Preliminary Ground-Water-Flow Model of a Coastal Bedrock-Aquifer System, Southeastern New Hampshire

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ABSTRACT

The State of New Hampshire and the U.S. Geological Survey are investigating the sustainability of ground-water resources in a 100-square mile (mi^2) area of coastal New Hampshire. The study area is characterized as a fractured-crystalline bedrock aquifer system, much of which is bounded by saltwater bodies. This bedrock aquifer is being developed to meet the growing demand for water without a thorough conceptual understanding of the aquifer system. Increased ground-water withdrawals could create a reduction in streamflow, loss of supply wells through water-level declines, and possibly saltwater intrusion. A preliminary steady-state regional ground-water-flow model was developed to help conceptualize the aquifer system and evaluate data needs. The finite-difference model was developed using statewide surficial-aquifer investigations, bedrock mapping, and digital-elevation-model (DEM) data. Parameter-estimation techniques were used to assess bedrock-aquifer characteristics and evaluate model parameter sensitivities. Existing and approximated head and streamflow observations were evaluated to assess how data coverage and accuracy affect the confidence in model parameter estimates. Results of preliminary simulations indicate that bedrock hydraulic conductivities may be estimated to within an order of magnitude, given sufficient head and withdrawal data coverage. Where this information is lacking, bedrock characteristics are poorly estimated. The preliminary model, therefore, is useful for understanding the ground-water-flow system and prioritizing data needs for detailed model development and calibration.

INTRODUCTION

The Seacoast region of New Hampshire (fig. 1) has undergone significant population growth and development over the past 20 years. Increased withdrawals, primarily from the fractured bedrock aquifer, raise concern for the sustainability of ground-water resources in the region. Numerical ground-water-flow simulation allows an integrated assessment of various hydrologic data and complex boundaries, and can be used to calculate ground-water availability for a drainage basin or regional setting. This paper briefly describes preliminary ground-water model construction, and assesses the conceptual understanding of the system and the data needs for model calibration and water-resource analysis. The analyses were done at a regional scale and are considered preliminary because they are based on limited, or estimated data, and are part of an ongoing investigation.

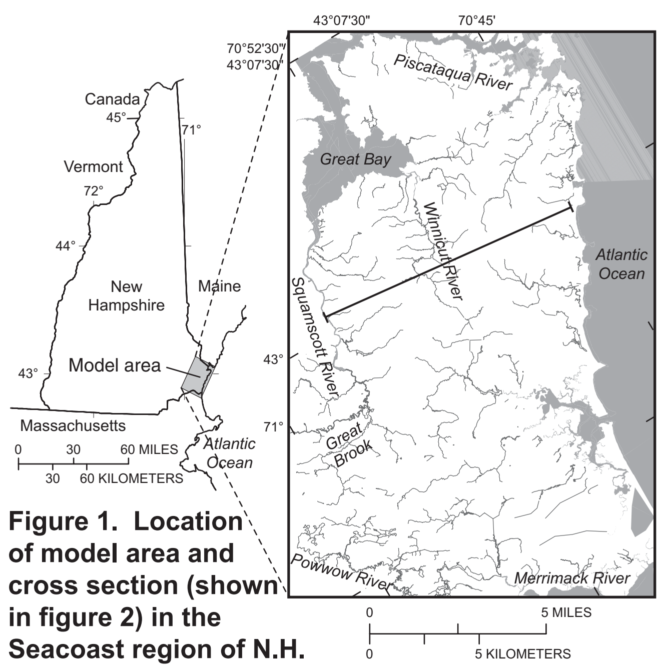

Figure 1. Location of model area and cross section (shown in figure 2) in the Seacoast region of N.H.

PRELIMINARY MODEL DEVELOPMENT

The regional ground-water-flow system is one of relatively thin and discontinuous surficial aquifers underlain by a fractured crystalline-bedrock aquifer. The ground-water-flow system was simulated using MODFLOW-2000 (Harbaugh and others, 2000). The parameter-estimation tools in MODFLOW-2000 (Hill and others, 2000) were then used to assess the preliminary ground-water-flow model. Lateral model boundaries were selected to coincide with major hydrologic features, including tidal water bodies (Squamscott River, Great Bay, Atlantic Ocean, Piscataqua River, and Merrimack River) along most of the model boundary, and the freshwater Powwow River and Great Brook drainage divide to the southwest (fig. 1).

Most of the model was simulated with a surface grid-cell size of 400 by 400 feet. The upper surface of the model, layer 1, corresponds to the land-surface elevation provided by the DEM. The model is subdivided vertically into seven layers (fig. 2). The lateral extents of all model layers below layer 1 were simulated as no flow boundaries. Parameters were used to describe the hydraulic conductivity, or multiplier of conductivity, of various geologic units or zones, riverbed conductivity, constant-head-cell conductivity, and recharge. Bulk hydraulic properties are usually sufficient to describe regional ground-water recharge, discharge, and storage (Shapiro, 2002).

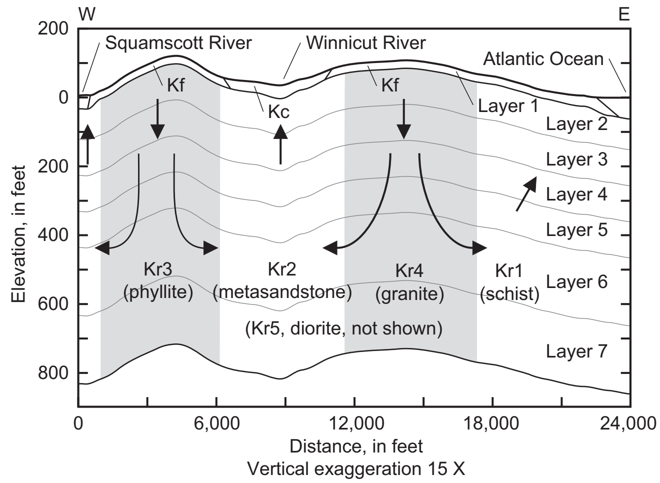

Figure 2. Diagrammatic cross section through model area and preliminary model parameters. Arrows show general direction of ground-water flow.

Coarse-grained glacial sediments cover about 20 percent of the simulated area and have a hydraulic conductivity of about 10 to more than 100 feet per day (ft/d). The thickness and hydraulic conductivity of stratified-drift aquifers were determined by previous investigations (Moore, 1990; Stekl and Flanagan, 1992). Coarse-grained sediments are represented by a parameter (Kc) that acts as a multiplier of hydraulic conductivity in model layer 1. Most of the surficial sediments in the study area (greater than 50 percent) are comprised of till and have a hydraulic conductivity of about 1 ft/d, and a thickness of zero to a few 10s of feet. Surficial sediments include fine-grained marine silt and clay with a hydraulic conductivity less than 1 ft/d. Till and other fine-grained sediments were assigned a model parameter (Kf), with an initial hydraulic conductivity of 1 ft/d and a thickness of 20 ft. Further differentiation of surficial sediments, and approximation of thickness, is part of the ongoing study.

Bedrock in the study area consists of crystalline meta-sedimentary and igneous rocks (Novotny, 1968). The model grid was oriented to the northeast-southwest trending regional structural pattern. Depending on the bedrock fracture network and investigation scale, the hydraulic conductivity of the bedrock aquifer spans several orders of magnitude. Regionally, the hydraulic conductivity of the bedrock aquifer is controlled by the small fractures of the pervasive fracture network (Tiedeman and others, 1997). The regional hydraulic conductivity estimated for crystalline rock in northern New Hampshire ranged from about 0.1 to 0.01 ft/d (Tiedeman and others, 1997). In the model, the bedrock aquifer was divided into two 400-ft thick units (fig. 2). Layers 2-5 represent the depth that contains most bedrock wells and are 100-ft thick. Layers 6 and 7 represent the depth of the few deep bedrock wells in the study area and are 200-ft thick. Bedrock (layers 2-7) was represented by five parameter zones (four of which are shown in fig. 2), based on major rock type (Novotny, 1968); and hydraulic conductivities were estimated in the parameter estimation process.

Average recharge (R) was estimated to be 1.6 feet per year based on hydrograph-separation analysis of a 12-mi^2 drainage basin 5 mi to the northwest of the study area (Robert Flynn, U.S. Geological Survey, written commun., 2003). Streams were simulated using the MODFLOW-2000 River package and stage elevations interpreted from the DEM. Ponds and wetlands that are isolated from other surface-water bodies were not explicitly simulated as they do not actively remove water from the system as a stream would. However, ponds and freshwater wetlands represent the water-table surface and are considered to be an “observation” of the water-table surface in this study. All tidal water bodies were simulated as constant head boundaries, in model layer 1, where an “equivalent-freshwater” head was calculated as one half the depth of the saltwater body times the density of saltwater. Tidal water bodies were simulated as "flow-through" cells with a thickness equal to the water depth and a hydraulic conductivity of 10,000 ft/d.

Water uses in the Seacoast include surface- and ground-water withdrawals, interbasin transfers, and returns. Major water withdrawals (greater than 20,000 gallons per day) are incorporated in the model for assessing the conceptual ground-water-flow system. Other water uses are not considered in the preliminary model. A detailed water-use investigation is ongoing (Marilee Horn, U.S. Geological Survey, oral commun., 2003), the results of which will be incorporated into the final model.

PRELIMINARY GROUND-WATER-FLOW MODEL AND OBSERVATIONS

Measured and approximated head and discharge observations were used to assess the preliminary ground-water-flow model. Observation weights were calculated following the methods of Hill (1998) and allow for comparison of data with different units and accuracies. Accurate bedrock aquifer heads from 118 wells, with an accuracy of ± 0.1 ft or better, were available for the northwest part of the model area (Roseen, 2002; Julia Widman, Montgomery Watson Herzog, Inc., written commun., 2003). Less accurate (± 10 ft) historical bedrock heads from 62 wells were evenly distributed over the entire model area. Heads for about 700 layer-1 model cells, primarily in the central part of the model area, were approximated by pond and wetland surface elevations (± 10 ft). Estimated annual baseflow for the six largest drainage basins in the study area (fig. 1), assumed to be accurate to 10 percent, were used as observations of basin discharge.

GROUND-WATER-FLOW SIMULATION

Simulated bedrock-aquifer heads for model layer 2 are shown in figure 3. Ground water generally follows short flow paths (a few hundred feet) from areas of high hydraulic head (fig. 3) and discharges to nearby streams or tidal water bodies (similar to the generalized directions of flow shown in fig. 2). Most flow paths remain in the upper model layers, unless diverted deeper by withdrawal wells, while some regional flow paths may be nearly 2 mi long. Regional head in the bedrock aquifer generally reflects the topography. Steep head gradients are in areas of high relief and low hydraulic conductivity. Head gradients are shallow in areas of low relief and high hydraulic conductivity. A plot of weighted observations verses weighted simulated equivalents (fig. 4) with a correlation coefficient of 0.98 indicates a good overall model fit. If the model fit is consistent with data accuracy the standard error of regression is about 1 (Hill, 1998). The standard error is typically greater than 1, reflecting model and measurement error (Hill, 1998), and is 4 for the preliminary model. Most of the weighted residuals (weighted observation minus weighted simulated equivalent) are within 2 standard errors (± 8) and are randomly distributed about zero with an average weighted residual of -0.6. About 25 percent of the accurate heads residuals are outside 3 standard errors.

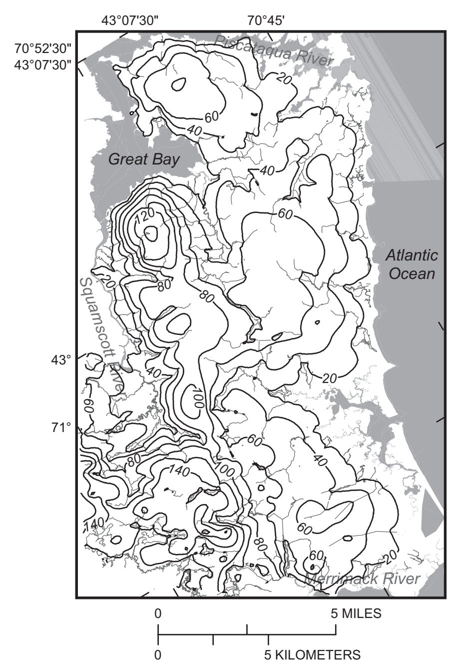

Figure 3. Simulated bedrock-aquifer head contours for model layer 2.

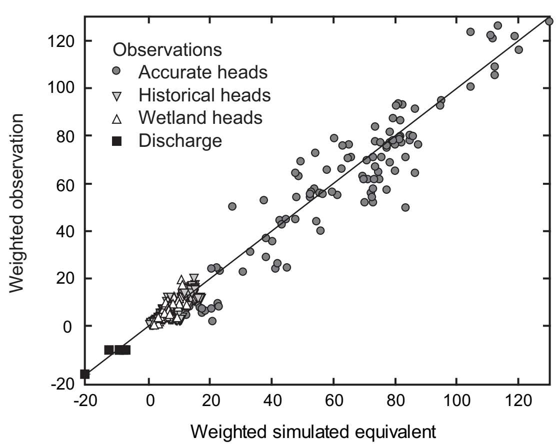

Figure 4. Weighted observations versus weighted simulated equivalents.

Examination of individual bedrock aquifer heads (not shown) indicates that there are large head differences (tens of feet) from well to well (within 400 ft) that vary most in areas of high relief. The largest residuals, however, may be due to drawdown or location errors in the head data. For the regional model, a head observation accuracy of about 1 ft is sufficient and the regional variation in heads can be simulated (fig. 3). However, the inherently large variation in heads from well to well at the local scale cannot be simulated.

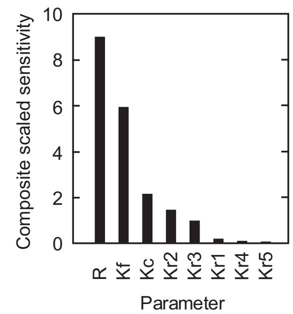

Figure 5. Composite scaled sensitivities for selected model parameters.

The sensitivity of the preliminary model to selected model parameters is shown by comparing composite scaled sensitivities (fig. 5). The model is most sensitive to recharge (R); the model is also sensitive to parameters that represent fine-grained surficial sediments (Kf), coarse-grained sediments (Kc), and bedrock zones Kr2 and Kr3. The fine-grained sediments are important in the simulation because they cover most of the model area, whereas bedrock zones Kr2 and Kr3 contain most of the bedrock aquifer. However, there is a 98-percent correlation between Kf and Kr3, which indicates that there is not enough information to estimate these parameters independently. There are numerous head observations in Kr3 but no simulated withdrawal stresses, and this zone is coincident with Kf. The parameter Kf is important in the preliminary model, therefore, a better approximation of its thickness (set at an assumed 20 ft in the preliminary model), and a further differentiation of fine sediments (undifferentiated in the preliminary model), is needed. The ground-water-flow simulation was not sensitive to bedrock zones Kr4 and Kr5 because their area is small and there are few observations or simulated stresses in these zones. Model sensitivity is low (less than 1) for parameter Kr1 because there are few head observations and few simulated withdrawals in this zone. However, the bedrock represented by Kr1 is an area of recent ground-water exploration and large withdrawals. This information is not in the preliminary model and would likely increase the sensitivity of the model to Kr1. The model was not sensitive to parameters that represented the streambed or constant-head-cell hydraulic conductivity (less than 0.05, not shown in fig. 5). Regionally, the boundaries represented by these parameters are drains where the hydraulic conductivity simply needs to be large.

With sufficient data, some model parameters can be estimated with a confidence interval within one order of magnitude. Upper and lower 95-percent confidence intervals for selected preliminary model parameters are shown in table 1. Bedrock parameters Kr1 and Kr2 are estimated with a small range in confidence interval (within one order of magnitude). Parameters Kr4 and Kr5 are estimated with confidence intervals ranging 2 and 3 orders of magnitude. With few discharge observations or simulated stresses (withdrawals), it is not possible to accurately estimate hydraulic conductivity for Kr4 and Kr5. Parameter Kr2 is estimated with the smallest confidence interval because the Winnicut River drainage basin is coincident with this zone (fig. 2), there is a large amount of accurate head data in this zone, and there are large ground-water withdrawals in this zone. Eliminating wetland-head observations leads to larger confidence intervals for most bedrock parameters. Removing a few selected head observations with the largest weighted residuals (suspected to be poorly located points) improves the confidence intervals for some bedrock parameter zones. Without either the accurate or historical-head observation data sets, confidence intervals could not be calculated.

95-Percent Confidence Interval	Parameter Confidence Intervals						
	Kf	**Kc**	**Kr1**	**Kr2**	**Kr3**	**Kr4**	**Kr5**
Upper	2.4E+1	1.5E+0	6.7E+0	1.5E+0	3.9E-1	3.6E+1	1.6E+2
Lower	1.4E+1	1.0E-0	4.4E-1	7.2E-1	2.0E-2	3.1E-1	3.1E-1

Table 1. 95-percent confidence intervals for selected parameters in the preliminary model.

[E, exponential notation = n x 10^n]

Streams account for a large part of the total regional water balance. The preliminary ground-water-flow model simulates streams as a specified-head boundary based on a DEM-derived stage in a 400-ft^2 cell. An improved approach would be to simulate streams using a streamflow-routing package to avoid a stage-dependant boundary, for future transient simulations, and to use smaller cells to better approximate stream locations. Continuous drainage-basin discharge observations will provide additional confidence in recharge, an important model parameter, and subregional water-balance calculations.

SUMMARY

The ground-water-flow model presented in this paper is preliminary and will be revised as the study progresses. Results indicate that a regional ground-water-flow model can be developed and parameter-estimation techniques are useful for assessing the conceptual model and ground-water-flow system. Additional geohydrologic data, particularly thickness and differentiation of surficial sediments, distributed head data, and detailed water-use information are needed for further model development. Continuous drainage-basin discharge data are needed to have confidence in recharge and water-balance calculations. Because of the inherent variations in bedrock heads, a large number and distribution of observations, with an accuracy of about 1 ft, may be more important than an observation data set consisting of fewer highly accurate data. A combination of heads and discharge observations, and detailed water-use information, will permit more accurate parameter estimations to be calculated and, therefore, greater confidence in ground-water-flow simulations. The final ground-water-flow model should be useful in estimating regional heads and water balance but will not accurately simulate the complex head variations observed from well to well in the study area.

REFERENCES

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water-flow model—user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: U.S. Geological Survey Water-Resources Investigation Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to the observation, sensitivity, and parameter-estimation process and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, p. 209.

Moore, R.B., 1990, Geohydrology and water quality of stratified-drift aquifers in the Exeter, Lamprey, and Oyster River Basins, Southeastern, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 88-4128, 61 p., 8 pls.

Novotny, R.F., 1968, Geologic map of the seacoast region, New Hampshire bedrock geology: New Hampshire Department of Resources and Economic Development, 1 sheet, scale: 1,62,500.

Roseen, R.M., 2002, Quantifying ground-water discharge using thermal imagery and conventional ground-water exploration techniques for estimating the nitrogen loading to a meso-scale inland estuary: University of New Hampshire, Durham, N.H., PhD. Dissertation, 188 p.

Shapiro, A.M., 2002, Characterizing fractured rock for water supply: From the well field to the watershed: *in* National Ground Water Association, Fractured-Rock Aquifers 2002, Denver, Colo., March 13-15, 2002, Proceedings: Denver, Colo., National Ground Water Association, p. 6-9.

Stekl, P.J., and Flanagan, S.M., 1992, Geohydrology and water quality of stratified-drift aquifers in the Lower Merrimack and Coastal River Basins, Southeastern, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 91-4025, 75 p., 7 pls.

Tiedeman, C.R., Goode, D.J., and Hseih, P.A., 1997, Numerical simulation of ground water flow through glacial deposits and crystalline bedrock in the Mirror Lake Area, Grafton County, New Hampshire: U.S. Geological Survey Professional Paper 1572, 50 p.