88 – the North American Vertical Datum of 1988 is the vertical datum that was established as vertical control for surveying in the United States.

OWTS – Onsite Wastewater Treatment Systems

RSLR – Relative Sea Level Rise

Introduction

Coastal flooding is occurring in New Hampshire (NH) as sea levels rise and storms become more intense. Relative sea level (RSL) in the area has risen 7.5 to 8.0 inches from 1912-2018 and is projected to continue to rise with consequences for coastal properties, infrastructure, human health, and natural resources [*Wake et al.,* 2019]. While surface-water flooding is dramatic and impactful, a more insidious process is also happening with relative sea level rise (RSLR). This is the increase in groundwater tables in areas where the groundwater is not confined. Rising groundwater can lead to inland flooding hazards (groundwater inundation in low-lying areas), the weakening of coastal-road pavements, early deterioration or the failure of underground infrastructure, foundation weakening, changes in the hydrology of natural resources, and harm to both groundwater and surface-water quality [*Knott et al.,* 2017; *Knott et al.,* 2019; *Wake et al.*, 2019; *Befus et al.,* 2020; *Habel et al.,* 2020].

The University of New Hampshire, the NH Department of Environmental Services (NHDES), and the NH Coastal Flood Risk Science and Technical Advisory Panel (*NH STAP*) produced the NH Coastal Flood Risk Summary Part I: Science [*Wake et al.*, 2019] and Part II: Guidance [*NH STAP*, 2020] with funding from the National Oceanic and Atmospheric Administration (NOAA) to help decision makers develop adaptation strategies for resilience in NH's 17 coastal communities[1] to face the rapidly accelerating effects of climate change. This study uses the RSLR projections developed in the NH Seacoast in Part I: Science as the coastal boundary conditions for modeling groundwater rise and saltwater intrusion in the Town of Durham, NH over the next century. The goal is to identify, with the Strafford Regional Planning Commission (SRPC), coastal infrastructure, on-site waste treatment systems (OWTSs), hazardous waste disposal areas, stormwater systems, and other assets that may be vulnerable from slow but continuously rising groundwater caused by RSLR. The RSLR scenarios used in this study correspond with Curve #5 and Curve #7 (**Figure 1**). Scenario #5 is recommended for projects that have a high tolerance for flood risk and Scenario #7 is recommended for projects that have a low tolerance for flood risk [*NH STAP*, 2020].

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[1] Dover, Durham, Exeter, Greenland, Hampton, Hampton Falls, Madbury, Newfields, Newington, Newmarket, New Castle, North Hampton, Portsmouth, Rollinsford, Rye, Seabrook, and Stratham.

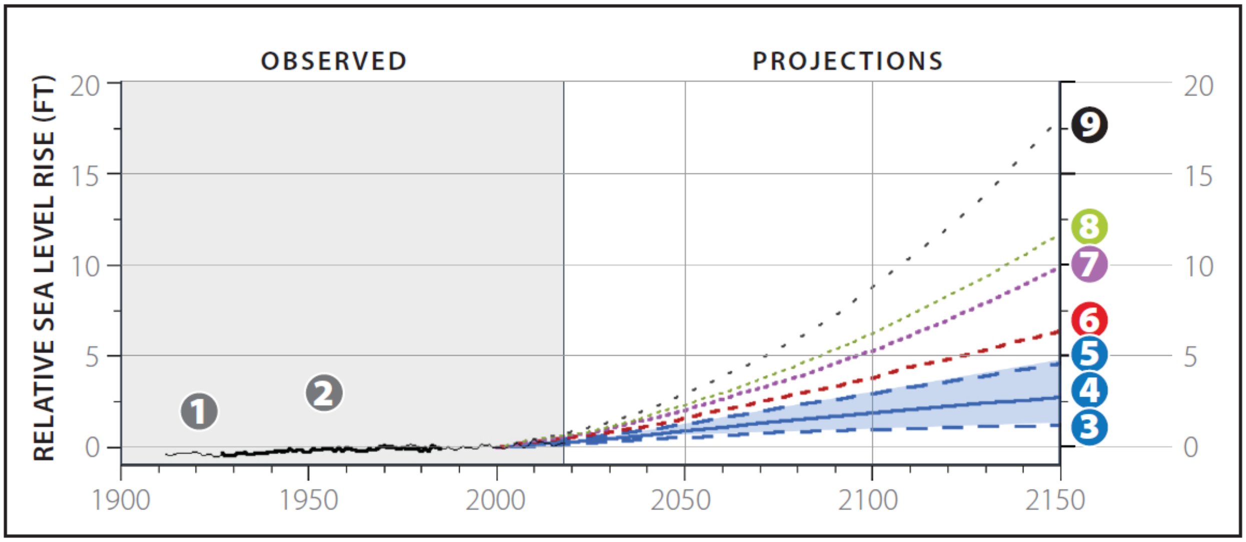

Figure 1. Global mean sea-level-rise scenarios relative to 2000 from the NH Coastal Risk Summary Part 1: Science; 1. Historical data for Portland, ME, 2. Historical data for Seavey Island, ME, 3. Lower end of "likely range", 4. Central estimate, 5. Upper end of "likely range", 6. 1-in-20 chance estimate, 1-in-100 chance estimate, 1-in-200 chance estimate, 1-in-1000 chance estimate. [*Wake et al.*, 2019]

Hydrogeology

The Seacoast Region of NH is characterized by thin glacial and marine sediments and a topography that generally follows the bedrock surface [*Mack*, 2009]. The land-surface altitude in Durham ranges from approximately 12 feet above the North American Vertical Datum of 1988 (NAVD88) at the mouth of the Oyster River to approximately 291 feet at Beech Hill along the northern border between Durham and Madbury [*NH Coastal Lidar*, 2011]. The surficial geology consists of fine-grained till and marine silts and clays and coarse-grained stratified drift consisting of sands and gravels in the unconsolidated deposits overlying the bedrock surface. The underlying bedrock consists of crystalline metamorphic rock of sedimentary origin and igneous bedrock [*Mack*, 2009].

The surficial deposits, mapped by [*Moore*, 1990; *Stekl and Flanagan*, 1992] are typically less than 40 feet thick in the region with deposits of up to 100 feet thick occurring in the Newmarket Plains Aquifer located in the southwestern section of Durham along the boundaries with Newmarket and Lee (NH Geological Survey (NHGS)). A stratified drift aquifer in the western part of Durham, the Spruce Hole Aquifer, is approximately 80 feet deep. The Spruce Hole and the Newmarket Plains Aquifers consist of the most permeable geologic materials in the area with hydraulic conductivities ranging from 50 to more than 200 feet/day. In contrast, the hydraulic conductivities of the fine-grained sands range from 2 to 15 feet/day [*Ayotte and Toppin*, 1995; *Medalie and Moore*, 1995; *Mack*, 2009]. Another permeable stratified drift aquifer is located along the coast in northeastern Durham but is not used for public water supply.

Two bedrock aquifers are utilized for public water supplies. One is in south-central Durham along the border with Newmarket and the other is slightly north of the Oyster River. The coarse-grained stratified drift aquifers and the bedrock public water supplies are shown in **Figure 2**

[*Town of Durham Master Plan*, 2015]. In addition to public water supply wells, there are many domestic wells in Durham, most of which have been drilled deep into bedrock [*Mack*, 2009]. Slightly less than one-half of the precipitation, averaging 40-45 inches historically through 2016 in NH, recharges the aquifer with the rest being lost to evapotranspiration and runoff *[Mack*, 2009*; Runkle et al.*, 2017*; Bjerklie & Sturtevant*, 2018]. Recharge is projected to increase in coastal NH with climate change; however, this increasing trend may be countered by projected increases in population and impervious surface area from development in the area that would reduce recharge [*Bjerklie & Sturtevant*, 2018].

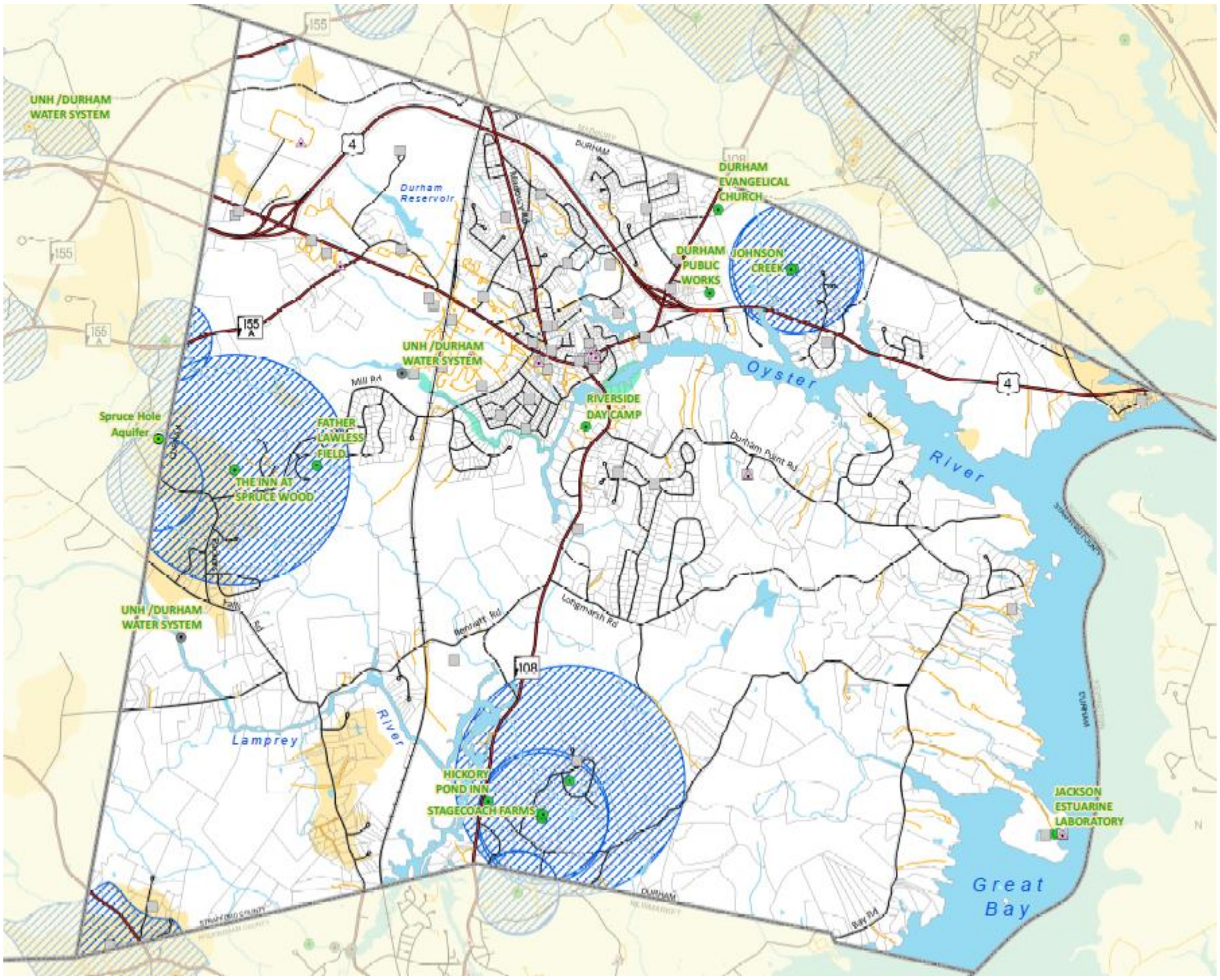

Figure 2. Aquifers and Public Water Supplies in Durham, NH. The blue hatched areas are wellhead protection areas[2], and the stratified drift aquifers are delineated by the tan shading. [*Town of Durham Master Plan*, 2015]

Groundwater typically flows from areas of high groundwater altitude toward natural discharge areas in the Oyster River and Great Bay [*Mack*, 2009]. Groundwater piezometric heads (heads) were compiled from 1960 through 2018 from several sources including the NH NHDES and the

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[2] Wellhead protection areas are considered sensitive data and should not be made publicly available.

New Hampshire Geological Survey (NHGS). Average groundwater heads measured in 98 wells, installed in the unconsolidated deposits, and 127 wells, installed the bedrock, were used to construct groundwater contour maps of the existing groundwater-flow regime and to identify target wells for use in model calibration.

Groundwater heads were obtained from GEOLOGs (NHGS) and the water well inventory (NHDES). GEOLOGs are a compilation of boring and well information from NHDES, NH Department of Transportation (NHDOT) and the US Geological Survey (USGS) [*Barker*, 2016]. The water well inventory is a database of boring and well information compiled by the NHDES from wells installed for domestic and industrial water supply, exploration, and testing. Groundwater levels in this dataset were recorded by drillers during installation and are the most uncertain (NHDES). The piezometric head along the shoreline of Great Bay was assumed to be mean sea level (MSL) as recorded at the NOAA tidal gauge at Seavey Island, ME and converted to NAVD88 [*NOAA*, 2021].

Modeling Process

USGS MODFLOW2000 [*Harbaugh et al.,* 2000] and the variable-density flow package SEAWAT2000 [*Langevin et al.,* 2007] were used to model the effects of sea-level rise on groundwater levels and saltwater intrusion in the Town of Durham. The model area includes all of Durham and parts of the adjacent communities Dover, Madbury, Barrington, Nottingham, Lee, Epping, and Newmarket (**Figure 3**).

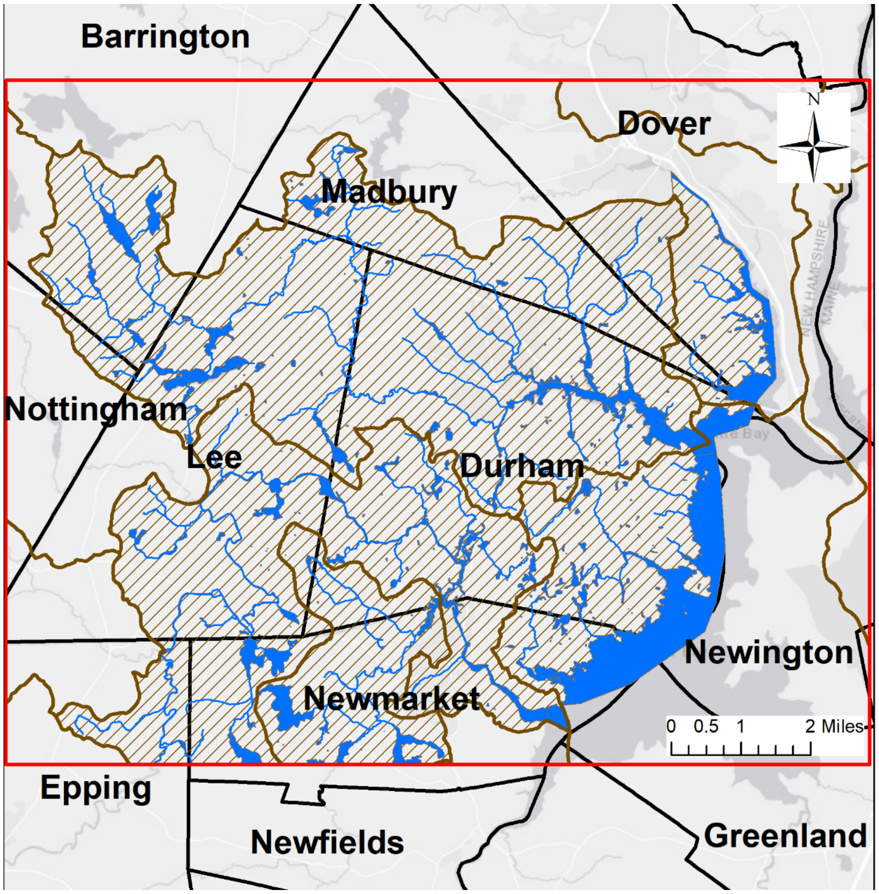


Figure 3. Study area of the groundwater modeling study in Durham, NH. The entire model domain is shown in red, but the active model cells are within the brown hatched areas defined by drainage divides. The surface water is shown in blue. [*ArcGIS*, 2020]

The model grid consists of uniformly spaced cells that are 200 feet x 200 feet. The grid consists of 260 rows and 330 columns with 22 layers that extend from the water table to a uniform depth of 1100 feet below current MSL. The layer thicknesses are shown in **Table 1** and vary from 15 to 100 feet thick. Many layers are needed to simulate the location of the freshwater/saltwater interface. Typically, the bottom of the model is defined by the bedrock surface, but in this area of NH the bedrock surface is shallow, less than 100 feet below ground surface within the study area, and many of the residential and public water-supply wells remove water from the fractured bedrock. Unconsolidated deposits were simulated in layers 1 through 6 to a depth of 110 feet below MSL and bedrock was simulated in layers 7 through 22 down to a depth of 1100 feet below MSL. This depth was chosen to include water supply wells in the area, the maximum depth of which is approximately 1100 feet below mean sea level in Lee, NH (NHDES).

Table 1. Layer thicknesses in the model (OVB = overburden; BDR = bedrock; Lidar = ground surface elevation relative to NAVD88)

Layer	Layer thickness (ft)	Top elevation (ft)	Layer bottom (ft)	Geology
1	Variable	Lidar	-15	OVB
2	15	-15	-30	OVB
3	20	-30	-50	OVB
4	20	-50	-70	OVB
5	20	-70	-90	OVB
6	20	-90	-110	OVB
7	40	-110	-150	BDR
8	50	-150	-200	BDR
9	50	-200	-250	BDR
10	50	-250	-300	BDR
11	50	-300	-350	BDR
12	50	-350	-400	BDR
13	50	-400	-450	BDR
14	50	-450	-500	BDR
15	50	-500	-550	BDR
16	50	-550	-600	BDR
17	50	-600	-650	BDR
18	50	-650	-700	BDR
19	100	-700	-800	BDR
20	100	-800	-900	BDR
21	100	-900	-1000	BDR
22	100	-1000	-1100	BDR

Elevation is relative to NAVD88

The freshwater aquifer receives water from aquifer recharge, 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]. The infiltration rate depends on precipitation, the permeability of the soil, and other factors such as storm intensity, storm duration, and snow cover. Areal recharge rates used in the groundwater model were calculated by the NHGS using the Dripps model. This is a soil-water model that accounts for interception, evapotranspiration, partitioning of run-off, soil infiltration or snow-pack storage, and soil-moisture partitioning [*Dripps and Bradbury,* 2007]. It is based on the water budget equation and compares favorably with standard base-flow separation techniques (Barker, personal communication).

A map of the areal distribution of recharge within the model domain is shown in **Figure 4**. Infiltration from the surface-water such as Oyster River and Great Bay is simulated as head-dependent boundary conditions and not aquifer recharge, hence the low values for recharge in these areas.

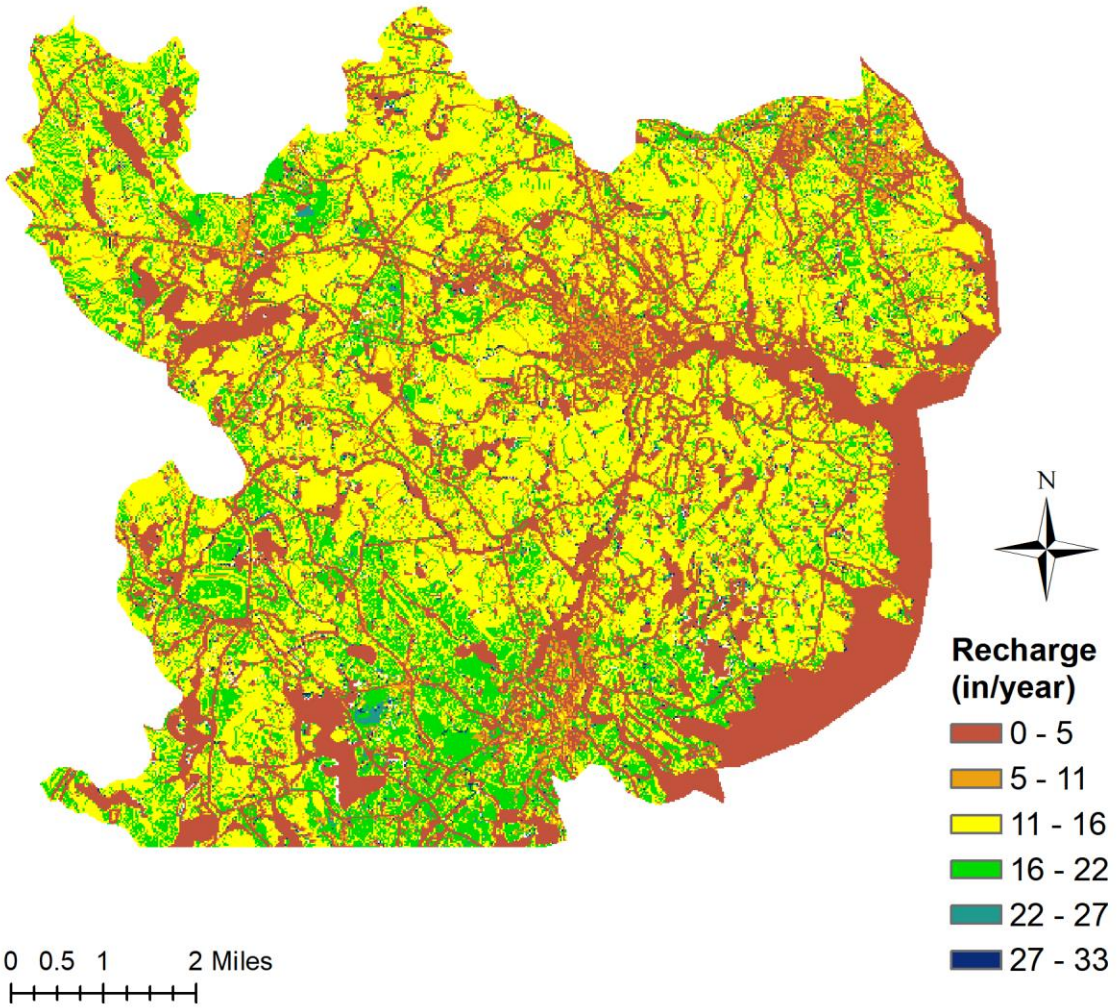


Figure 4. The distribution of aquifer recharge within the model domain.

The lateral boundaries of the model are the drainage divides to the North, South, and West and discharge areas along Great Bay and the Little Bay to the East (**Figure 3**). The rivers, constant head, and specified head boundaries of the model in layer 1 are shown in **Figure 5**.

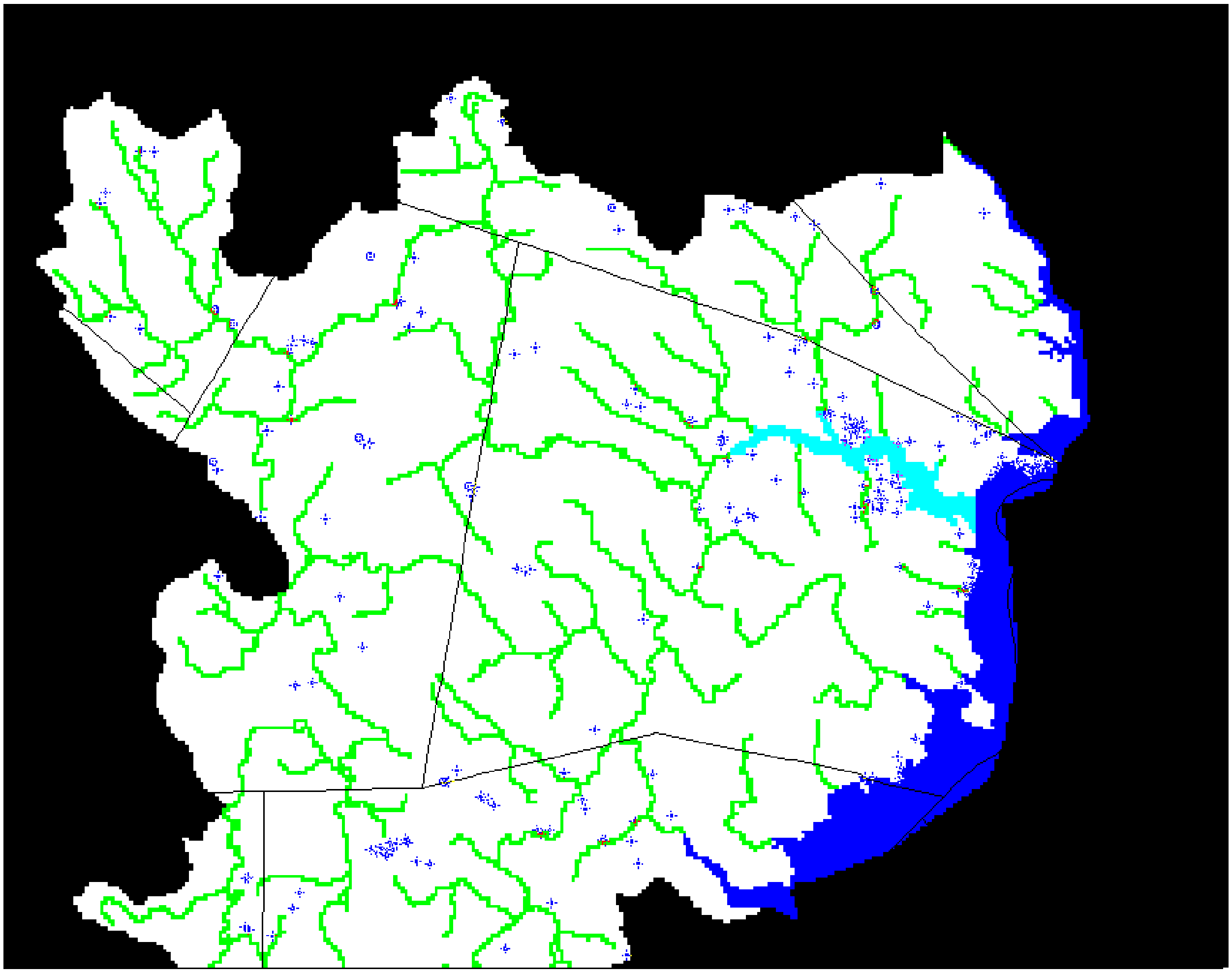


Figure 5. Boundary conditions in the model including rivers (green), constant head boundaries (blue), and general head boundaries (cyan). The targets for model calibration are also shown as blue crosses on this map.

The top two layers are bounded to the east by constant head/concentration cells down to depth of 15 feet. The constant head in Great Bay and Little Bay (MSL) in the near term is simulated at 0.19 feet below NAVD88. Head-dependent boundaries were assigned to cells in layers 3 to 22 to allow for fresh groundwater discharge to the sea. All coastal boundary cells were assigned an initial relative concentration of 1 for saltwater (1= saltwater and 0 = freshwater). The concentration in the constant-head cells remains constant but the concentration in the head-dependent cells can vary. Cells at the outer edge of the model are assigned constant head/concentration for all 22 layers. This is a requirement of SEAWAT to ensure that enough saltwater is available to meet the simulation requirements [*Langevin et al.*, 2007]. Rivers, streams, and wetlands are also simulated as head-dependent flux boundaries in layer 1 of the model using the river package in MODFLOW [*Harbaugh et al.*, 2000]. Rivers and streams in the model area were digitized into reaches using the National Hydrologic Dataset and high-resolution aerial photographs in GIS [*NH Hydrography*, 2006; *Aerial Photos*, 2011]. Stream stage at the beginning and end of each reach was determined from bare earth LiDAR data and linearly interpolated between points [*NH Coastal Lidar*, 2011]. The river properties include the hydraulic conductivity and thickness of the stream bed and the average stream width and depth. These properties were varied spatially in the model according to stream order based on information from Hergott (2012), Wilson et al. (2014), and Truslow (2009) (**Table 2**).

Table 2. Stream properties used in the model: Stream order is the level of branching in a stream from small (1) to large (6), width is the average stream width, depth is the average stream depth, K is the hydraulic conductivity of the streambed, and bottom thickness is the thickness of the stream bed.

Stream Order	Width (ft)	Depth (ft)	K (ft/day)	Bottom Thickness (ft)
1	8	1	2	1
2	10	1	2	1
3	29	1.7	0.6	1.5
4	36	1.8	0.6	1.5
5	40	1.8	0.6	1.5
6	40	1.8	0.6	1.5

The hydrologic properties of the geologic materials include hydraulic conductivity, saturated thickness, storage coefficient, specific yield, and porosity. These were initially estimated using typical values based on surficial and bedrock geology [*Walton*, 1970; *Lyons et al.*, 1998; *NH State Geologist*, 2004; *Mack*, 2009] and then adjusted during the calibration process. Aquifer properties were assigned to 23 zones representing unconsolidated deposits and bedrock formations. The unconsolidated materials are represented by 12 zones consisting of deposits from estuarine (salt marsh) to glacial till (**Figure 6**). Bedrock zones represent 11 geologic formations and bedrock lineaments (indicative of fracturing) within these formations [*Lyons et al.*, 1998; *Mack*, 2009] (**Figure 7**). **Tables 3 and 4** list the property values used in the calibrated model by zone for the unconsolidated deposits and the bedrock, respectively.

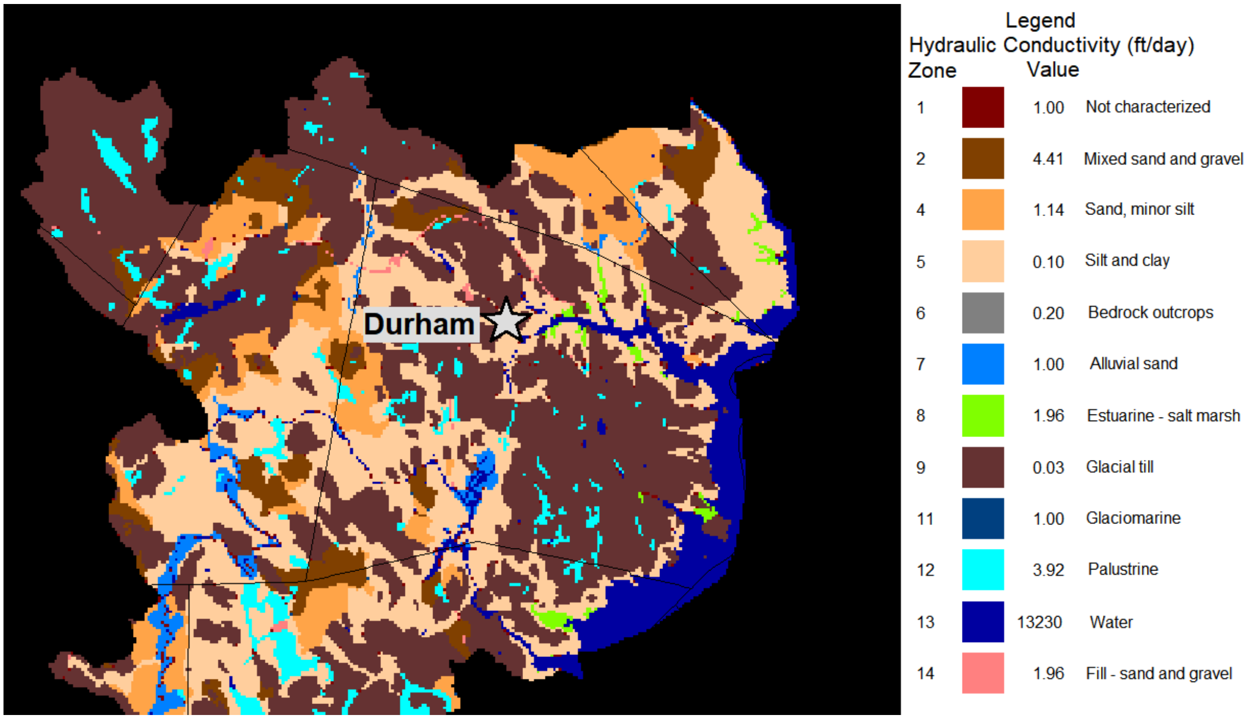


Figure 6. Surficial geology and hydraulic conductivity in the overburden [*NH State Geologist,* 2004]

Table 3. Unconsolidated geologic material properties organized by zones in the model

Property Zones in Model		Hydraulic Conductivity (ft/day)			Storage/Porosity		
Zone	Description	K_x	K_y	K_z	Specific Storage	Specific Yield	Porosity
1	Not categorized	1.00	1.00	0.10	-	0.25	0.35
2	Mixed sand and gravel	4.41	4.41	0.50	-	0.25	0.35
4	Sand, minor silt	1.14	1.14	0.02	-	0.30	0.40
5	Silt and clay	0.10	0.10	0.01	-	0.20	0.45
6	Bedrock outcrops	0.20	0.20	0.20	1.00E-05	-	0.10
7	Alluvial sand	1.00	1.00	0.01	-	0.30	0.40
8	Estuarine - salt marsh	1.96	1.96	0.50	-	0.30	0.35
9	Glacial till	0.03	0.03	0.03	-	0.20	0.20
11	Glaciomarine - undifferentiated	1.00	1.00	0.01	-	0.30	0.40
12	Palustrine	3.92	3.92	0.75	-	0.30	0.35
13	Water	13230	13230	5000	-	0.30	0.35
14	Fill - sand and gravel	1.96	1.96	0.50	-	0.25	0.35

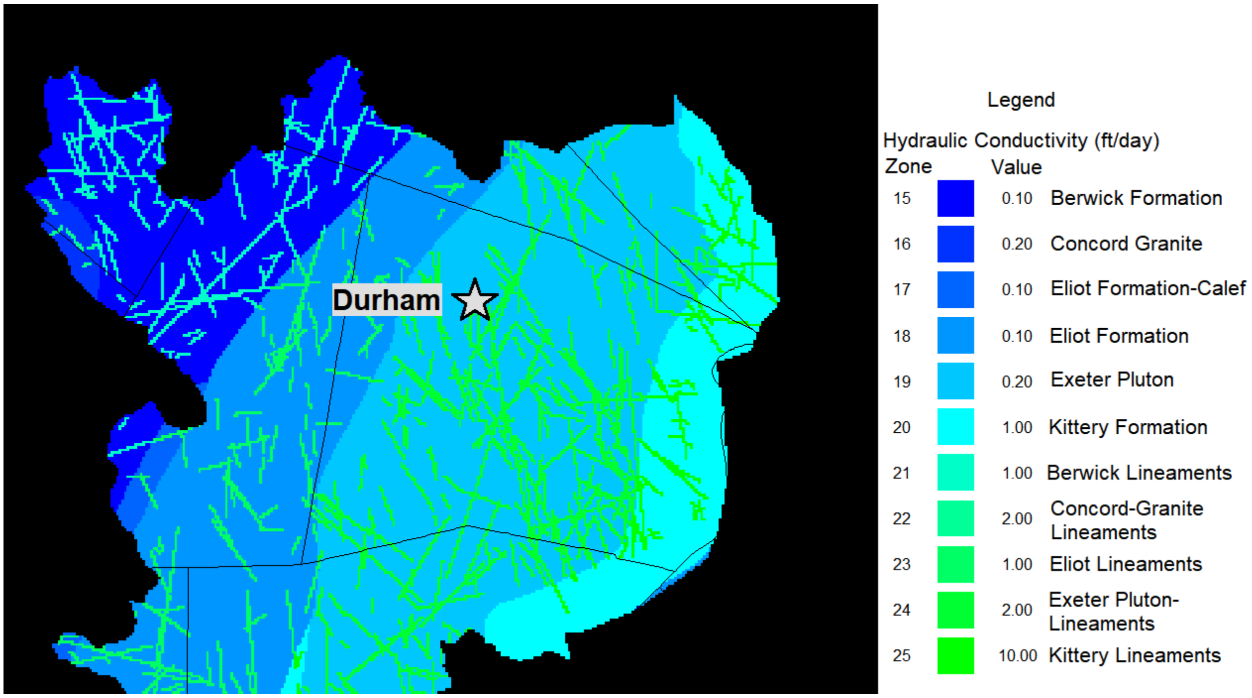


Figure 7. Bedrock geology zones with lineaments and hydraulic conductivity in the bedrock. [*Lyons et al.*, 1998]

Table 4. Bedrock geologic material properties organized by zones in the model

Property Zones in Model		Hydraulic Conductivity (ft/day)			Storage/Porosity	
Zone	Description	K_x	K_y	K_z	Specific Storage	Porosity
15	Berwick Formation	0.1	0.1	0.1	1.00E-05	0.1
16	Concord Granite	0.2	0.2	0.2	1.00E-05	0.1
17	Eliot Formation - Calef	0.1	0.1	0.1	1.00E-05	0.1
18	Eliot Formation	0.1	0.1	0.1	1.00E-05	0.1
19	Exeter Pluton	0.2	0.2	0.2	1.00E-05	0.1
20	Kittery Formation	1.0	1.0	1.0	1.00E-05	0.1
21	Berwick Lineaments	1.0	1.0	1.0	1.00E-03	0.2
22	Concord-Granite-Lineaments	2.0	2.0	2.0	1.00E-03	0.2
23	Eliot Formation-Lineaments	1.0	1.0	1.0	1.00E-03	0.2
24	Exeter Pluton-Lineaments	2.0	2.0	2.0	1.00E-03	0.2
25	Kittery Formation-Lineaments	10.0	10.0	10.0	1.00E-03	0.2

Public water supply information including well locations, depths and pumping rates were provided by NHDES. Pumping rates were held constant during the entire simulation and the withdrawal volumes were distributed over all screened (overburden) or open borehole (bedrock) layers.

Model Calibration

The steady-state flow model was calibrated to historical data. The model was calibrated using the automated calibration procedure from Groundwater Vistas [*Rumbaugh and Rumbaugh*, 2017] to groundwater levels measured in overburden and bedrock wells in the area over the period from 1960 to 2018. This calibration procedure uses inverse methods to determine the model parameters that best fit a set of target observations and employs Marquardt's modification to the Gauss-Newton nonlinear least-squares parameter estimation technique [*Levenberg,* 1944; *Marquardt*, 1963]. The model was calibrated to 366 target wells located in all 22 layers of which 250 wells, or 68%, are in the unconsolidated deposits or weathered bedrock simulated in layers 1 through 6 of the model. This is primarily where the groundwater table resides near the coast. Average piezometric heads from each target well were verified with the overburden or bedrock contour maps generated from the observations and assigned to the model layer in which the bottom of the well is located. The following statistics were generated for the model. The residual mean is -0.14 feet, the negative indicating that the computed values are slightly higher than the observed values. The absolute residual mean is 4.19 feet and the residual standard deviation of the fit (or the overall spread of the residuals) is 5.10 feet or 1.7 percent of the range of observations. Less than 10 percent is considered a good calibration [*Rumbaugh and Rumbaugh*, 2017].

Plots of the observations and the residuals versus the simulated values are presented in **Figure 8**. A random distribution of residuals around zero indicates that systematic errors, i.e., the simulations trending high or low, are minimal.

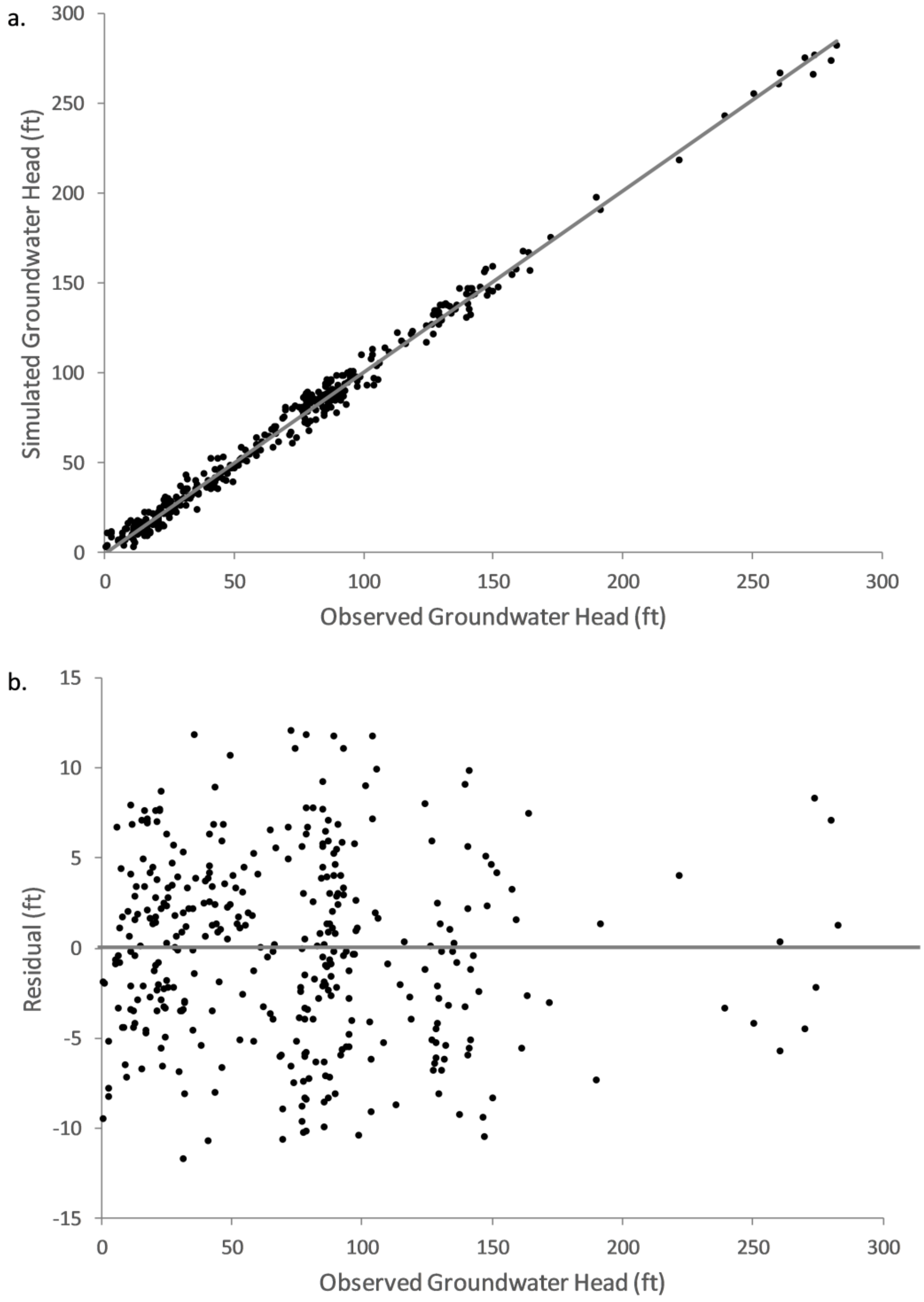
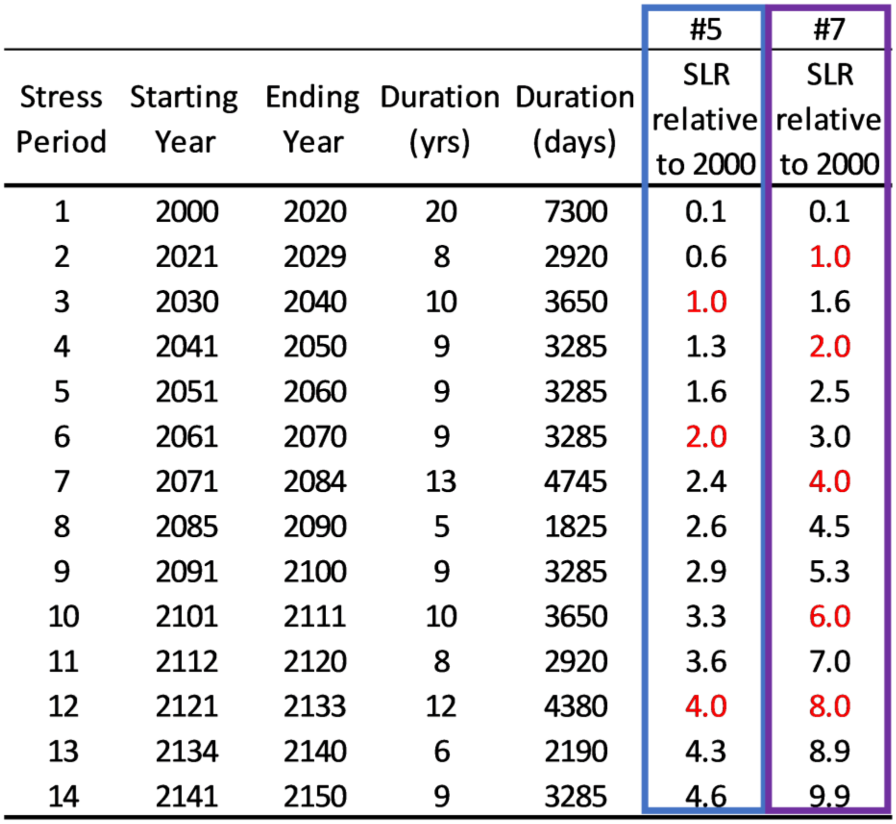


Figure 8. a) Groundwater heads in observation wells from all 22 layers in the modeled area versus simulated groundwater heads, and b) groundwater-head residuals (observed minus simulated heads) versus observed groundwater heads.

Sea-Level Rise Scenarios and Model Simulations

Following calibration, the model was run to quasi-steady state with SEAWAT for   to establish saltwater/freshwater equilibrium in the geologic materials. The very long-time scales associated with salt-water intrusion necessitates the initial quasi-steady state run. The concentration output file at the end of the quasi-steady state run was used as the starting concentrations in the transient simulation. The transient simulation was run using the stress periods and the corresponding RSLR presented in **Table 5** for the periods from 2000 to the year 2150. The current MSL used is 0.19 feet below NAVD88 measured at the Seavey Island, ME tidal gauge in the year 2000 [*NOAA*, 2021]. Coastal NH sea levels were calculated by adding the RSLR projections presented in **Figure 1** at the beginning of the stress period (**Table 5**) to the current MSL. The boundary head is a step function, changing at the beginning of each stress period and remaining constant for the time steps within each stress period. Model output in the form of piezometric head was generated for 1, 2, 4, 6, and 8 feet of RSLR. This corresponds to the years 2021, 2041, 2071, 2101, and 2121, respectively, under scenario #7 in Table 4 and **Figure 1** [*Wake et al.*, 2019]. This scenario is recommended when designing projects with low-risk tolerance [*NH STAP*, 2020]. Incremental RSLR of 1, 2, and 4 feet corresponds to years 2030, 2061, and 2121, respectively, under scenario #5 in **Table 5** and **Figure 1**. This scenario is recommended when designing projects with high-risk tolerance [*NH STAP*, 2020].

Table 5. Groundwater flow stress periods and corresponding RSLR based on the NH Coastal Flood Risk Summary, Parts I and II [*Wake et al.*, 2019; *NH STAP*, 2020]



					#5	#7
Stress Period	Starting Year	Ending Year	Duration (yrs)	Duration (days)	SLR relative to 2000	SLR relative to 2000
1	2000	2020	20	7300	0.1	0.1
2	2021	2029	8	2920	0.6	1.0
3	2030	2040	10	3650	1.0	1.6
4	2041	2050	9	3285	1.3	2.0
5	2051	2060	9	3285	1.6	2.5
6	2061	2070	9	3285	2.0	3.0
7	2071	2084	13	4745	2.4	4.0
8	2085	2090	5	1825	2.6	4.5
9	2091	2100	9	3285	2.9	5.3
10	2101	2111	10	3650	3.3	6.0
11	2112	2120	8	2920	3.6	7.0
12	2121	2133	12	4380	4.0	8.0
13	2134	2140	6	2190	4.3	8.9
14	2141	2150	9	3285	4.6	9.9

Model Limitations

The groundwater model created for this project is a conceptual model to investigate the effects of RSLR on groundwater levels and saltwater intrusion. It is not designed to predict groundwater head and/or concentration at individual wells, but to simulate groundwater-flow patterns and trends with RSLR. Uncertainties are associated with the groundwater measurements, bedrock geology, properties of the geologic materials, salinity distribution at the coast, and RSLR scenarios. The location of fracture zones in bedrock, which could have significant effect on saltwater intrusion, are not well known. Pumping is assumed to be at a constant rate throughout the simulation and there is uncertainty in the vertical distribution of withdrawal volumes. Despite these limitations, the groundwater model is useful in identifying the areas that are most at risk from saltwater intrusion (both shallow and deep in the geologic materials) and zones of groundwater rise caused by RSLR. This information can be used to direct monitoring programs, target areas for additional studies and data collection, assist in managing assets that may be vulnerable to premature failure, and protect both surface and groundwater quality.

Results

Groundwater rise ranging in magnitude from less than one foot to 8 feet is predicted to occur up to 1.5 miles inland from the Durham coastline with 8 feet of RSLR. The maximum extent of the groundwater-rise zone (GWRZ) for the RSLR scenarios considered is shown as the hatched area in **Figure 9**. The tidally influenced Oyster River contributes to the inward extent of the groundwater-rise signal resulting in a farther inland extent of groundwater rise than areas not influenced by the estuary. The projected magnitude of groundwater rise is indicated by the colors ranging from green to red for 2, 4, 6, and 8 feet of RSLR in **Figures 9a-d**. The magnitude of groundwater rise is highest along the coast of Little Bay, Great Bay, and the Oyster River and decreases farther inland from the shoreline.

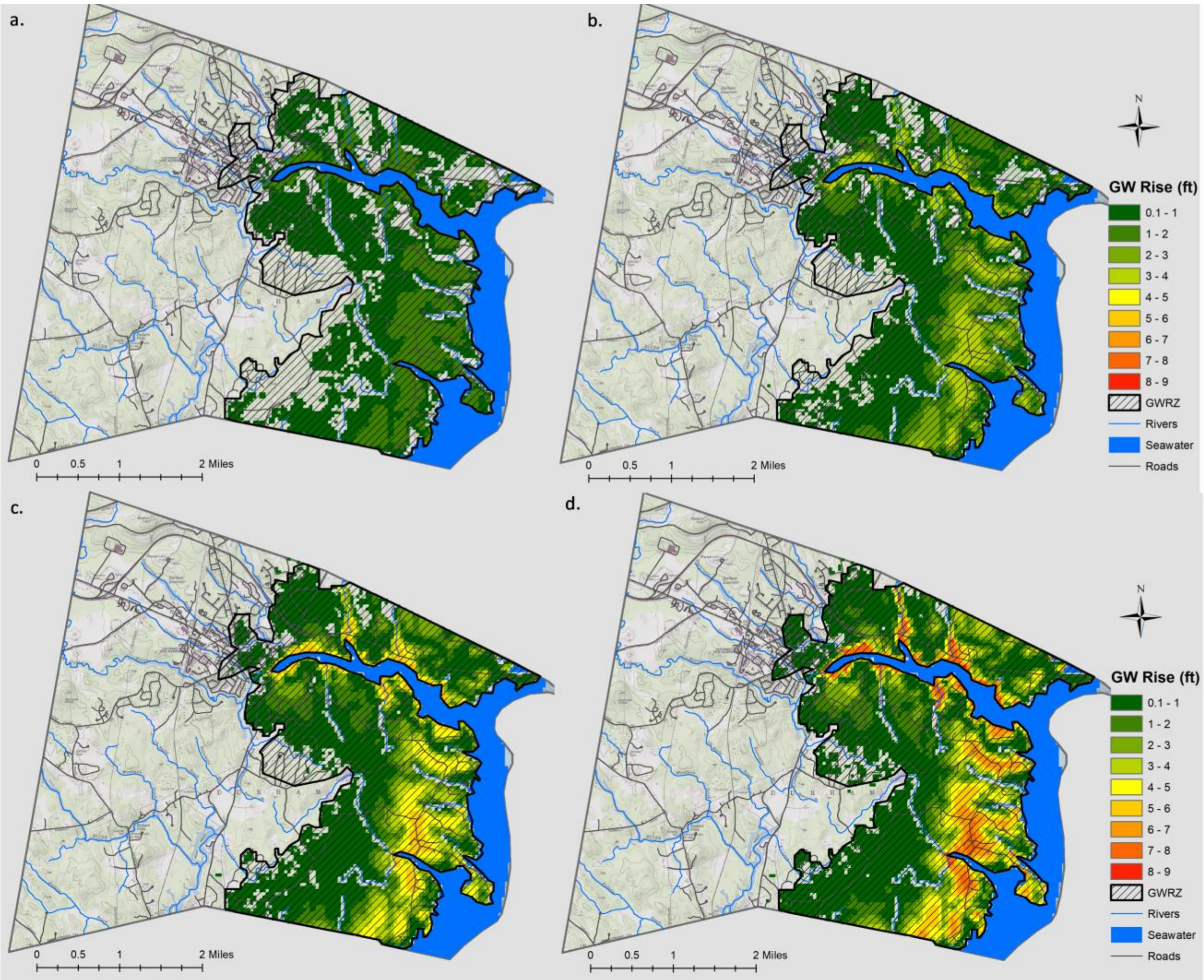


Figure 9. Projected groundwater rise caused by RSLR for four levels of RSLR: a) 2 feet, b) 4 feet, c) 6 feet, and d) 8 feet in Durham, NH. The hatched area shows the maximum extent of the GWRZ with 8 feet of RSLR, the maximum magnitude of RSLR simulated in the study.

The increasing head along the shoreline of the estuaries reduces the amount of groundwater discharge to the coast. Conversely, as groundwater rises near freshwater rivers and streams (not tidally influenced), groundwater discharge to the stream increases due to the increased gradient between the groundwater and the head in the stream which is controlled by streambed and bank topography. This results in a dampening of the groundwater rise near freshwater streams (**Figure 9**) as has been noted in other studies [*Masterson*, 2004; *Walter et al.*, 2016; *Befus et al*., 2020]. The changes in groundwater/surface water flux as RSL and groundwater levels rise are shown in **Figure 10**. The estimated net flow from the groundwater to the surface water in the Oyster River is projected to drop from 8 cfs to zero and the net groundwater discharge to freshwater streams is projected to increase 12% with 8 feet of RSLR. While this is small relative to the change in flux between groundwater and the Oyster River due to the difference in area for groundwater/surface-water interactions, it can be important for flooding and the ecology of the freshwater streams.

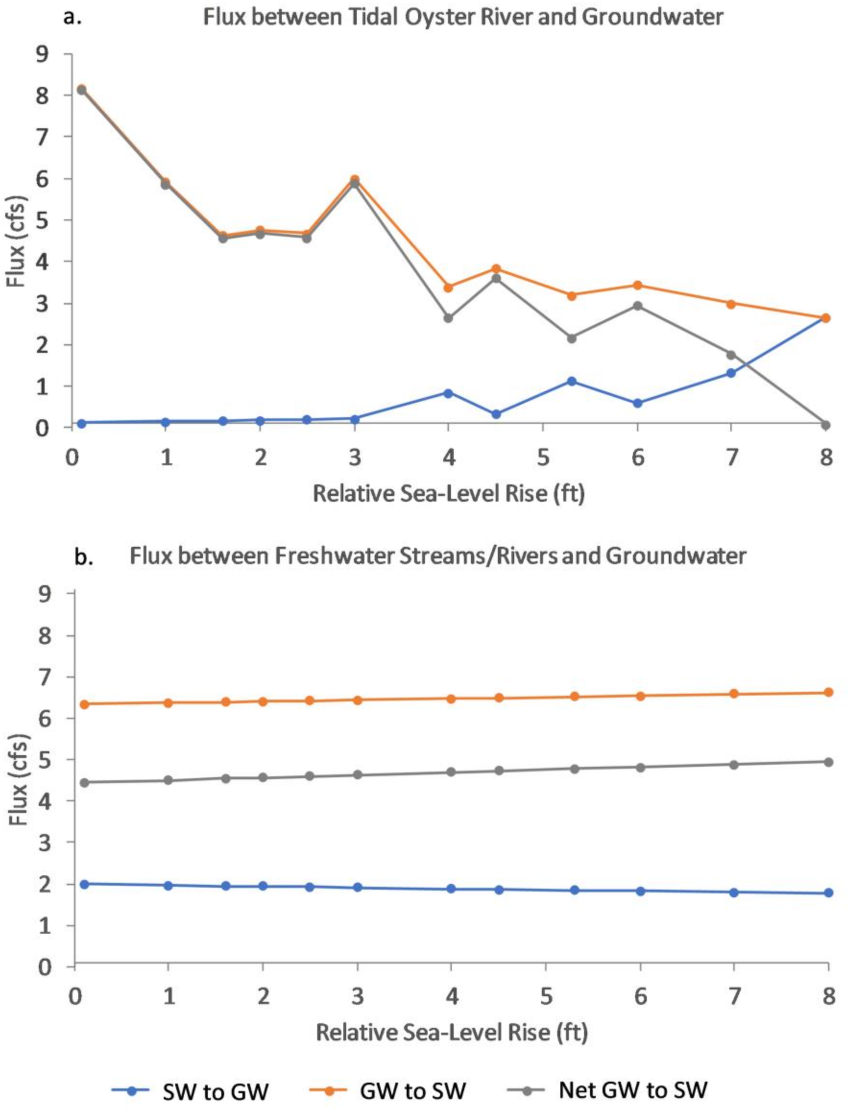


Figure 10. Flux between groundwater and surface water: a) Oyster River (tidal estuary), and b) freshwater streams (non-tidal) in the study area.

Rising water tables can damage underground infrastructure in areas where the water table is shallow [*Befus et al.*, 2020; *Habel et al.*, 2020]. To investigate this is in Durham, we combined the groundwater head dataset with LiDAR land surface elevation to identify areas where the groundwater is currently shallow, i.e., less than 15 feet from the land surface. Using this information with the groundwater rise modeling results, we were able to identify sections of coastal roadways within the GWRZ where rising groundwater has the potential to damage underground infrastructure and the pavement structure. In addition, we identified on-site wastewater treatment systems (OWTSs) located within 1 kilometer of the coast that may be vulnerable to failure as the water table rises. These areas of vulnerability are shown in **Figure 11**.

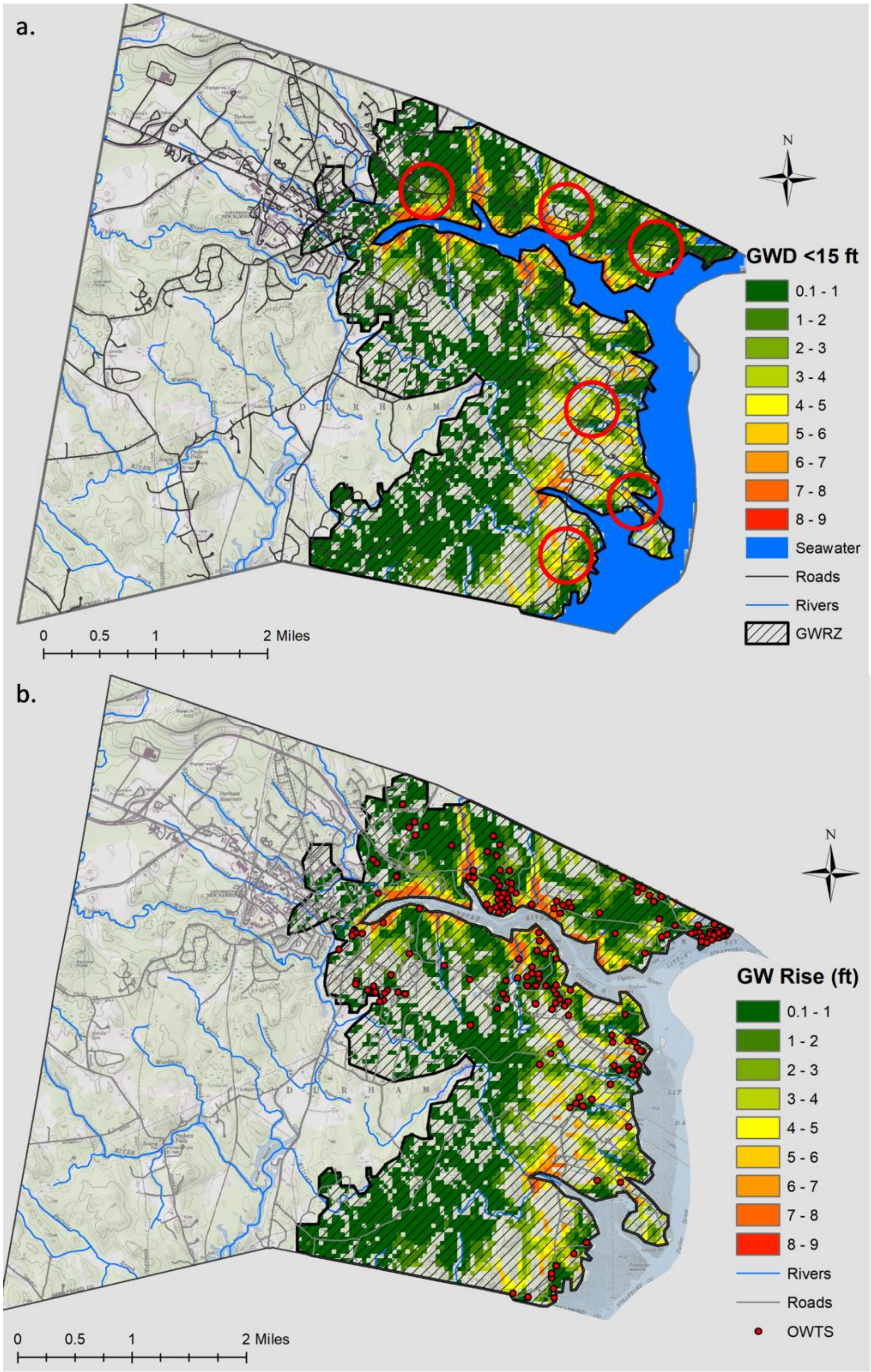


Figure 11. Vulnerable areas, defined as areas within the GWRZ with 8 feet of RSLR, where current groundwater levels are less than 15 feet below the land surface. The two figures are: a) potentially vulnerable pavements (shown with red circles) and underground infrastructure, and b) potentially vulnerable onsite wastewater treatment systems (OWTSs).

Saltwater intrusion modeling in Durham using SEAWAT projects negligible impact of RSLR on salt concentrations in public supply wells. Neither the stratified drift aquifers nor the bedrock aquifers currently being used or contemplated for public water supply are predicted to be impacted by saltwater intrusion because of RSLR. This can be seen by comparing the simulated present day saltwater intrusion with that projected with 8 feet of RSLR (**Figure 12**). The coastal stratified drift aquifer in the northeastern portion of Durham may experience saltwater intrusion if it has not already. The inland extent of the salt concentrations increases with depth. The two images presented in **Figure 12** show salt-water intrusion in the upper-most layers at 15 feet below land surface and in the deepest layer of the model at 1100 feet below land surface. The farthest inland extent of non-zero relative salt concentrations is deep in the bedrock. This suggests that drinking water wells both public and domestic drilled deep into bedrock near the coast are the more vulnerable to saltwater contamination than shallower wells. Shallow wells, however, are more vulnerable to surface pollutants in the absence of clay confining layers between the land surface and the well screen than the deep wells. Also, the extent of salt-water intrusion and the resultant impact on bedrock drinking water is dependent on the pattern of fracture zones in the bedrock.

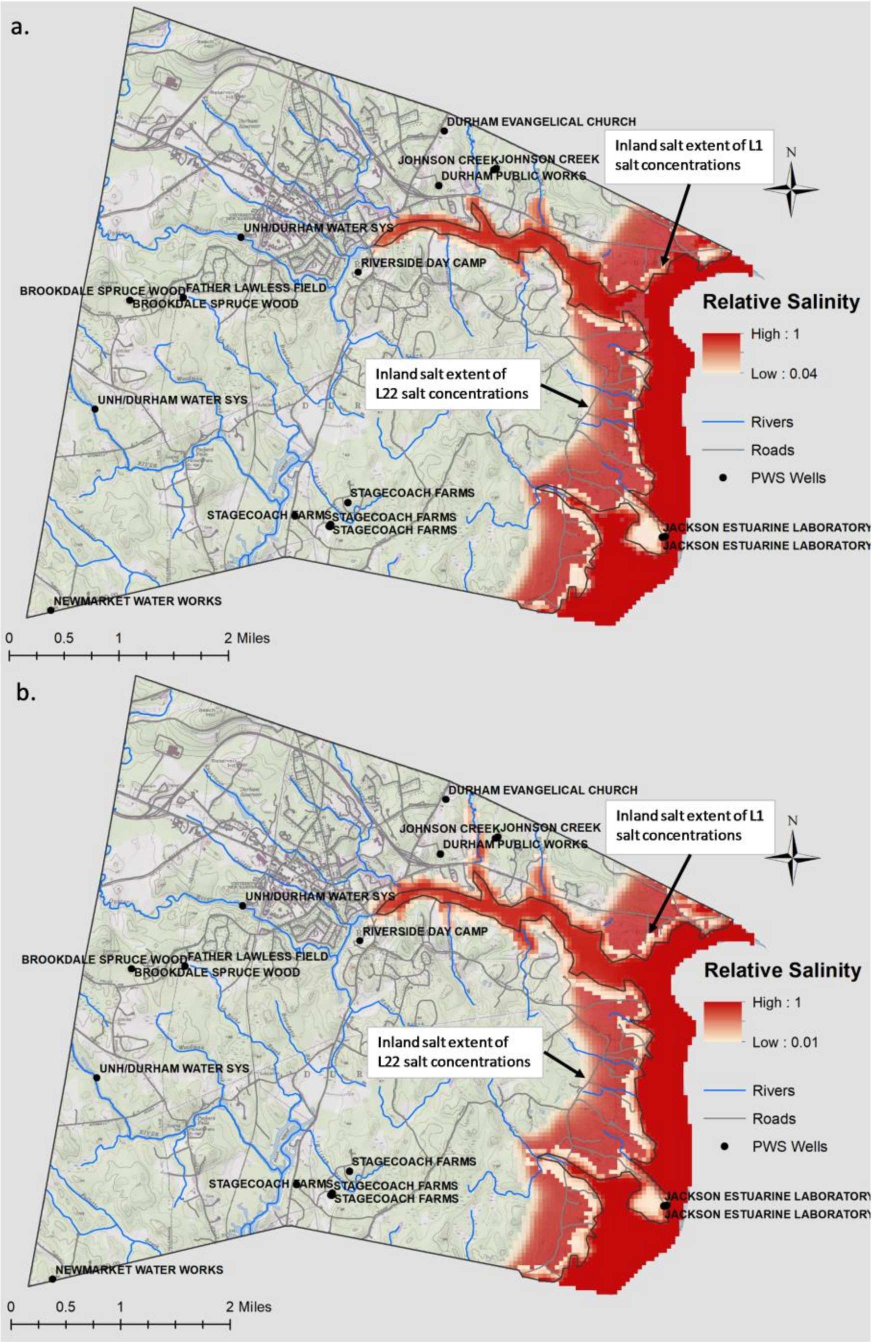


Figure 12. Simulated relative salt concentrations in Durham, NH for a) current MSL b) MSL with 8 feet of RSLR. Two layers are shown: layer 1 (at a depth of 15 feet below land surface) and layer 22 (at a depth of 1100 feet below land surface). Relative salt concentrations are defined as 1=seawater and 0=freshwater. Concentration colors in L22 are muted slightly using transparency to distinguish between the layers.

Summary

In summary, groundwater is projected to rise in Durham, NH with RSLR projected to occur in the Oyster River, Little Bay, and Great Bay estuaries. The groundwater rise signal is predicted to extend up to 1.5 miles inland from the coastline with 8 feet of RSLR and has the potential to weaken or damage coastal roads, underground infrastructure, historic structures, and OWTSs in areas where groundwater is already shallow. This may result in increased maintenance and repair costs and water-quality concerns. An increase in saltwater intrusion caused by RSLR does not appear to be a concern under current pumping conditions; however, it may become problematic at the Durham Public Works or Johnson Creek water supplies if pumping rates are increased at these locations. Saltwater intrusion could be a concern in the stratified drift aquifer beneath Cedar Point in northeastern Durham if it is developed as a public water source.

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