Prepared in cooperation with the Maine Geological Survey

Simulation of Groundwater Flow and Streamflow Depletion in the Branch Brook, Merriland River, and Parts of the Mousam River Watersheds in Southern Maine

Scientific Investigations Report 2014–5235

U.S. Department of the Interior
U.S. Geological Survey

Front cover photo. Branch Brook.

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SALLY JEWELL, Secretary

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Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F–32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Abbreviations

GHB	general head boundary
GIS	geographic information system
GPS	global positioning system
MODFLOW	modular three-dimensional finite-difference groundwater model
MOVE.1	maintenance of variance, type 1
MGS	Maine Geological Survey
USGS	U.S. Geological Survey

Simulation of Groundwater Flow and Streamflow Depletion in the Branch Brook, Merriland River, and Parts of the Mousam River Watersheds in Southern Maine

By Martha G. Nielsen and Daniel B. Locke

Abstract

Watersheds of three streams, the Mousam River, Branch Brook, and Merriland River in southeastern Maine were investigated from 2010 through 2013 under a cooperative project between the U.S. Geological Survey and the Maine Geological Survey. The Branch Brook watershed previously had been deemed "at risk" by the Maine Geological Survey because of the proportionally large water withdrawals compared to estimates of the in-stream flow requirements for habitat protection. The primary groundwater withdrawals in the study area include a water-supply well in the headwaters of the system and three water-supply wells in the coastal plain near the downstream end of the system. A steady-state groundwater flow model was used to understand the movement of water within the system, to evaluate the water budget and the effect of groundwater withdrawals on streamflows, and to understand streamflow depletion in relation to the State of Maine's requirements to maintain in-stream flows for habitat protection.

Delineation of the simulated groundwater divides compared to the surface-water divides suggests that the groundwater divides in the headwater areas do not exactly correspond to the surface-water divides. Under both pumping and non-pumping conditions, groundwater flows from the headwaters of the Branch Brook watershed into the Mousam River watershed. Pumping in the Mousam River watershed captures a small amount of groundwater from the Branch Brook basin.

The cumulative effect of groundwater withdrawals on base flows in two rivers in the study area (Branch Brook and the Merriland River) was evaluated using the groundwater flow model. Streamflow depletion in the headwaters of Branch Brook was 0.12 cubic feet per second (ft^3/s) for the steady-state simulation, or about 10 percent of the average base flow at that location. Downstream on Branch Brook, the total streamflow depletion from all the wells was 0.59 ft^3/s, or 3 percent of the average base flow at that location. In the Merriland River downstream from the Merriland River well, the total amount of streamflow depletion was 0.6 ft^3/s, or about 7 percent of the average base flow.

The groundwater model was used to evaluate several different scenarios that could affect streamflow and groundwater discharging to the rivers and streams in the study area. The scenarios were (1) no pumping from the water-supply wells; (2) current pumping from the water-supply wells, but simulated drought conditions (25 percent reduction in recharge); (3) current recharge, but with increased pumping from the large water-supply wells; and (4) drought conditions and increased pumping combined.

Simulations of increased pumping in the water-supply wells resulted in streamflow depletion in the headwaters of Branch Brook increasing to 16 percent of the headwater base flow. Simulated increases in the pumping in the coastal plain wells increased the amount of streamflow depletion to 6 percent of the flow in Branch Brook and to 8 percent of the flow in the Merriland River. The additional stress of a drought imposed on the model (25 percent less recharge) had a substantial impact on streamflows, as expected. If the simulated drought occurred simultaneously with an increase in pumping, the base flows would be reduced 48 percent in the headwaters of Branch Brook, compared to the no-pumping scenario. Downstream in Branch Brook, the total reduction in flow would be 29 percent of the simulated base flows in the no-pumping scenario, and in the Merriland River, the reduction would be 33 percent of the base flows in the no-pumping scenario.

The study evaluated two different methods of calculating in-stream flow requirements for Branch Brook and the Merriland River—a set of statewide equations used to calculate monthly median flows and the MOVE.1 record-extension technique used on site-specific streamflow measurements. The August median in-stream flow requirement in the Merriland River was calculated as 7.18 ft^3/s using the statewide equations but was 3.07 ft^3/s using the MOVE.1 analysis. In Branch Brook, the August median in-stream flow requirements were calculated as 20.3 ft^3/s using the statewide equations and 11.8 ft^3/s using the MOVE.1 analysis. In each case, using site-specific data yields an estimate of in-stream flow that is much lower than an estimate the statewide equations provide.

Introduction

In 2009, the U.S. Geological Survey (USGS) and the Maine Geological Survey (MGS) began a cooperative project to provide a rigorous evaluation of the hydrologic effects of withdrawals in "watersheds at risk" in the State of Maine (Nielsen and Locke, 2011). The results of the initial study under this cooperative project, in Freeport, Maine, indicated the importance of high-quality site-specific data in analyzing the hydrologic effects of withdrawals. That study of a small watershed (less than 10 square miles [mi^2]) having only one withdrawal well served as a pilot for the overall project. The Freeport aquifer study concluded that using site-specific streamflow data provided estimates of the monthly median streamflows that were significantly different from the standard estimation method for determining seasonal in-stream flows, which uses statewide equations for the monthly median flows, particularly in a very small watershed (Nielsen and Locke, 2011). The use of a numerical groundwater flow model in that study indicated how streamflow depletion from withdrawal wells could be quantified and used to estimate summertime pumping effects on streamflow under drought conditions, potential future increased withdrawals, or both. The construction and calibration of the Freeport aquifer groundwater flow model revealed groundwater flow directions and connections between deep and shallow aquifers that were not otherwise apparent (Nielsen and Locke, 2011).

As a second study under the USGS-MGS cooperative project, a study of watersheds in the towns of Kennebunk, Wells, and Sanford, Maine, was begun in 2010, using similar methods to the Freeport aquifer study but on a larger study area with more complex geology and groundwater withdrawals. The study uses an evaluation of the water budget and simulations of streamflow depletion, determined through use of a numerical groundwater flow model, to evaluate the effect that groundwater withdrawals have on streamflows and groundwater within the system. This study, like the earlier Freeport aquifer study (Nielsen and Locke, 2011), is intended to provide insight into the effect of withdrawals on streamflows under a certain set of conditions (that is, the withdrawal conditions and aquifer geometry presented by the specific study area) and is intended to help understand streamflow depletion in light of the State requirements to maintain in-stream flows for habitat protection.

The MGS identified two adjacent watersheds in the Kennebunk, Maine, area (fig. 1) as having permitted groundwater and surface-water withdrawals in combination with flows required to meet in-stream flow requirements that are quite large in comparison to the total annual runoff (Robert G. Marvinney, Maine Geological Survey, written commun., 2011). These watersheds (the Branch Brook and Merriland River watersheds) and the glacial aquifer from which water is withdrawn are the focus of the study area. Adjacent parts of the Mousam River watershed are included in the study area because of uncertainty in the position of the groundwater divide and groundwater flow directions between the Branch Brook and Merriland River watersheds and the Mousam River watershed.

The use of a numerical groundwater flow model, which allows water to be accounted for as it flows through the groundwater system to the surface-water system, was intended to address several areas of concern in the study area. These include (1) to evaluate the effect of water management practices on streamflow and quantify streamflow depletion in Branch Brook and the Merriland River, (2) to help refine the conceptual model of groundwater flow in the study area, as the possible source of groundwater to some of the withdrawal wells was poorly understood at the outset, and (3) to delineate the groundwater divide between the Mousam River, Branch Brook, and the Merriland River watersheds. The study had two additional goals in support of a better understanding of water resource management in the watersheds, which were to fully account for all water withdrawals, not just permitted withdrawals, and to evaluate two different methods of calculating in-stream flow requirements for Branch Brook and the Merriland River.

This report describes the determination of total water use in the study area, the use and calibration of a steady-state groundwater flow model of the Branch Brook, Merriland River, and part of the Mousam River watersheds, and its use in evaluating the effect of groundwater withdrawals on streamflow in those watersheds. The data collected to construct and calibrate the groundwater flow model are presented. Simulation results for varying water withdrawal and climatic scenarios on the water budgets for Branch Brook, the Merriland River, and part of the Mousam River watershed are described. The parameter estimation used for model calibration, model sensitivities and limitations, and prediction uncertainties also are reported for the model. The report presents a summary of the effect of withdrawals on streamflows in the study area and on the overall movement of water through the hydrologic system. In addition, an analysis of two methods for the calculation of state in-stream flow requirements for Branch Brook and the Merriland River are presented.

Description of the Study Area

The study area includes the Branch Brook and Merriland River watersheds and part of the Mousam River watershed south of the Mousam River and east of Sanford (total area 51.8 mi^2) in southern coastal Maine (fig. 1). This includes parts of the towns of Kennebunk, Wells, and Sanford. The groundwater model covers the entire study area. Although the primary focus of the study is Branch Brook and the Merriland River, the adjacent parts of the Mousam River watershed were included in the study and the groundwater model because of uncertainties in the hydrologic boundaries along the Branch Brook-Mousam River divide and the Merriland River-Mousam River divide. The study area forms a northwest-southeast trending oblong-shaped area that has its headwaters in the eastern part of the city of Sanford and ends in a narrow

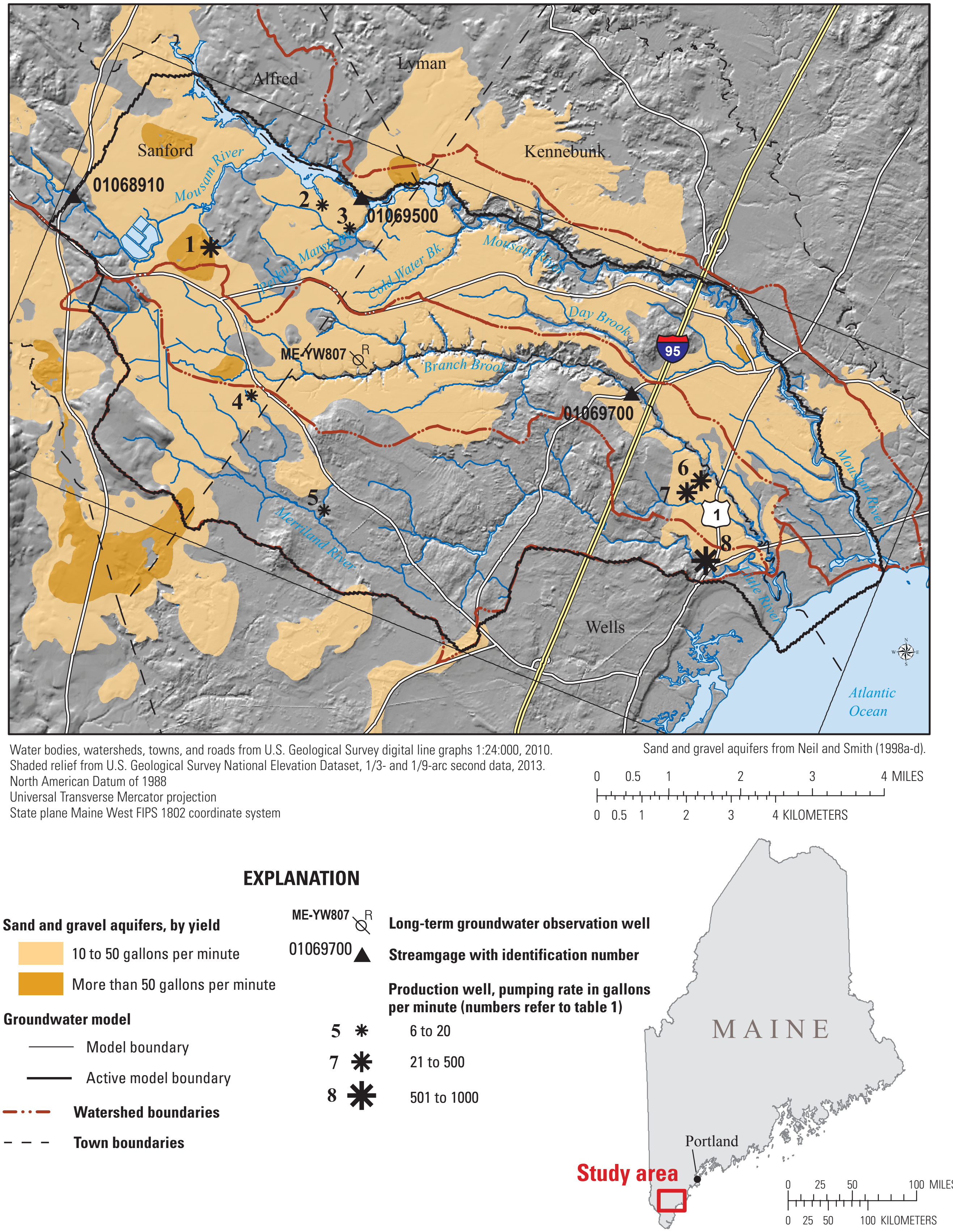


Figure 1. Location of the study area, extent of the groundwater model area, and sand and gravel aquifers in the Branch Brook, Merriland River, and parts of the Mousam River watersheds in southern Maine.

strip along the ocean 10 miles (mi) farther to the east. All of the primary surface-water features (the Mousam River, Branch Brook, and Merriland River) flow from west to east towards the ocean. The study area (and groundwater model) is 6 miles across in the north-south direction and 13 miles long in the east-west direction.

Within about 2–3 miles of the coastline, the study area consists of a generally flat coastal plain. A series of northeast-southwest trending ridges (of about 125 to 150 feet high) separates the coastal plain area from the inland areas. Inland of these ridges, the Branch Brook/Mousam River watershed areas are characterized by a sandy, gently sloping plateau (sloping northeast towards the Mousam River) which is dissected by streams (primarily Branch Brook and its tributaries). South of the Branch Brook watershed, the Merriland River watershed is underlain primarily by till and thin-soil-covered bedrock uplands. Farther to the west, the sandy plateau broadens to include all three watersheds. Furthest to the west, the study area ends in the hills to the south of Sanford, and in uplands across the West Branch of the Mousam River. The Mousam River forms the northernmost boundary of the study area. Total topographic relief is 370 feet.

The Merriland River watershed composes 16.4 mi^2, or 31.7 percent of the study area. The Branch Brook watershed (13.7 mi^2, or 26.4 percent of the study area), the Mousam River watershed (20.3 mi^2, 39.2 percent), and a small coastal section (1.4 mi^2, 2.7 percent of the total study area) compose the remainder of the study area. The Merriland River watershed is underlain by till and bedrock in its lower reaches and converts precipitation into runoff more quickly than the Branch Brook watershed, which has abundant sandy soil and greater opportunity for groundwater recharge and has more consistent groundwater discharge during dry periods.

Most of the study area has been mapped as a significant sand and gravel aquifer by the MGS (fig. 1; Neil and Smith, 1998a–d). The Branch Brook watershed and Mousam River watershed area are almost entirely designated as significant sand and gravel aquifers, as are the headwater areas of the Merriland River watershed.

The mean annual precipitation in the study area from 1961 through 1990 is 45.9 inches (Oregon State University, 2010; Natural Resources Conservation Service, 1998). The closest long-term temperature station is in Portland, Maine, 23 mi northeast of the center of the study area. The average annual temperature for the Portland station is 45.7 degrees Fahrenheit (°F) (National Weather Service, 2010), which is expected to be the same in the Kennebunk/Wells/Sanford area because of similar elevation, distance from the Atlantic Ocean, and proximity to each other.

Land use in and around the study area is primarily rural residential with the exceptions of the commercial-industrial area of South Sanford and the Sanford airport, residential areas of the town of Kennebunk, and the U.S. Route 1 corridor, which has a substantial amount of commercial development. The rural residential areas are largely forested with interspersed areas of hayfields along roadways and areas of unbroken forest between adjacent road and residential corridors. Several large areas of blueberry barrens and other open space cover the flat sandy plateau in the center of the study area near Branch Brook. The population density in most of the study area is less than 200 persons per square mile. Small rural subdivisions (in the range of 10 to 50 houses) can have population densities of 1,000 persons per square mile or more, and residential neighborhoods in the towns of Kennebunk and Sanford have population densities of 1,000 to 3,000 persons per square mile (U.S. Census Bureau, 2010). Total population in the study area is 11,962 (U.S. Census Bureau, 2010).

There are four large water-supply withdrawal wells (pumping between 150 and 1,000 gallons per minute) in the study area and four small water-supply wells (pumping less than 20 gallons per minute) (fig. 1, table 1). The four large withdrawal wells include a well in the western part of the study area in the town of Sanford, a well in the coastal plain near the Merriland River, and two wells near Branch Brook, also in the coastal plain area. The four small withdrawal wells are scattered across the central part of the study area. The large water-supply wells, plus a direct surface-water withdrawal from Branch Brook, together make up a relatively large total use of water in this study area compared to its size, according to analyses by the MGS (Robert G. Marvinney, written commun., 2011).

Previous Studies and Sources of Data

Information on the geology and hydrogeology of the Branch Brook-Merriland River study area is available from many sources. The State of Maine has published a series of bedrock geologic maps, surficial geologic maps and reports, and significant sand and gravel aquifer maps that cover the study area (Hussey and others, 2008; Neil and Smith, 1998a–d; Tolman and others, 1983; Smith, 1999a–f). The

Table 1. Water-supply wells in the Branch Brook, Merriland River, and parts of the Mousam River watersheds in southern Maine.

[Large wells in the study area pumping between 150 and 1,000 gallons per minute. Small wells pump less than 20 gallons per minute.]

Map number (figure 1)	Well name	Well type
1	Sanford well	Large water-supply well
2	Mobile home park “A” well	Small water-supply well
3	Mobile home park “B” well	Small water-supply well
4	Mobile home park “C” well	Small water-supply well
5	Mobile home park “D” well	Small water-supply well
6	Plant well	Large water-supply well
7	Harriseckett well	Large water-supply well
8	Merriland River well	Large water-supply well

hydrologic framework and surficial geology in the central part of the study area, known as the Sanford outwash plain, has been reported on by several investigators (Bloom, 1959; D'Amore, 1983; Hanson, 1984; Tary, 1999; Tary and others, 2001; and Schnitker and others, 2001). Interpretations of the hydrogeology of this area have been discussed by Bloom (1959), Robert G. Gerber, Inc. (1981), D'Amore (1983), and Hanson (1984). Well logs and other hydrologic data for the York County and southern Cumberland County area were published in Prescott and Drake (1962) and Tolman and others (1983). Long-term continuous groundwater level data are available from USGS well ME YW-807 (http://me.water.usgs.gov; fig. 1), and continuous-record streamflow data for USGS streamgages are available for stations 01069500, 01069700, and 01068910 (http://me.water.usgs.gov; fig. 1). Both of the large water utilities in the study area, the Sanford Water District (SWD) and Kennebunk, Kennebunkport, and Wells Water District (KKWWD), have collected data and conducted small-scale hydrogeological investigations in the study area. These have been a source of most of the well logs used in this study as well as a source of additional hydrogeologic information (Camp, Dresser, and McKee, 1965; Robert G. Gerber, Inc., 1981; Whitman and Howard, Inc., 1981; Whitman and Howard, Inc., 1984; Caswell, Eichler, and Hill, Inc., 1989; Robert G. Gerber, Inc., 1993; Caswell, Eichler, and Hill, Inc., 1995a; Caswell, Eichler, and Hill, Inc., 1995b; Caswell, Eichler, and Hill, Inc., 1995c; CEH-Jacques Whitford, 1997; GS Environmental and Groundwater Associates, Inc., 2002).

Additional sources of data include boring logs from the Maine Turnpike Authority (Maine Turnpike Authority, written commun., 2012), well drillers' reports from the MGS, and surficial seismic lines collected by the MGS for this study (Maine Geological Survey, written commun., 2012).

Groundwater and Surface-Water Resources

The hydrologic system in the study area can be described by the groundwater and surface-water resources that exist within the geologic setting. The geologic materials in the study area are generally saturated with water throughout, except for a shallow unsaturated zone in either the surficial materials or shallow fractured bedrock exposed on hilltops. Rainfall penetrating the surficial materials becomes groundwater, which flows through the surficial glacial materials and shallow bedrock to discharge zones in the streams, rivers, and ocean. Flow paths through the unconsolidated materials are generally short, as the distance to the nearest river or stream discharge point is short (less than 5 miles) for any given location in the glacial aquifer in the study area. Flow paths for groundwater that penetrates deep into the bedrock can be much longer, although shallow bedrock flow paths also may be quite short (less than a few miles) (Gerber, 1988).

Geologic Setting

The geologic units in the study area include fractured crystalline bedrock and stratified, unconsolidated glacial and post-glacial deposits that are draped over the bedrock. The glacial deposits include till (in moraines and as a blanket deposit), stratified marine sand and gravel, marine silt and clay, beach and nearshore sand and gravel deposits, and sandy deltaic deposits. (Smith, 1999e, d, f). More recent sediments include Holocene stream alluvium and Holocene wetlands.

Surficial Geology and Mapped Soils

As numerous authors have written about the glacial and post-glacial history and surficial geology of the coast of Maine south of Portland, this report will not attempt to provide a thorough summary of these studies. Readers are referred to Bloom (1959), Upson and Spencer (1964), D'Amore (1983), Hanson (1984), Smith (1999e,d,f), Tary (1999), Schnitker and others (2001), and Tary and others (2001) for further details of the surficial geology and geologic history of the study area.

In brief, after the last glacial maximum, the melting glacier retreated northward past coastal Maine, leaving numerous deposits as the retreat occurred. The retreat was accompanied by a marine transgression onto the depressed land surface so that sediments carried by the melting glacier were deposited in a shallow marine environment (Weddle and Retelle, 1995; Neil, 1997; Smith 1999d). Deposited underneath the glacier, dense unsorted sediment (till) is the stratigraphically lowermost unit in the study area, overlying the bedrock surface. As the glacier retreated, meltwater carried coarse-grained sediment in channels under the glacier, which settled out as coarse-grained deltaic deposits near the toe of the retreating glacier, most likely in the marine environment (Bloom, 1959; D'Amore, 1983; Weddle and Retelle, 1995; Tary, 1999; Tary and others, 2001), although some ascribe these deltaic deposits to a subaerial deposition framework (Smith, 1999d). These submarine deltaic deposits form most of the sand and gravel aquifers within the study area. Smaller areas of ice-contact deposits (sand and gravel) also are found in a few places in the northwestern one-half of the study area and compose some of the most high-yielding aquifer zones. Farther out to sea from the zone of delta deposition, finer sediments were being deposited across the submarine landscape, with deposits being thicker in the deepest troughs and thinner to non-existent in the shallower areas because of the distribution of ocean currents and wave action (D'Amore, 1983). This deposit formed a widespread silt and clay layer known as the Presumpscot Formation (Bloom, 1960; 1963).

As the glacier retreated farther inland, the land surface rebounded, exposing the marine sediments first to wave action and then to subaerial erosion and deposition. During this phase, the top layer of marine sediments was reworked by wave action, leaving widespread nearshore sandy deposits over some areas of the silt and clay (Weddle and Retelle, 1995; Smith, 1999d). Wind and water further reworked these sediments, creating dune features, exposing till uplands, and filling in stream valleys with alluvial deposits.

A simplified map of the surficial geology of the study area is shown in figure 2. Cross sections showing the interpreted glacial geology at depth in three parts of the study area are shown in figure 3 (see fig. 2 for cross-section locations). A combination of surficial geology mapped by the Maine Geological Survey in the Wells, Kennebunk, Alfred, and North Berwick 1:24,000 quadrangles (Neil, 1999; 1999a–e) and interpretation from recently acquired (2010) lidar data are shown in figure 2. The lidar data primarily were used to adjust the boundaries between the geologic units in areas covered by thick forest cover, as the earlier mapping had much less detailed topographic information to use in drawing the boundaries between units.

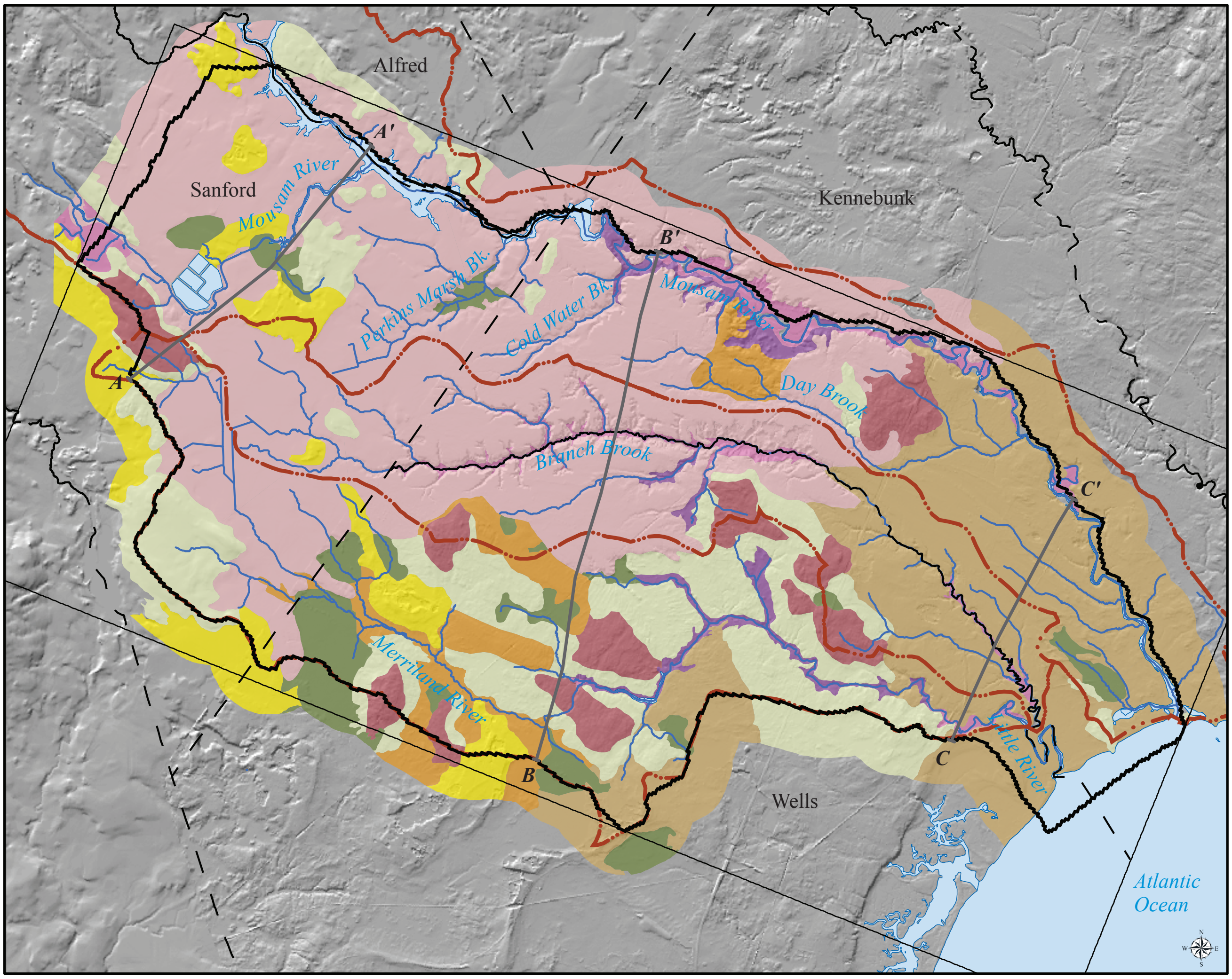
Till is the stratigraphically lowest glacial unit in the study area and directly overlies the bedrock. The till can range from 0 to more than 20 feet thick in well logs, but it is widely distributed across the study area. There are many areas where the glacial deposits are quite thin, and these have been mapped as thin glacial deposits over bedrock (fig. 2). A thin, dense till unit (less than 5 ft thick) is found to directly overlie the bedrock in most drilling records that go all the way to the bedrock surface and is shown as an inferred unit on top of the bedrock in figure 3.

The ice-contact and marine deltaic deposits (described by Smith [1999d, e] as ice-frontal marginal deltas or ice-contact deltas) occur primarily in the western one-third of the study area (figs. 2 and 3, cross section *A–A′*). These are the most coarse-grained deposits described in the study area and are composed of coarse sand and gravel grading to sand. The distal delta deposits (called outwash deltas by Smith [1999d, e]) are more fine grained and overlie a large part of the study area. They are composed of stratified sand, gravel, and silt. They overlie the silt and clay of the Presumpscot Formation in most locations (example shown in fig. 3, cross section *B–B′*). In areas of poor access or exposure (or both), the marine deposits are mapped as “undifferentiated” and may be sandy or silt-clay deposits, or sandy deposits over silt and clay or till.

The stratigraphically uppermost glacial units are nearshore marine deposits, generally deposited above the silt and clay of the Presumpscot Formation in the coastal plain area (fig. 3, cross section *C–C′*). Sandy deposits overlying the silt and clay of the Presumpscot Formation have often been identified as an upper nearshore sand facies of the formation but have sometimes been determined to unconformably overlie the silt and clay (Weddle and Retelle, 1995). Post-glacial alluvium can be found in many of the stream valleys in the study area. Wetlands cover many areas that are flat and poorly drained, either because of underlying fine-grained material (Presumpscot Formation) or the presence of a high water table, or both.

The glacier scoured a surface that ranges from the bedrock highs (340 ft) to buried troughs as much as and exceeding 150 ft below sea level (Upson and Spencer, 1964, D’Amore, 1983, Tary, 1999), which were filled in with glacial sediments during the glacial and post-glacial history described above. The surficial geologic maps do not provide information on the distribution of the geologic units at depth, and the surficial geologic reports provide only a conceptual glacial stratigraphic framework. For this study, more than 150 well logs (fig. 4) contained in numerous consulting reports were examined to help determine the thickness and grain size of the glacial materials below the surface, and more than 500 data points were used (including well and boring logs, outcrops, seismic lines, and drillers reports) to determine the elevation of the bedrock surface. MGS collected an additional 10 seismic lines for this study to help determine the depth to bedrock in the coastal plain area (Camp, Dresser, and McKee, Inc., 1965; Whitman and Howard, Inc., 1981; Whitman and Howard, Inc., 1984; Caswell, Eichler, and Hill, Inc., 1989; Caswell, Eichler, and Hill, Inc., 1995a; Caswell, Eichler, and Hill, Inc., 1995b; Caswell, Eichler, and Hill, Inc., 1995c; CEH-Jacques Whitford, 1997; GS Environmental and Groundwater Associates, Inc., 2002; Scott J., Minor, KKWWD, written commun., 2012; Maine Turnpike Authority, written commun., 2012; Maine Geological Survey, written commun., 2012; Henry Sweatt, private driller, oral commun., 2012). The cross sections (fig. 3) were developed using all of these data. The total thickness of the materials above the bedrock surface and the texture of the materials at depths greater than about 25 feet below the land surface are shown in figure 4.

In the central part of the study area, the geologic materials below the surficial deltaic deposits are silt and clay (Presumpscot Formation; fig. 4). There is a very deep (more than 150 foot [ft]) trough in this area, and the well log for the only boring that penetrated this depth indicated silt and clay all the way to the basal till just above the bedrock (Tolman and others, 1983). In the western one-third of the study area, the total thickness of the surficial materials ranges from 25 to greater than 100 ft (figs. 3 and 4). These surficial materials include a stratified mix of silt (and some clay) and sand that grade westward into coarser materials (predominantly sand and gravel) located in the area of the ice-contact and deltaic deposits deposited closest to the edge of the glacier. Little silt and clay is found at depth in the northwestern and northern part of the study area. In the southeastern part of the study area, a deep trough trends generally north-south; the surficial materials are generally from 50 to 100 ft thick, and are more than 150 ft thick in some places (figs. 3 and 4). Close to the Atlantic Ocean, the materials at depth are described in the well logs to be dominated by silt and clay (Presumpscot Formation); farther inland there is a more heterogeneous mix of silt and clay and sand with little silt and clay in some areas (fig. 4). On the basis of well logs for production and monitoring wells between Branch Brook and the Merriland River (Scott J. Minor, written commun., 2012), there is a deep buried gravel aquifer below the Presumpscot Formation silt and clay not described in any of the previous studies (fig. 4). The sediments described in these well logs include some very coarse gravel deposits interbedded with sand. Figure 3 shows an outline of the possible extent of this buried gravel aquifer. Few well logs in this area penetrated as deep as the bedrock, so this buried aquifer could extend farther north or south than shown.



Water bodies, watersheds, towns, and roads from U.S. Geological Survey digital line graphs 1:24:000, 2010.
Shaded relief from U.S. Geological Survey National Elevation Dataset, 1/3- and 1/9-arc second data, 2013.
North American Datum of 1988
Universal Transverse Mercator projection
State plane Maine West FIPS 1802 coordinate system

Surficial geology modified from Smith (1993, 1999c,d) and Neil (1999)

0 0.5 1 2 3 4 MILES

0 0.5 1 2 3 4 KILOMETERS

EXPLANATION

Surficial geology

- Wetlands
- Alluvium
- Nearshore marine deposits (sandy)
- Ice-frontal marine delta deposits
- Distal delta deposits
- Undifferentiated marine deposits
- Presumpscot Formation
- Till
- Thin glacial deposits over bedrock
- Water bodies

Groundwater model

- Model boundary
- Active model boundary

Watershed boundary

Town boundary

Cross section location

Figure 2. Simplified surficial geology in the area in and around the Branch Brook watershed in southern Maine.

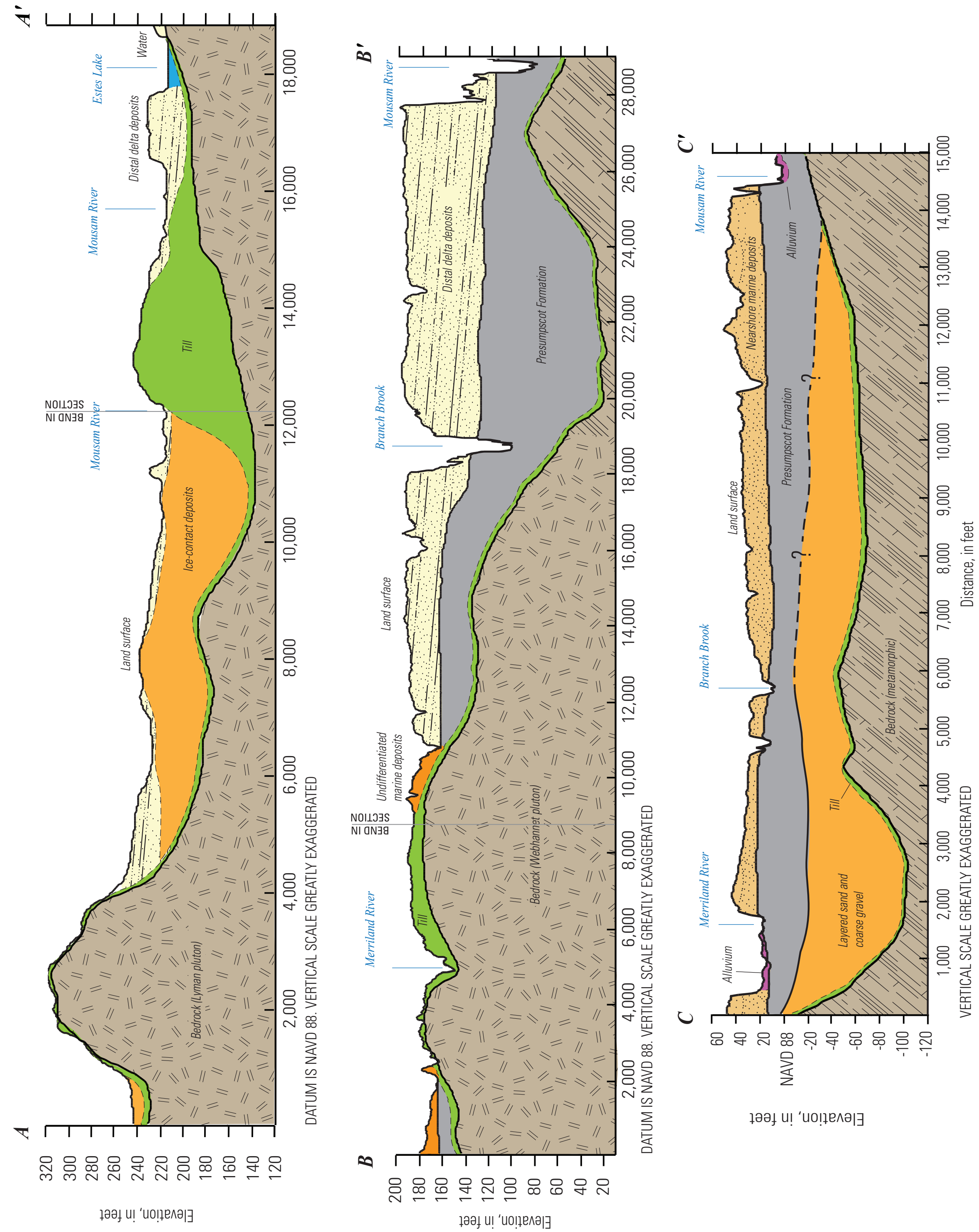
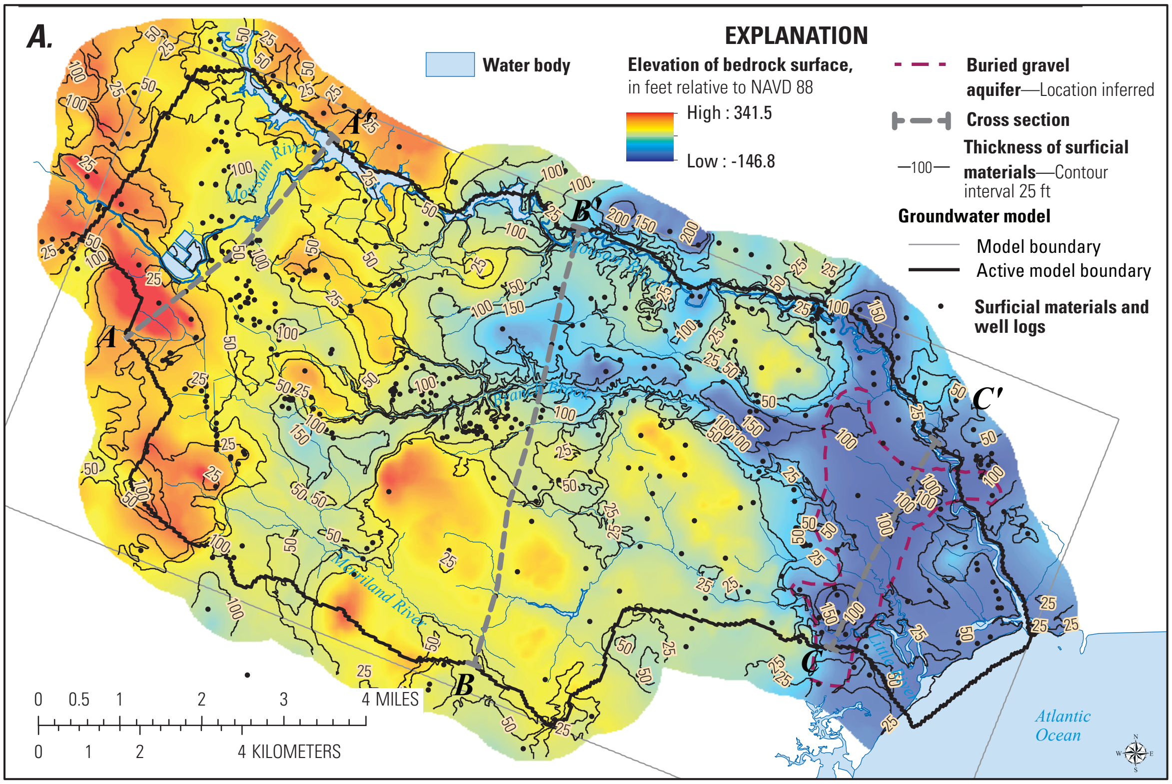


Figure 3. Geologic cross sections *A–A′*, *B–B′*, and *C–C′* for the area in and around the Branch Brook watershed in southern Maine.



Water bodies from U.S. Geological Survey digital line graphs, 1:24,000, 2010. Universal Transverse Mercator projection, zone 19
State plane Maine West FIPS 1802 coordinate system
North American Datum of 1988

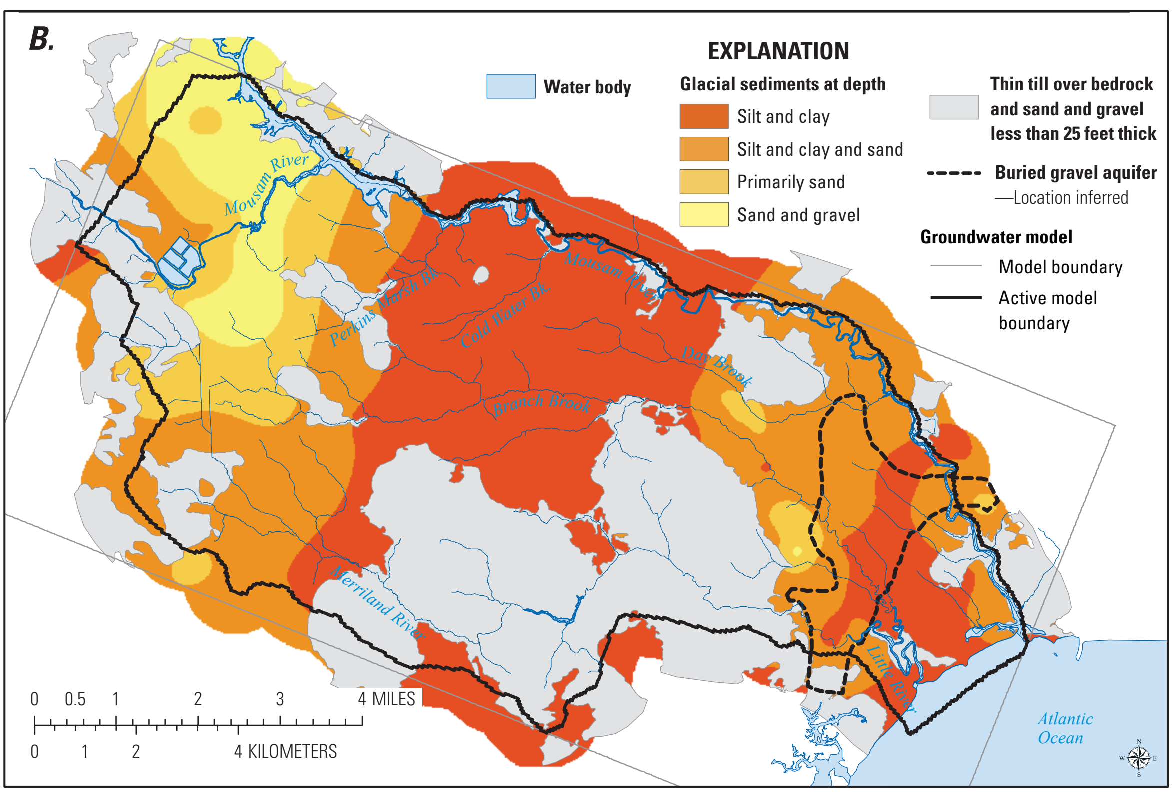


Figure 4. Generalized glacial geology at depths greater than 25 feet below the land surface in the area in and around the Branch Brook watershed in southern Maine: *A*, altitude of bedrock surface and thickness of surficial materials, and *B*, composition of glacial sediments at depth. Datum is North American Vertical Datum of 1988 (NAVD 88).

Bedrock

Bedrock in the study area consists of several Silurian- and Siluro-Ordovician-aged metamorphic rock units intruded by igneous rocks of Permian, Devonian, and Carboniferous age (Hussy and others, 2008). The metamorphic rock units trend northeast-southwest parallel to the coastline. The Silurian Berwick Formation is thrust over the older Siluro-Ordovician rocks of the Merrimack Group along the Nonesuch River fault (Hussey and others, 2008), which crosses the study area along a line roughly parallel to the Sanford town line (fig. 1). The location of this fault is inferred, as the rocks are deeply buried in this location. The western one-third of the study area is underlain by the Permian age Lyman pluton, which is a granite-pegmatite unit (fig. 3, cross section *A–A′*). The Devonian Webhannet pluton (granite) underlies much of the eastern one-half of the Merriland River watershed and the central part of the Branch Brook watershed (Hussey and others, 2008; see fig. 3, cross section *B–B′*).

Groundwater Resources

Groundwater resources in the study area occur in the bedrock units and in the unconsolidated surficial deposits, but the surficial deposits provide the great majority of the available groundwater resource for human use. Groundwater occurs in the bedrock units in fractures, faults, and joints, and the bedrock is generally capable of supplying only a few gallons per minute of water to wells, so it is not considered a major groundwater resource.

Groundwater resources in the study area have been explored since the 1960s when local water utilities searched for sources to use for drinking water supply (for example, Camp, Dresser, and McKee, 1965). The hydrogeologic units supplying groundwater to the public supply wells, irrigation wells, and to a lesser extent domestic wells are primarily the sands and gravels of the ice-contact and marine deltaic deposits (including both the deposits mapped as “ice-frontal marine delta” and “distal delta” deposits) and nearshore marine deposits (fig. 2). The distal deltaic deposits have been explored for public supply purposes and have previously been used for irrigation (D’Amore, 1984; Scott J. Minor, oral commun., 2011) but currently supply only domestic wells. Since 1992, the Maine Department of Conservation, Maine Geological Survey has been delineating sand and gravel glacial deposits in the State that are determined to be a “significant” aquifer, based on field observations of surficial materials, wells, test borings, municipal well inventories, well driller reports, and geophysical investigations. The significant sand and gravel aquifers have been mapped at a scale of 1:24,000 (Neil and Smith, 1998a–d). A “significant” aquifer is one having the potential to yield 10 gallons per minute (gal/min) or more of water to a properly constructed well. In some areas, a thin layer (usually less than 10 ft) of water-bearing sand and gravel material may be readily identifiable on the surface, but if that area was determined as unable to sustain a yield of 10 gal/min or more (because it is not fully saturated or too small in area), that area was not mapped as an aquifer. Conversely, if materials with poor water-bearing properties overlie coarse-grained sediments, the underlying deposit may not have been recognized as a potentially significant aquifer (Dudley, 2004). Figure 1 shows the significant sand and gravel aquifers mapped for this study area (Neil and Smith, 1998a–d) expected to yield (a) 10–50 gallons per minute and (b) more than 50 gallons per minute to a properly constructed well. The delineated aquifers in the study area do not include the buried valley sand and gravel deposit underlying the coastal plain area in Kennebunk and Wells.

Hydraulic Properties

Published estimates of the hydraulic properties (transmissivity or hydraulic conductivity) of the hydrogeologic units in the study area are available from several studies (table 2). These estimates are based on calibrated groundwater modeling studies, aquifer tests, grain-size analysis, slug tests (single-well tests) and other sources. Many of these studies were summarized in Nielsen and Locke (2011) and were done in areas with hydrogeologic units similar to those found in the study area.

Investigations into the hydrogeology of the sand and gravel aquifers in the study area have been limited to the sand and gravels in the central and western part of the study area. The high-yielding aquifer in the town of Sanford has been studied during the process of expanding the municipal water supply and also in protecting it from local point-source contamination sites (Camp, Dresser, & McKee, Inc., 1965; Whitman and Howard, Inc., 1981; Whitman and Howard, Inc., 1984; Robert G. Gerber, Inc., 1993). Pump tests in the coarse sandy ice-contact deposits (mapped as ice-frontal marine delta deposits, fig. 2) yielded transmissivities ranging from 62,000 to 82,000 gallons per day per foot (gpd/ft), or 80–150 feet per day (ft/d) hydraulic conductivities (saturated thicknesses ranging from 70 to 100 ft). Farther east, in the central part of the Branch Brook watershed (mapped as distal delta deposits, fig. 2), the aquifer has been studied for its use for the irrigation of blueberries in the past and was considered for possible use for bottled water extraction (Robert G. Gerber, 1981; Caswell, Eichler, and Hill, Inc., 1989; Caswell, Eichler, and Hill, Inc., 1995a; Caswell, Eichler, and Hill, Inc., 1995b; CEH-Jacques Whitford, 1997; GS Environmental and Groundwater Associates, Inc., 2002). These studies reported pump tests yielding transmissivities ranging from 6,000 to 13,000 gpd/ft or hydraulic conductivities of 40–90 ft/d (saturated thicknesses ranging from 16 to 20 ft). Single-well tests on monitoring wells with shorter screens yielded hydraulic conductivities ranging from 0.8 to 78 ft/d (median of nine tests was 6.4 ft/d) (Caswell, Eichler, and Hill, Inc., 1989). The discrepancy between the single-well tests and the pumping tests suggests that there is considerable heterogeneity in the stratified sand and gravels in this part of the study area and that an average effective hydraulic conductivity for the whole area may be

Table 2. Hydraulic properties of hydrogeologic units in the area in and around the Branch Brook watershed in southern Maine.

[ft/d, foot per day; K, hydraulic conductivity; --, not applicable]

Hydrogeologic unit, location	Horizontal hydraulic conductivitiy, in ft/d	Vertical hydraulic conductivity, in ft/d	Source	Method
Very fine to medium sand, with some silt (similar to marine nearshore sands), Fryeburg, Maine	2 to 5	--	Tepper and others (1990)	Model
Marine nearshore sandy deposits, Freeport aquifer	--	--	Nielsen and Locke (2011)	Model
Presumpscot Formation silt/clay (unweathered), central Maine	6.2×10^{-3} (mean of 32 measurements)	1.4×10^{-4} to 5×10^{-6} (range of three methods)	Brainerd and others (1996)	Movement of natural tracers, age dating, rising-head tests
Presumpscot Formation silt/clay, Saco, Maine	--	2.7×10^{-5}	Nielsen and others (1995)	Movement of natural tracers
Presumpscot Formation silt/clay (several sites)	--	1.2×10^{-4} to 5×10^{-4}	Gerber and Hebson (1996)	Models–compilation of several studies
Stratified outwash sands, Oxford, Maine	15 to 80	--	Morrissey (1983)	Model
Sand and gravel deposits in and near the Branch Brook watershed (central and western portions of the study area)	40 to 170 (range from 5 aquifer tests)	--	Whitman and Howard, Inc., (1981), Caswell, Eichler, and Hill, Inc. (1995a), Caswell, Eichler, and Hill, Inc. (1995b), GS Environmental and Groundwater Associates (2002)	Aquifer tests
Sand and gravel in the central Branch Brook watershed area	0.8 to 78 (median 6.4) from 9 single-well aquifer tests	--	Caswell, Eichler, and Hill, Inc. (1989)	Slug tests
Till, Bald Mountain, Maine	0.045 to 0.91	--	Gerber and Hebson (1996)	Model
Till, Fryeburg, Maine	4	--	Morrissey (1983)	Model
Till, Freeport Aquifer	0.69	--	Nielsen and Locke (2011)	Model
Fractured crystalline bedrock, Connecticut	0.5	--	Melvin and others (1995)	Model
Fractured bedrock aquifer, Meddybemps, Maine	Less than 0.01 ft/d	--	Lyford and others (1998)	Model
Fractured bedrock, Corinna, Maine	0.1 to 1 ft/d	--	Mack and Dudley (2001)	Model

lower than the pump tests suggest if the lower hydraulic conductivity (K) parts of the aquifer materials are widespread.

Streambed and riverbed hydraulic conductivities typically are not measured in the field. Values used in other groundwater modeling studies in Maine and New England range from 0.02 ft/d (Nielsen and Locke, 2011) and 1 ft/d (DeSimone, 2004) to 2–5 ft/d (Tepper and others, 1990).

Recharge

Recharge in the study area has been estimated but not directly measured. D'Amore (1984) reported an estimated recharge amount of 47 percent of precipitation using an energy-balance method. The theoretical maximum amount of shallow recharge to sandy soils is about 25 inches per year (in/yr), based on the Lyford and Cohen (1988) method, or about 54 percent of precipitation. However, more recent studies of the hydrogeology in the study area determined recharge to the sandy aquifer in the Sanford outwash plain area to be very high for Maine, on the order of 60 percent or more of total precipitation (Gerber and Hebson, 1996; Robert G. Gerber, Ransom Environmental Services, Inc. [retired], oral commun., 2013). Nielsen and Locke (2011) reviewed the literature on recharge to several hydrogeologic units in southern Maine and New Hampshire with hydrologic settings similar to the study area, including till, the silt-clay Presumpscot Formation, and sand and gravel deposits. Recharge to the groundwater flow model developed for the Freeport aquifer (Nielsen and Locke, 2011) ranged from 5 inches in till and shallow bedrock areas to 25 inches in the sandy surficial aquifer areas. Published values of recharge into the Presumpscot Formation have been summarized by Gerber and Hebson (1996). Table 3 summarizes available information on recharge to the various hydrogeologic units in the Branch Brook-Merriland River study area.

The presence of unsewered suburban housing developments could add to the total amount of recharge entering the unsaturated zone in some locations. Houses in the study area that are not served by public water supply use either deep bedrock wells or shallow dug wells for their water supply, which is largely returned to the subsurface by way of individual septic systems. Although this process does not change the overall recharge rate, it could act to move water from the bedrock aquifer into the unsaturated zone, effectively increasing the local recharge rate to the uppermost hydrogeologic units. Most houses in the study area use dug wells in the shallow sandy aquifer, so the overall potential increase in recharge to the upper sandy units from septic systems is likely to be very small.

Groundwater Levels

Historical groundwater level measurements in the study area are reported in well logs and some of the consultant's reports, but these are not widely distributed across the study area and cover different time periods. Additional water-level data are available from a long-term groundwater monitoring well (well ME-YW 807) and from a one-time synoptic water-level survey that was conducted for this study in June 2012. Monthly groundwater levels in eight wells in the study area were published for 5 months in 1981–1982 (Tolman and others, 1983), but the wells were not clearly located.

Long-Term Groundwater Levels

The USGS operates a long-term groundwater monitoring well tapping the unconfined aquifer in the middle of the study area (well no., ME-YW 807, site ID 432310070393301), having periodic data going back to 1988. Groundwater levels for this well can be retrieved by visiting the USGS Groundwater Watch web page (http://groundwaterwatch.usgs.gov). Daily water levels in this well are available from the current time (2014) back to October 1989. Figure 5 shows the monthly water-level statistics for this well for the period of record. The median monthly water levels range from 17 to 19.5 feet below land surface, a relatively narrow range that reflects the abundant recharge and coarse-natured aquifer in this area.

Table 3. Recharge rates to unconsolidated and shallow bedrock aquifer materials in southern Maine from previously published studies.

[in/yr, inches per year]

Hydrogeologic unit	Recharge rates reported in literature (from Nielsen and Locke, 2011), in/yr	Recharge rates in calibrated groundwater flow model, Freeport Aquifer (Nielsen and Locke, 2011), in/yr	Recharge rates from other investigations[2] in the Branch Brook area, in/yr
Shallow bedrock	2 to 11[1]	5	1 to 2.5
Till	3.5 to 8	5 to 7	2.5 to 5
Presumpscot Formation silt/clay (fresh, unweathered)	0.5 to 1.9	0.75	
Sand and gravel deposits	22 to 25	24 to 25	19 to 28

[1]Values originally from Nielsen (2002).

[2]Investigations include D'Amore (1983), Robert G. Gerber, Inc. (1981), Robert G. Gerber, oral commun., 2013.

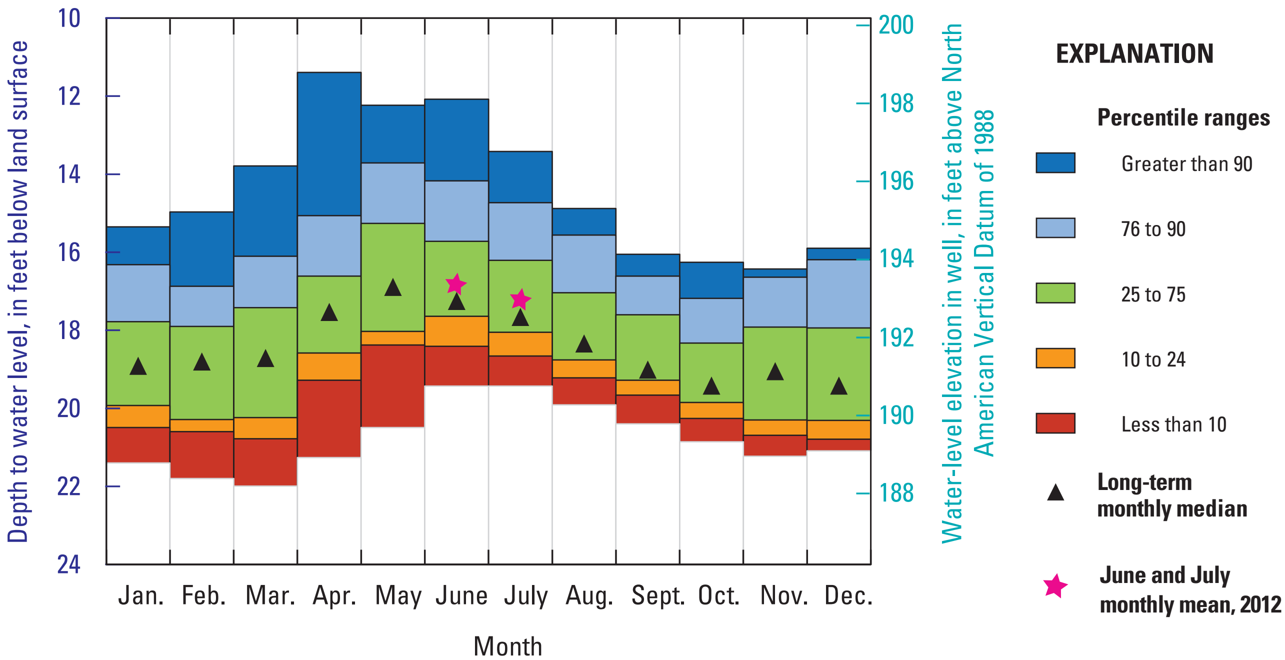


Figure 5. Long-term monthly water-level statistics for the U.S. Geological Survey groundwater monitoring well ME–YW 807 in Sanford, Maine.

Synoptic Water-Level Survey

A synoptic survey of groundwater levels was conducted in late June 2012 to use for calibration points in the model. This time period was chosen because water levels in June and July are normally very close to the annual average water levels in this area, as determined using the ME-YW 807 well (fig. 5) and other USGS sand and gravel monitoring wells in Maine. In the case of June–July 2012, water levels were slightly above the average (fig. 5). Precipitation that occurred in the week prior to the water-level survey resulted in water levels that were generally rising during the week of the survey.

The water-level measurements for this survey were collected from a combination of monitoring wells and homeowner wells (fig. 6). The monitoring wells included wells established by the KKWWD and SWD for periodic monitoring of groundwater levels near their current pumping wells but also in areas that had been considered for other pumping wells. Monitoring wells for some chemical contamination sites in Sanford were included in this survey, along with the ME-YW 807 long-term monitoring well. In total, water levels in 96 monitoring wells were measured between June 21 and June 29, 2012, for this effort, along with water levels in 34 homeowner wells (23 dug wells and 11 bedrock wells). The 10 wells used for a Maine Department of Environmental Protection (DEP) contamination-monitoring study in Sanford were measured on May 23, 2012 (Matthew Reynolds, written commun., 2012). Overall, 130 wells were measured for this effort (wells are listed in appendix 1).

The homeowner wells were measured by USGS staff, and the monitoring wells were measured by a combination of USGS staff, water district employees, Maine DEP and MGS employees, and a consultant hired by the KKWWD. Water-level measurement training was provided to all personnel involved in the water-level survey.

Water levels during the synoptic survey ranged from within 0.1 ft of the land surface to more than 58 ft below land surface. The water-level elevations ranged from a high of 230–232 ft in the water-table aquifer in the Sanford area to 15 ft below sea level in the (confined) buried aquifer near the Merriland River pumping well. Water levels in the sand and gravel monitoring wells averaged about 14–16 feet below land surface in the Sanford and central Branch Brook watershed areas. A limited number of shallow-deep well pairs indicated a slight downward gradient in the Sanford area and the area just north of Branch Brook, and a stronger downward gradient in the sand plain to the south of Branch Brook. Wells in the headwaters of Branch Brook indicated an upwards hydraulic gradient. In the areas around the pumping wells in the southeastern part of the study area, water levels averaged more than 33 ft below land surface in the upper unconfined sand and gravel aquifer and more than 42 ft below land surface in the confined aquifer near the Merriland River pumping well. The only shallow-deep well pairs near the Harriseckett and Plant wells were too close to the pumping wells to determine a representative hydraulic gradient. Water levels in a shallow-deep well pair 800 ft from the Merriland well indicated a strong downward

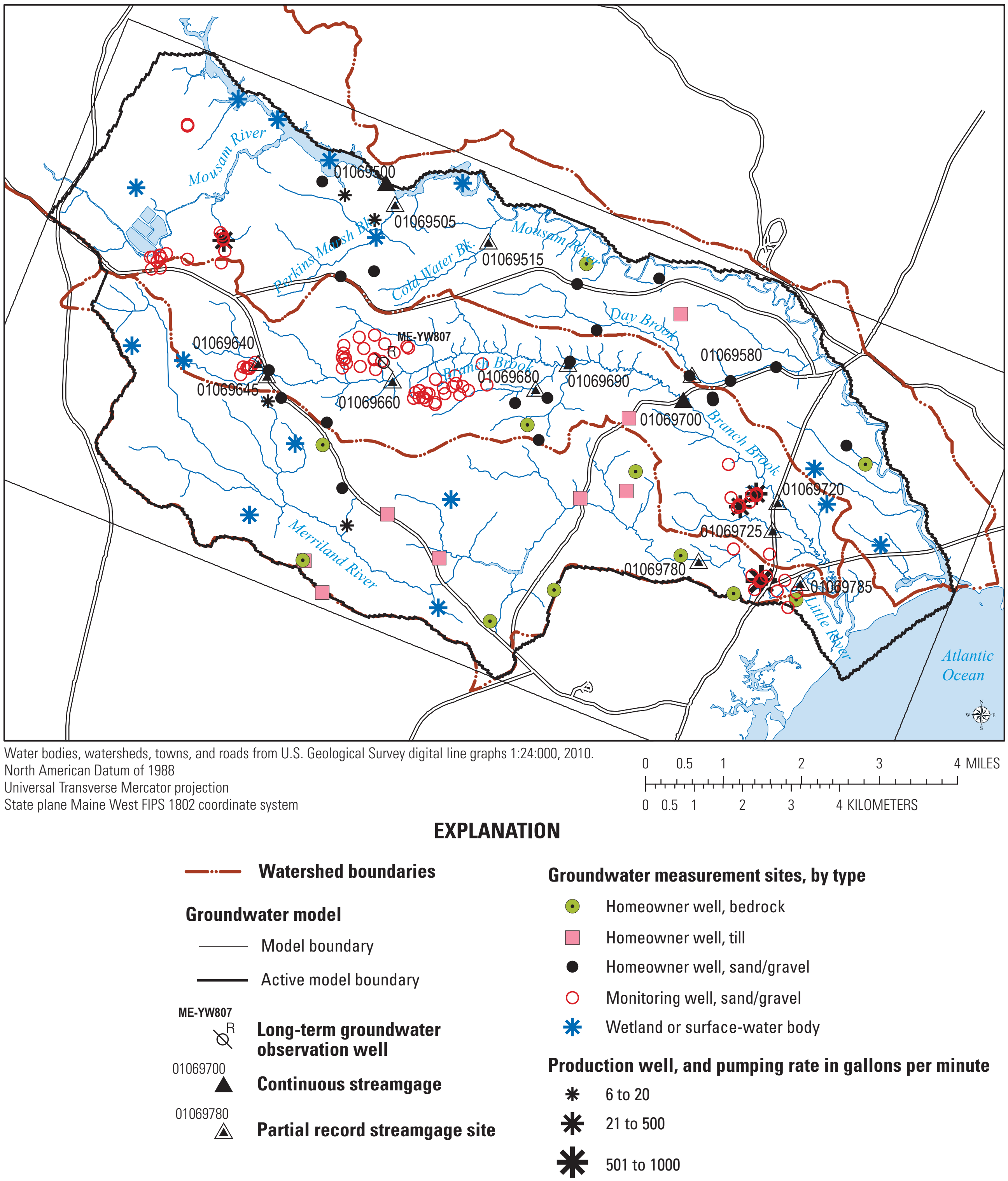


Figure 6. Locations of groundwater and streamflow measurement sites in the area in and around the Branch Brook watershed in southern Maine from 2010 through 2012.

gradient. Water levels in the homeowner wells were generally shallower; water levels in the till and sandy aquifer dug wells averaged less than 5 ft below land surface. In bedrock wells, water levels averaged 16 ft below land surface. There were no well pairs that included bedrock wells.

Groundwater Flow System

The groundwater levels and geometry of the surface-water system indicate the general groundwater flow directions within the study area, whereas the hydrogeologic units are defined by the surficial geology. The groundwater flows generally from west to east, following the overall topographic trend, and from the topographic highs between rivers and streams towards the closest surface-water feature.

In the western part of the study area (Sanford area), the sand and gravel deposits are quite thick (60 ft to over 100 ft; see figs. 3 [cross-section *A–A′*] and 4). The Mousam River acts as a regional groundwater discharge zone in this area, and groundwater generally flows towards the closest surface-water body. There is no large-scale confining unit, although silt/clay lenses are interspersed in the sand and gravel. A groundwater divide exists somewhere between the headwaters of Branch Brook and the Mousam River. Because the surface of the outwash delta deposits has such low relief, the location of the groundwater divide is not well defined by the surface topography. Another groundwater divide separates groundwater flowing to the headwaters of Branch Brook from water flowing to the headwaters of the Merriland River. Similarly, its location is not well-defined by the surface topography (fig. 1).

In the Branch Brook watershed, the Presumpscot Formation fills a deep bedrock valley (fig. 4*A*), and the significant aquifer materials are deposited in a 30- to 50-ft thick sandy unit above the Presumpscot Formation. The saturated thickness of these units ranges from 10 to approximately 40 ft. Branch Brook itself is incised completely through the sand and gravel and into the Presumpscot Formation, and groundwater flows towards the river, discharging in springs and short, steep tributaries incised into the sand and gravel. Recharge percolates through the surficial sandy soils to the water table. North of the Branch Brook watershed, the shallow groundwater discharges to tributaries to the Mousam River and to the Mousam River itself, which forms a regional groundwater divide. The Presumpscot Formation acts as a significant barrier to vertical groundwater flows between the surficial aquifer and bedrock in the central part of the study area (fig. 3).

In the headwaters of the Merriland River watershed, groundwater flow is considered to be from northwest to southeast, based on the topography and location of the mapped sand and gravel aquifer materials and location of streams. However, some groundwater may flow directly to the east, towards Branch Brook (which is topographically lower than the Merriland River headwaters), and some groundwater may flow south across the watershed boundary where the mapped sand and gravel aquifer straddles the watershed boundary in the southern part of Sanford (fig. 1). There were not enough groundwater wells in this area to determine flow directions independently. Groundwater in the rest of the Merriland River watershed exists in thin sand or till deposits over bedrock or in thicker till, neither of which are significant groundwater resources. Groundwater flow is generally from the upland areas towards the nearest surface-water body.

The central part of the study area is separated from the coastal plain by a northeast-southwest trending bedrock ridge, through which the Merriland River, Branch Brook, and the Mousam River flow (fig. 2). This bedrock high limits shallow groundwater flow towards the ocean and the coastal plain, as the shallow sandy aquifer material in the Branch Brook and Mousam River valleys is severely constricted in this area.

East of the bedrock high, the topography is relatively flat, and the three river valleys flatten and join in the coastal plain area, discharging to the ocean quite close to one another. In this area (generally east of Interstate-95, fig. 1), groundwater is found in shallow, unconfined aquifer areas and in a deeper sand and gravel aquifer underneath the coastal plain.

The shallow sediments in the coastal plain are a layered mix of coarse to fine sand and silt and clay. They are coarsest near the bedrock ridge and get progressively finer towards the ocean. The surficial sandy units are approximately 20 to 50 ft thick over the Presumpscot Formation. In some places, mucky peat overlies the silt and clay of the Presumpscot Formation instead of sand. At depth, a deep buried valley is at least partially filled with coarse sand and gravel. This is largely covered with the silt and clay of the Presumpscot Formation, which forms a partial confining unit that overlies much of this aquifer (figs. 3 and 4). The extent of this sand and gravel deposit is not well mapped, but from well logs it appears to trend in a northeast-southwest direction. Seismic lines were used to help identify the extent of the bedrock valley but could not be used to determine the nature of the sediments filling the valley. The source of recharge to this unit, which is used as a drinking water supply by the local water utility, is not well defined. On the basis of pumping and water-level records on file with the local water utility, this sand and gravel deposit is at least partially connected to the shallower coarse sands near the bedrock high (to the west-northwest) and extends south beyond the Merriland River watershed boundary.

On the southwest side of Branch Brook, water levels are 20–40 ft below land surface, and natural flow gradients are somewhat disrupted by the Harriseckett and Plant pumping wells, but flow gradients are still generally towards the Merriland River and Branch Brook surface-water features. Between Branch Brook and the Mousam River, the water table gradients are particularly flat, and the water table is quite shallow. Much of this area is covered by forested wetlands because of the high water table and, in some areas, because of the presence of the Presumpscot Formation silt/clay, which retards vertical groundwater movement. Beneath the Presumpscot Formation in the buried gravel aquifer, the groundwater flow is affected primarily by the Merriland River pumping well, which draws groundwater from both the north and south within this aquifer.

Groundwater in the bedrock units in the study area is assumed to discharge to the local surface-water bodies (rivers and streams or the ocean) where the Presumpscot Formation does not directly overlie the bedrock and act as a barrier to flow. There is little evidence indicating whether or not there is groundwater exchange between the bedrock units and the surficial aquifers in the study area. Although there is a large regional fault system that crosses the study area, it is just as likely to act as a barrier to bedrock groundwater flow as it is to act as a conduit. There are no data to indicate that the fault system affects the surficial aquifers in any particular manner. Besides this feature, it is expected that there would be some small amount of groundwater interaction between the coarse-grained units that overlie the bedrock and the shallow bedrock but an insignificant amount of interaction where the Presumpscot Formation overlies the bedrock.

Surface-Water Resources

There are three primary rivers within the study area. They are, from north to south, the Mousam River, which defines the northern boundary of the study area; Branch Brook; and the Merriland River, which is farthest to the south. The Branch Brook and Merriland River watersheds (13.4 and 17.3 mi^2, respectively) together cover most of the study area and are of primary concern in this study. The remainder is the part of the Mousam River watershed that falls between the Branch Brook watershed and the Mousam River itself to the north. (figs. 1 and 6). The USGS has operated a streamgage on the Mousam River (station 01069500) from 1939 to 1985 and 2008 to the present (2014) and has operated a streamgage on Branch Brook (station 01069700) since 2008. In order to better understand the groundwater–surface-water interactions within the study area, 12 additional streamflow monitoring sites were established for this study (fig. 6) and are described below.

Streamflow monitoring sites were established on the Merriland River, Branch Brook, and tributaries to the Mousam River (fig. 6). Approximately 16 measurements were made at each of these sites during 2010–11 (table 4). Six separate locations along Branch Brook were measured between U.S. Route 1 (fig. 1) and the headwaters (including the USGS streamgage [station 01069700] and stations 01069640, 01069645, 01069660, 01069690, and 01069720). Two tributaries to Branch Brook also were measured (stations 01069680 and 01069725). Two sites on the Merriland River were measured, one above the confluence with Branch Brook and the Little River (station 01069785) and the other about 1.5 miles upstream (station 01069780). The Merriland River pumping well is located between these two sites. Finally, three tributaries to the Mousam River were measured—Day Brook

Table 4. Streamflow measurement site information, Mousam River, Branch Brook, and Merriland River watersheds in southern Maine from 2010 through 2012.

[ID, identification number; USGS, U.S. Geological Survey; mi^2, square miles; ft^3/s, cubic feet per second; --, not applicable; S., south; ME, Maine; Trib, tributary; Br., brook; nr, near; Rte, U.S. Route; R., river]

Station number	Local ID	Station name	USGS continuous gaging station	Drainage area (mi^2)	Number of measurements (2010–12)	Range in measured streamflows (in ft^3/s)
		Mousam River Watershed				
01069505	Perkins Marsh	Perkins Marsh Brook near South Sanford, Maine	--	2.74	17	0.77–8.59
01069515	Cold Water	Cold Water Brook near Kennebunk, Maine	--	0.84	16	1.46–2.88
01069580	Day Brook	Day Brook at Whitten Road near Kennebunk, Maine	--	1.78	16	.87–5.08
		Branch Brook Watershed				
01069640	BB#7	Branch Brook near South Sanford, Maine	--	1.41	16	.31–11.03
01069645	BB#6	Branch Br. at Sam Allen Hill Rd., S. Sanford, ME	--	1.74	17	.48–10.81
01069660	BB#5	Branch Brook near Saywards Corner, Wells, Maine	--	3.51	17	2.48–17.8
01069680	BB#4	Trib to Branch Br. nr Hobbs Crossing, Wells, ME	--	1.17	17	.23–3.21
01069690	BB#3	Branch Brook near Wells, Maine	--	7.60	17	7.67–24.8
01069700	BB#2	Branch Brook near Kennebunk, Maine	Yes	9.67	--	
01069720	BB#1	Branch Br. at Post Rd (Rte 1), Kennebunk, Maine	--	11.6	18	.04–33.0
01069725	BB#8	Trib to Branch Br. at Post Rd (Rte 1) nr Wells, ME	--	1.04	17	.22–4.29
		Merriland River Watershed				
01069780	Merri#2	Merriland River at Coles Hill Rd nr Wells, Maine	--	15.8	16	2.76–41.5
01069785	Merri#1	Merriland R. at Skinner Mill Rd near Wells, Maine	--	16.7	16	2.07–33.6

(station 01069580), Cold Water Brook (station 01069515), and Perkins Marsh Brook (station 01069505). These three flow generally northward from the edge of the Branch Brook watershed to the Mousam River. All these sites were measured to gain an understanding of how groundwater discharge was distributed geographically around the study area to use in calibrating the groundwater flow model.

Streamflow Measurements

Between 15 and 17 measurements representing a range of flows were obtained at each station (table 4) so that mean monthly flow estimates and base-flow estimates could be computed for each site. Most sites had 16 measurements completed. All the measurements were made following standard USGS techniques, using a pygmy meter, AA meter, or a 3-inch modified Parshall flume (Rantz and others, 1982). Measurements were made between June 1, 2010, and April 7, 2012, with more measurements being made during the summer than during the spring and fall. No measurements were made between the middle of November and April during this period. The flows measured ranged from low summer flows through high flows in the spring and fall. At the most downstream measurement site on Branch Brook (BB#1, station 01069720, at the U.S. Route 1 bridge), measurements were made downstream from the intake for surface-water withdrawals. The amount of withdrawal was added back to the measured flows to obtain the flow at that site before the withdrawal.

A summary of the measurements taken along Branch Brook is shown in figure 7. The flows for a representative selection of dates are plotted in downstream order at each of the Branch Brook measurement sites, illustrating the downstream accumulation of flow from the uppermost site (BB#7, station 01069645) to the most downstream site (BB#1, station 01069720) to the intake just below BB#1. Flows increase in a linear manner all along the length of the stream until the segment between BB#2 (USGS streamflow gage, station 01069700) and BB#1 where the increase in flow slows down.

The Branch Brook streamgage (station 01069700) has not been operating long enough to collect long-term statistics, but the mean annual flow for 2011–13 was 21.6 ft^3/s. The mean annual flow at the Mousam River site (station 01069500) for the same years was 201 ft^3/s, as compared to the long-term mean of 188 ft^3/s; this suggests that the data-collection time period was somewhat wetter than average for the study area.

Although the total runoff in cubic feet per second per square mile (ft^3/mi^2) from Branch Brook is similar to the State average (2.24 ft^3/mi^2 in Branch Brook at station 01069700 for water years[1] 2011–2013, compared to the statewide median for water years 2011–2013 of 2.34 ft^3/mi^2), a larger percentage of that runoff likely occurs as groundwater discharge (base flow) rather than as direct runoff from precipitation events because of the coarse-grained soils and small number of surface tributaries in the watershed. The groundwater model, described in the section on the simulation of groundwater flow later in this report, can simulate groundwater discharge (base flow) but not direct runoff from individual precipitation events nor total runoff (base flow plus direct runoff).

Calculation of State Requirements for In-stream Flows

The in-stream flow requirements (seasonal aquatic base flows) for the State of Maine (also known as the Chapter 587 rules) are designed to protect the aquatic health of riverine ecosystems and vary with the seasons (Maine Department of Environmental Protection, 2007). The State uses estimates of natural monthly flows, sometimes combined with site-specific geomorphic analysis, to evaluate streamflow requirements in support of aquatic habitat where a proportionally large withdrawal is identified in a watershed. The in-stream flow requirements are specific to six time periods—winter (January 1 to March 15), spring (March 16 to May 15), early summer (May 16 to June 30), summer (July 1 to September 15), fall (September 16 to November 15), and early winter (November 16 to December 31); each of these is based on estimates of median monthly streamflows. Chapter 587 states that, without site-specific flow data, the monthly median flows can be determined by using statewide flow equations developed by Dudley (2004). These equations use watershed characteristics (such as area and precipitation) to estimate monthly median flows and confidence intervals around those estimates. The State requirements also indicate that site-specific hydrologic data may be used to calculate the monthly median flows. Site-specific estimates of the median monthly flows is likely better suited to the specific site than the statewide equations (Nielsen and Locke, 2011).

For this study, a comparison was made between the in-stream flow requirements calculated from the statewide equation estimates of monthly median flows and monthly median flows calculated using site-specific data at the farthest downstream measurement sites in Branch Brook and the Merriland River (stations 01069725 and 01069785).

Monthly Median Streamflows and In-stream Flow Requirements Based on Statewide Flow Equations

The equations in Dudley (2004) were used to derive estimates of monthly median flows at stations 01069720 and 01069785 using watershed data given in table 5. Both watersheds have similar areas, precipitation amounts, and distances from the Gulf of Maine line, but differ dramatically in the percentage of mapped sand and gravel aquifers (table 5, fig. 1). This manifests primarily in the summer median monthly flows (table 6), as the differences in fall and winter median flows are driven by differences in drainage area size.

The six seasons that are defined in the Chapter 587 requirements are winter, spring, early summer, late summer, fall, and early winter. The streamflow requirements for those

[1]A water year is the 12-month period from October 1 to September 30. It is designated by the year in which it ends.

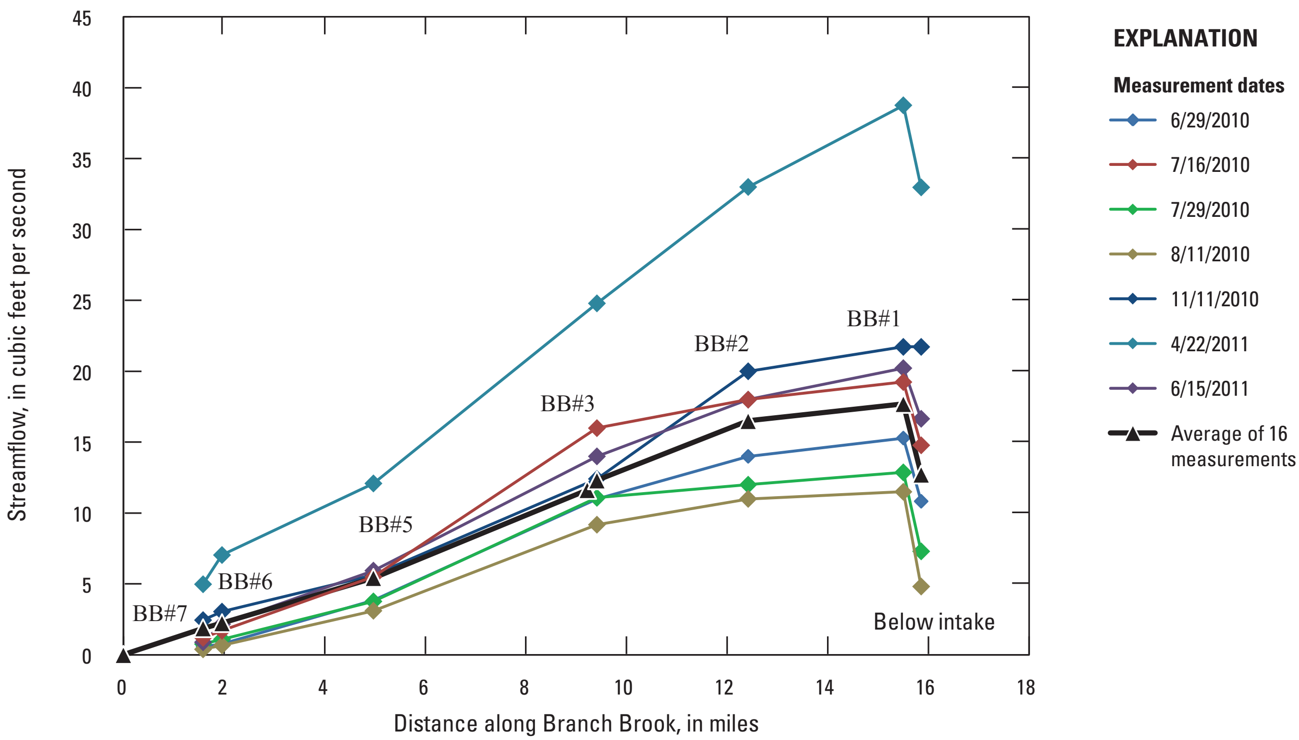


Figure 7. Streamflows measured on Branch Brook for selected dates between April 2010 and August 2011, southern Maine.

Table 5. Watershed characteristics for the calculation of monthly median streamflows for Branch Brook and the Merriland River in southern Maine.

[For definitions and derivations of watershed characteristics, see Dudley (2004)]

Watershed characteristic	Branch Brook (01069720)	Merriland River (01069785)
Drainage area, in square miles	13.6	16.7
Distance from Gulf of Maine line, in miles	27	27
Percent sand and gravel aquifer	65.3	23.2
Annual precipitation, in inches	47.1	47.1
Winter precipitation, in inches	11.5	11.5

Table 6. Median monthly streamflows in Branch Brook and the Merriland River in southern Maine based on statewide equations.

[ft³/s, cubic feet per second]

Month	Median monthly streamflows, in ft³/s	
	Branch Brook (01069720)	Merriland River (01069785)
January	25.1	31.1
February	27.6	34.1
March	57.8	71.0
April	66.0	81.2
May	19.6	24.4
June	12.2	15.2
July	19.5	9.22
August	20.3	7.18
September	19.2	7.17
October	26.9	11.4
November	16.8	20.6
December	30.1	37.0

seasons are based on the median flows for the months of February, April, June, August, October, and December. The seasonal in-stream flow requirements based on the statewide equations for Branch Brook (at station 01069720) and the Merriland River (at station 01069785) are shown in figure 8. Note that the June median flow for Branch Brook deviates from a smooth transition between the spring and summer flows because the statewide equation for June does not include a term for the percentage of sand and gravel aquifers, although the later summer months do.

Monthly Median Streamflows Based on Site-Specific Streamflow Measurements

As stipulated in the Chapter 587 rules, site-specific data may be used to calculate median monthly flows. In this study area, the streamflow measurements described above were used with streamflow data from several continuous-record streamflow gages to estimate the monthly median flows using the MOVE.1 method (Hirsch, 1982), as was done in the Freeport aquifer study (Nielsen and Locke 2011). The MOVE.1 regression method (also called the line of organic correlation) is used to estimate statistics representing long-term data at a given site, using short-term data collected over a range of hydrologic conditions at that site and concurrent data collected at a long-term index site (Hirsch, 1982; Helsel and Hirsch, 2002).

Several index stations in western Maine and southern New Hampshire were tested for correlations with the streamflows collected at the Branch Brook and Merriland River sites. The best correlations for the MOVE.1 regression were obtained for index stations close to and within the study area (Mousam R. [station 01069500] and Branch Brook [station 01069700]) and southeastern New Hampshire (Bearcamp River at Tamworth, New Hampshire, station 01064801). Whereas the correlation coefficients between the local sites and the Branch Brook streamgage were very high for both sites (greater than 0.90 for both locations), the Branch Brook streamgage does not have the minimum 10 years of continuous record for an ideal index site. Therefore, the other two index sites were used with the Branch Brook streamgage to calculate the monthly flow statistics, which are an average of the estimates using two index sites (table 7). It should be noted that the median monthly streamflow estimates from the two index sites used for each location differ slightly from one another. For example, the Branch Brook site (station 01069720) and the Branch Brook streamgage (station 01069700) yield estimates that are equal to or lower than the estimates from the Mousam River streamgage (station 01069500). Once the Branch Brook streamgage has the minimum 10 years of streamflow required for a statistically stable index site, a recalculation of these values could yield median monthly streamflow estimates for station 01069720 that are slightly lower in some months. The converse, however, holds for the Merriland River—that is, the Branch Brook streamgage yields somewhat higher estimates than the Bearcamp River streamgage (station 01064801).

Comparison of Monthly Median Streamflows and Late Summer In-stream Flow Requirements Using the Two Methods

The monthly median flows calculated using the site-specific data are considerably different from the median flows estimated from the statewide equations (fig. 9) for many months of the year. The annual hydrograph for Branch Brook calculated using the MOVE.1 technique is much flatter and shows much less variation than the annual hydrograph based on the statewide equations. The MOVE.1 annual hydrograph also does not display the same lack of smooth transitions from month to month seen in the statewide equation hydrograph. In the Merriland River, the annual hydrograph shows a similar degree of monthly variation using the two methods, but the MOVE.1 estimates are significantly lower for every month. However, as noted above, once the Branch Brook streamgage (station 01069700) reaches 10 years of continuous data, new calculations could raise the MOVE.1 estimates for the Merriland River.

The late summer season is normally the season with the lowest in-stream flow requirement, as it is typically the time of year when streamflows are lowest in Maine. The August median flow is used as the in-stream flow requirement for late summer if there is not a specific waiver or alternative-method flow established (such as a geomorphic analysis). The August median flow in the Merriland River was calculated as 7.18 ft^3/s using the statewide equations but was 3.07 ft^3/s using the MOVE.1 analysis. In Branch Brook, the August median flows were 20.3 ft^3/s using the statewide equations (which is higher than the June median flow) and 11.8 ft^3/s using the MOVE.1 analysis. Clearly, in each case, using site-specific data yields an estimate of the August median flow that is much lower than the statewide equations provide. Using site-specific data provides target median flows that are closer to actual conditions in the local streams than what the statewide equations provide and which would therefore be easier for a regulated utility to maintain for meeting in-stream flow requirements.

Because the statewide equations (Dudley, 2004) are predictions based on a statistical analysis of many other watersheds, the predicted residual sum of squares (PRESS) statistic can be used to calculate prediction intervals for each month, as well as the individual monthly predicted value (Dudley, 2004; Riggs, 1968). The prediction intervals (table 8) indicate the level of certainty surrounding the individual monthly predicted value. The flows bounded by the prediction interval would be expected to contain the *actual* (measured) flow for a given stream 90 percent of the time. The monthly median streamflows estimated using the record extension method (MOVE.1) for Branch Brook fall well within the 90-percent prediction intervals only for the months January, July, and November (table 8). The rest of the time, the MOVE.1 flows are either outside the 90-percent prediction interval or near the

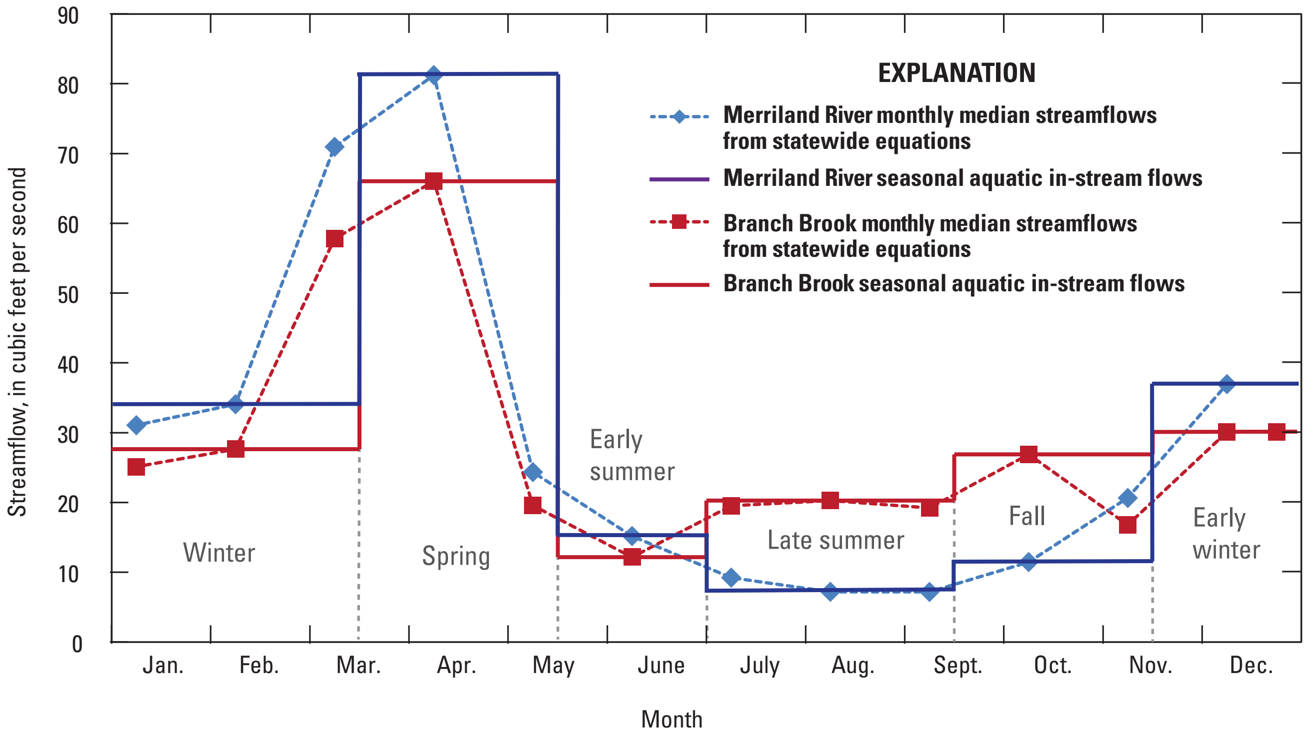


Figure 8. Seasonal aquatic in-stream flow requirements calculated for Branch Brook and the Merriland River in southern Maine from statewide equations.

Table 7. Median monthly flows in Branch Brook and the Merriland River in southern Maine based on site-specific streamflow data and regressions with local index sites.

[ft³/s, cubic feet per second; R., River]

Month	Branch Brook (01069720) median monthly streamflows, in ft³/s			Merriland River (01069785) median monthly streamflows, in ft³/s		
	Based on index sites		Mean of Branch Brook and Mousam R. medians	Based on index sites		Mean of Branch Brook and Bearcamp R. medians
	Mousam R. gage (01069500)	Branch Brook gage (01069700)		Bearcamp R. gage (01064801)	Branch Brook gage (01069700)	
January	25.7	20.2	**23.0**	9.63	12.1	**10.9**
February	26.0	20.2	**23.1**	7.82	12.1	**10.0**
March	33.5	34.2	**33.9**	19.3	43.7	**31.5**
April	42.2	35.3	**38.8**	34.2	47.2	**40.7**
May	30.1	24.5	**27.3**	18.4	19.4	**18.9**
June	22.5	22.4	**22.4**	7.58	15.5	**11.5**
July	15.7	15.9	**15.8**	4.13	6.77	**5.45**
August	12.0	11.6	**11.8**	2.99	3.15	**3.07**
September	13.8	12.2	**13.0**	3.12	3.52	**3.32**
October	18.4	15.9	**17.2**	7.95	6.77	**7.36**
November	23.1	19.7	**21.4**	15.7	11.3	**13.5**
December	26.9	24.5	**25.7**	14.8	19.4	**17.1**

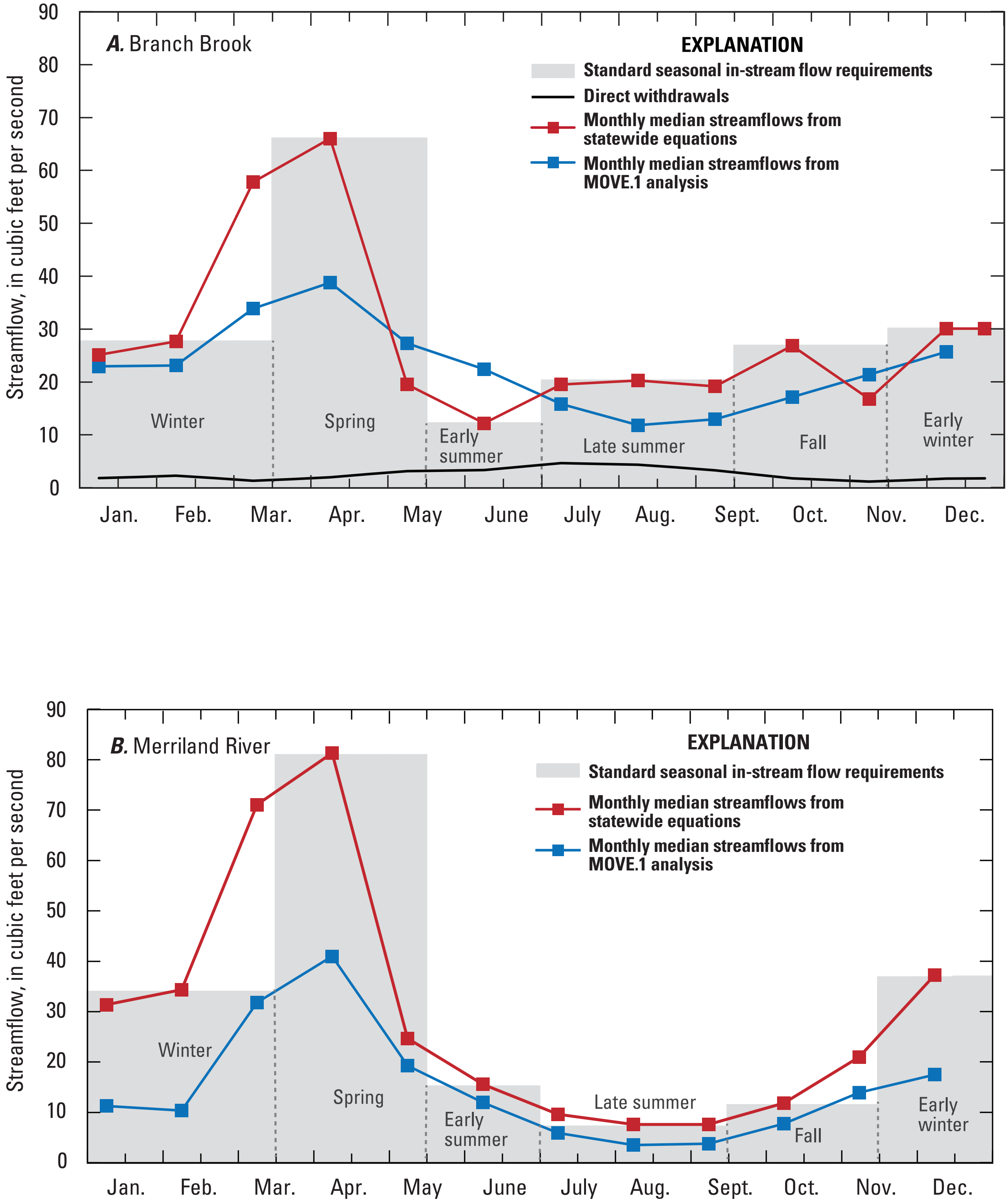


Figure 9. Comparison of annual hydrographs for *A*, Branch Brook and *B*, the Merriland River in southern Maine using two estimation methods, and the standard seasonal aquatic in-stream flow requirements calculated using statewide equations.

Table 8. Comparison of monthly median streamflows for Branch Brook and the Merriland River in southern Maine.

[Prediction intervals for monthly median streamflows estimated using the Maine statewide equations from Dudley (2004) and monthly median streamflows were calculated using a record extension technique for Branch Brook and the Merriland River. For method of calculating prediction intervals, see Dudley (2004). MOVE.1, method of variance extension, type 1, see Hirsch (1982)]

Month	Branch Brook estimates, in cubic feet per second				Merriland River estimates, in cubic feet per second			
	Monthly median streamflow estimated using record-extension technique (MOVE.1)	Monthly median streamflow calculated using statewide equations	Upper 90-percent prediction interval on statewide equation streamflows	Lower 90-percent prediction interval on statewide equation streamflows	Monthly median streamflow estimated using record-extension technique (MOVE.1)	Monthly median streamflow calculated using statewide equations	Upper 90-percent prediction interval on statewide equation streamflows	Lower 90-percent prediction interval on statewide equation streamflows
January	23.0	25.1	34.3	18.4	10.9	31.1	42.4	22.7
February	23.1	27.6	36.0	21.2	10.0	34.1	44.4	26.1
March	33.9	57.8	81.8	40.9	31.5	71.0	100.4	50.2
April	38.8	66.0	99.4	43.8	40.7	81.2	122.3	54.0
May	27.3	19.6	28.8	13.3	18.9	24.3	35.9	16.5
June	22.4	12.2	18.9	7.8	11.5	15.2	23.6	9.8
July	15.8	19.5	33.0	11.6	5.5	9.2	15.6	5.5
August	11.8	20.3	36.1	11.4	3.1	7.2	12.8	4.0
September	13.0	19.2	32.8	11.2	3.3	7.2	12.3	4.2
October	17.2	26.9	48.4	14.9	7.4	11.5	20.6	6.4
November	21.4	16.8	30.6	9.2	13.5	20.6	37.6	11.3
December	25.7	30.1	39.0	23.2	17.1	36.9	47.9	28.5

edge of it, indicating that the Branch Brook watershed is quite different from most of the watersheds that were used to derive the statewide equations. The MOVE.1-calculated streamflows for the Merriland River are well below the lower 90-percent prediction interval for the statewide equations calculated for the Merriland River for the months of December through April (table 8). The MOVE.1 estimates for the months of May through November are very close to the lower 90-percent prediction intervals from the statewide equations. In the case of the Merriland River, the apparent over-prediction of monthly median streamflows by the statewide equations may be an artifact of the possibly low estimates from the MOVE.1 method, as suggested above, or it may be because the regression equations used in the statewide flow statistics calculations do not include all the watershed characteristics that together explain the actual streamflows. In either case, as an alternative method of calculating or estimating the monthly median streamflows at these two sites, the MOVE.1 method is more apt to provide estimates that are closer to values that would be obtained from a long-term streamgage because it uses data collected at each specific site, and that are therefore likely closer to the “true” values of monthly median streamflows. The MOVE.1 analysis also was used to estimate early summer base flows to use as calibration targets for the groundwater flow model described later in the report.

Water Use and Withdrawals

Withdrawals of water for human use include drinking water, industrial, commercial, and agricultural (irrigation and other agricultural uses) from wells and streams, and rural domestic use from homeowner wells. Large water withdrawals in the State of Maine are governed by several Maine laws, implemented by multiple State agencies. Maine’s In-Stream Flows and Lake and Pond Water Level Rules (Chapter 587) apply to most water withdrawals and are intended to protect natural aquatic life and other designated uses in Maine’s waters. Under Chapter 587 rules, withdrawals are not regulated (and are not reported) if they do not affect river or stream flows by a certain percentage (which varies by the U.S. Environmental Protection Agency water-quality classification) or if they do not affect water levels in a lake or pond by a certain amount. The State laws are aimed at protecting the natural resource by requiring that flows be maintained but do not require reporting of water withdrawals for most water users. Because comprehensive reporting is not required, data on water withdrawals are not always available for a given watershed, and estimates based on water use coefficients or other methods must be applied to account for all potential water withdrawals.

Sources of Water Use Data

This study used a combination of reported and estimated withdrawal data to obtain an estimate of the total amount of water withdrawal in the study area. Reported withdrawals for public supply were obtained from the Maine Drinking Water Program in 2010 (Andrews Tolman, written commun., 2010). Estimates of withdrawals for rural domestic use, agricultural use, and commercial/industrial use that is not connected to the public water supply were made using methods described below. Wastewater discharge data are from the U.S. Environmental Protection Agency (undated) National Pollution Discharge permits.

Reported Withdrawals

There were six public water suppliers in the study area in 2010 that reported withdrawals to the State of Maine. Four of these were small community systems serving mobile home parks or subdivisions with their own water supply, each serving a population of less than 200 persons. The other two, the SWD and the KKWWD, each serve relatively large populations of 14,000 and 31,400, respectively. The SWD withdraws groundwater from a single source within the study area (although they use several other groundwater sources outside the study area); the KKWWD withdraws a mix of surface water (from Branch Brook) and groundwater from multiple wells, one of which is outside the study area. The reported withdrawals for KKWWD are not broken down by source, so staff at the KKWWD provided information on withdrawals from each of the groundwater sources (Scott D. Minor, Assistant Superintendent, KKWWD, written commun., 2013) and surface-water withdrawals. Commercial and industrial water users in the Sanford area generally are served by the Sanford Water District and are included in the public water supply category (table 9). In the KKWWD service area, there is little industrial activity, but commercial users within the service area are likewise included in the public water supply categories.

Estimated Withdrawals

Several methods were used to estimate other withdrawals in the study area. Domestic water usage from private wells was estimated using a geographic information system (GIS) analysis of houses located from high-quality aerial photography and maps of the extent of public water-supply service areas for the towns of Sanford, Kennebunk, and Wells. Rates of private water withdrawals were based on a per-person water use coefficient of 60 gal/d per person in Maine (U.S. Geological Survey water use compilation for Maine, unpub. data, 2010) and census data on the number of persons per household in each town (U.S. Census Bureau, 2010). Commercial and industrial water usage outside the public-supply service areas was estimated using a combination of GIS mapping, internet searches, and a commercially available business database (HarrisInfosource) to locate businesses, and the application of water-use coefficients for New England (Horn, 2000; Horn and others, 2007) for different types of industrial and commercial uses. Agricultural water use was estimated using information on irrigated acreage in the study area from the Maine Department of Environmental Protection (J. Harker, written commun., 2010), internet searches of farms in the study area, and irrigation rates determined for 2010 in the 2010 U.S. Geological Survey water use compilation for Maine (U.S. Geological Survey water-use compilation for Maine, unpub. data, 2010). Personal reconnaissance also was used to identify other water withdrawals (a fish hatchery).

Reported and Estimated Withdrawals in the Study Area

Surface-water withdrawals in the study area in 2010 were primarily withdrawals from Branch Brook by the KKWWD in the amount of 590 Mgal (2.63 ft^3/s). Agricultural irrigation from surface-water ponds was estimated to be about 9 Mgal.

Groundwater withdrawals account for the remainder of the withdrawals. These include the permitted public water supplies, domestic water use, commercial and industrial water use, and other agricultural water use (table 9). In 2010, permitted public water-supply withdrawals totaled 384.3 Mgal in the Merriland River watershed, 231.5 Mgal in the Mousam River watershed, and 32.2 Mgal in the Branch Brook watershed, for a total of 658.8 Mgal (2.79 ft^3/s). Domestic withdrawals from a total of 1,751 residences identified from aerial photos were split fairly evenly among the watersheds: 32.2 Mgal in the Merriland River watershed, 32.1 in the Mousam River watershed, and 24.6 in the Branch Brook watershed, with a small amount (0.15 Mgal) in the coastal areas (table 9). Domestic wells in the study include those using bedrock, till, and the sandy surficial aquifers. Of the domestic withdrawals, estimates of the percent that percolates back into the subsurface through individual septic systems range from 84 to 96 percent (Ralf Topper, Colorado Geological Survey, written commun., 2007). Commercial and industrial water use that is not served by public water suppliers in the study area is small in relation to these other uses: 1.1 Mgal in the Merriland River watershed, 0.7 Mgal in the Mousam River watershed area, and 0.5 Mgal in the Branch Brook watershed. The remaining agricultural usage that relies on groundwater in the study area is even smaller, less than 0.3 Mgal across the study area (table 9). In all, the study identified 599.6 Mgal/yr in surface-water withdrawals (2.54 ft^3/s) and 730.3 Mgal/yr in groundwater withdrawals (3.09 ft^3/s).

The Sanford Sewerage District operates a municipal wastewater-treatment facility near the Mousam River in the City of Sanford. This facility treats wastewater from the City of Sanford, including residential, commercial, and industrial water users in the northwestern section of the study area, including the area around the Sanford withdrawal well. Wastewater discharges for the Sanford Sewerage District averaged 660 Mgal/yr (or 1.8 Mgal/d, 2.8 ft^3/s) from 2009

Table 9. Estimated withdrawals from groundwater and surface water, 2010, for the area in and around the Branch Brook watershed in southern Maine by water use category.

[Mgal/yr, million gallons per year; R., River; Rd., Road; --, none]

Name or sub-category	Number of houses not on public supply	Estimated number of persons	Surface-water withdrawals, Mgal/yr			Groundwater withdrawals, Mgal/yr		
			Merriland River	Branch Brook	Mousam River	Merriland River	Branch Brook	Mousam River
Domestic and public water-supply withdrawals								
Domestic water use from private wells (estimated)								
Mousam R.	629	1,467	--	--	--	--	--	32.1
Branch Brook	488	1,123	--	--	--	--	24.6	--
Merriland R.	634	1,472	--	--	--	32.2	--	--
Public water supply withdrawals (reported values for 2010)								
Mobile home park "A" [1]			--	--	--	--	--	8.1
Mobile home park "B" [1]			--	--	--	--	--	3.3
Merriland well[2]			--	--	--	384.3	--	--
Harriseckett and Plant wells[2]			--	--	--	--	32.2	--
Branch Brook withdrawals[2]			--	590.5	--	--	--	--
Mobile home park "C" [1]			--	--	--	4.7	--	--
Mobile home park "D" [1]			--	--	--	6.1	--	--
Sanford well[3]			--	--	--	--	--	220.1
Subtotals, domestic and public water supply			--	**590.5**	--	**427.4**	**56.8**	**263.6**
Commercial and industrial withdrawals (estimated)								
Schools (very small)			--	--	--	0.085	--	--
Very small restaurant (<13 employees)			--	--	--	0.12	--	--
Small restaurants (13–17 employees)			--	--	--	0.26	--	--
Amusement facilities (small)			--	--	--	0.067	--	--
Special trade contractors, unclassified			--	--	--	0.30	--	--
Computer integrated systems design			--	--	--	0.29	--	--
Saw and planing mills			--	--	--	--	--	0.63
Nondurable goods, unclassified			--	--	--	--	--	0.08
Excavating and grading work			--	--	--	--	0.28	--
Hotel/motel (very small or seasonal)			--	--	--	--	0.21	--
Subtotals, commercial/industrial			--	--	--	**1.12**	**0.49**	**0.71**
Agricultural withdrawals (estimated)								
Irrigated cropland			3.1	--	6.0	--	.09	--
Livestock			--	--	--	--	--	.02
Fish hatcheries			--	--	--	--	.12	--
Subtotals, agriculture			**3.1**	--	**6.0**		**.21**	**.02**
Total estimated withdrawals, all categories								
Total withdrawals, all categories			**3.1**	**590.5**	**6.0**	**428.5**	**57.5**	**264.3**
Total withdrawals in cubic feet per second (ft^3/s)			**0.013**	**2.63**	**0.025**	**1.82**	**0.24**	**1.12**

[1]Maine Drinking Water Program, written commun., 2012. Names withheld for protection of sensitive infrastructure.

[2]Scott D. Minor, written commun., 2013.

[3]Sanford Water District, written commun., 2013.

through 2012. The Kennebunk Sewer Department operates a wastewater-treatment facility that discharges to the Mousam River approximately 2.75 mi upstream from the mouth of the Mousam River. Wastewater discharges for the Kennebunk Sewer Department averaged 290 Mgal/yr (0.8 Mgal/d, or 1.2 ft^3/s) from 2008 through 2011.

Approximately 6 mi^2 of the study area is served by public water districts, and approximately 4.6 mi^2 of the study area is served by public sewer systems. Wastewater from the unsewered areas that receive water supply from water districts returns to the groundwater system through domestic wastewater systems. The housing density within most of the approximately 1.4 mi^2 that returns wastewater to the groundwater system is generally low- to medium-density residential. Septic system return-flow rates for low- and medium-density residential areas could be on the order of 1.2 to 4.8 in/yr (DeSimone, 2004), or 0.08 to 0.3 Mgal/d, for the 1.4 mi^2 area.

Simulation of Groundwater Flow and Discharge to Streams

The groundwater modeling component of the study was used to further develop the conceptual model of groundwater flow and the interaction of groundwater with streamflow in the study area. A steady-state groundwater model of the study area was constructed using the three-dimensional, finite-difference groundwater flow modeling code, MODFLOW–2005 (Harbaugh, 2005). This model was used to simulate flow in the unconsolidated glacial deposits and shallow bedrock units.

Conceptual Model of the Groundwater Flow System

As described in the earlier section on groundwater flow, groundwater flow in the study area occurs primarily in the sand and gravel deposits overlying either bedrock or the fine-grained silt/clay sediments of the Presumpscot Formation, with the exception of the coarse-grained sand and gravel body under the coastal plain area, which is stratigraphically below the Presumpscot Formation. Thin deposits of till overlying the bedrock are not significant water-bearing deposits in the study area, although in some areas where till is at the land surface it is thick enough to provide water to shallow dug wells. Groundwater is recharged locally and discharges to the Mousam River, Merriland River, Branch Brook, water-supply wells, and the ocean.

Steady-State Numerical Groundwater Flow Model

The unconsolidated materials and shallow bedrock contained within an area defined by the watersheds of the Merriland River and Branch Brook plus adjacent parts of the Mousam River watershed were included in the groundwater flow model area shown in figure 10.

The groundwater system is represented by a 7-layer steady-state model (fig. 11); there were insufficient long-term groundwater level data available for a transient model of the whole study area. The bottom two layers represent the upper zone of the bedrock units, which were included in the model to investigate the potential amount of interaction between groundwater in the unconsolidated units and bedrock and to provide numerical stability for the model overall. The upper five layers represent the unconsolidated glacial materials and, in areas where the glacial material is thin, the upper zone of the bedrock aquifer.

The model was calibrated using available water-level data collected between June 21 and 29, 2012, which are considered a reasonable representation of the long-term average water levels (see earlier section on groundwater levels), and estimates of the long-term average base flows in the local rivers and streams.

Parameter estimation (also referred to as optimization) was used in the calibration phase. Model variables such as recharge, streambed conductance, and hydraulic conductivities were set up as parameters in the model. Head and streamflow measurements were set up as the calibration targets or observations. Insensitive parameters and others that could not be estimated were set and adjusted by hand using a trial and error process.

Spatial Discretization of the Model

The model area was discretized into a grid of 443 rows and 214 columns of cells with a uniform 150-ft spacing. The grid was rotated to the northeast at an angle of 23 degrees to coincide with the major axis of the deltaic deposits that compose the study area aquifers. Areas of the grid outside the modeled watersheds were inactive (fig. 10). The top of layer 1, the uppermost layer, is set equal to the land surface, which was interpolated from a lidar-derived digital elevation model in the eastern two-thirds of the model area, and from a standard 10-meter digital elevation model (DEM) derived from topographic maps in the town of Sanford (U.S. Geological Survey 1/3- and 1/9-arc second topographic data from the National Elevation Dataset at http://nationalmap.gov/elevation.html). The upper two layers are both convertible between confined and unconfined, depending on the vertical position of the water table. The bottom of layer 2 is either 25 ft below land surface or at the top of the silt-clay of the Presumpscot Formation, whichever is deeper (fig. 11). The composition of layers 1 and 2 varies spatially with the geology and includes the upper sandy aquifer materials, till, or bedrock, depending on the geology (fig. 11). Where the water table is below 17.5 ft from the land surface, layer 1 is inactive. If layer 1 is dry (inactive), layer 2 is unconfined.

The lower five layers of the model are simulated under confined conditions. Layers 3 through 5 consist of the

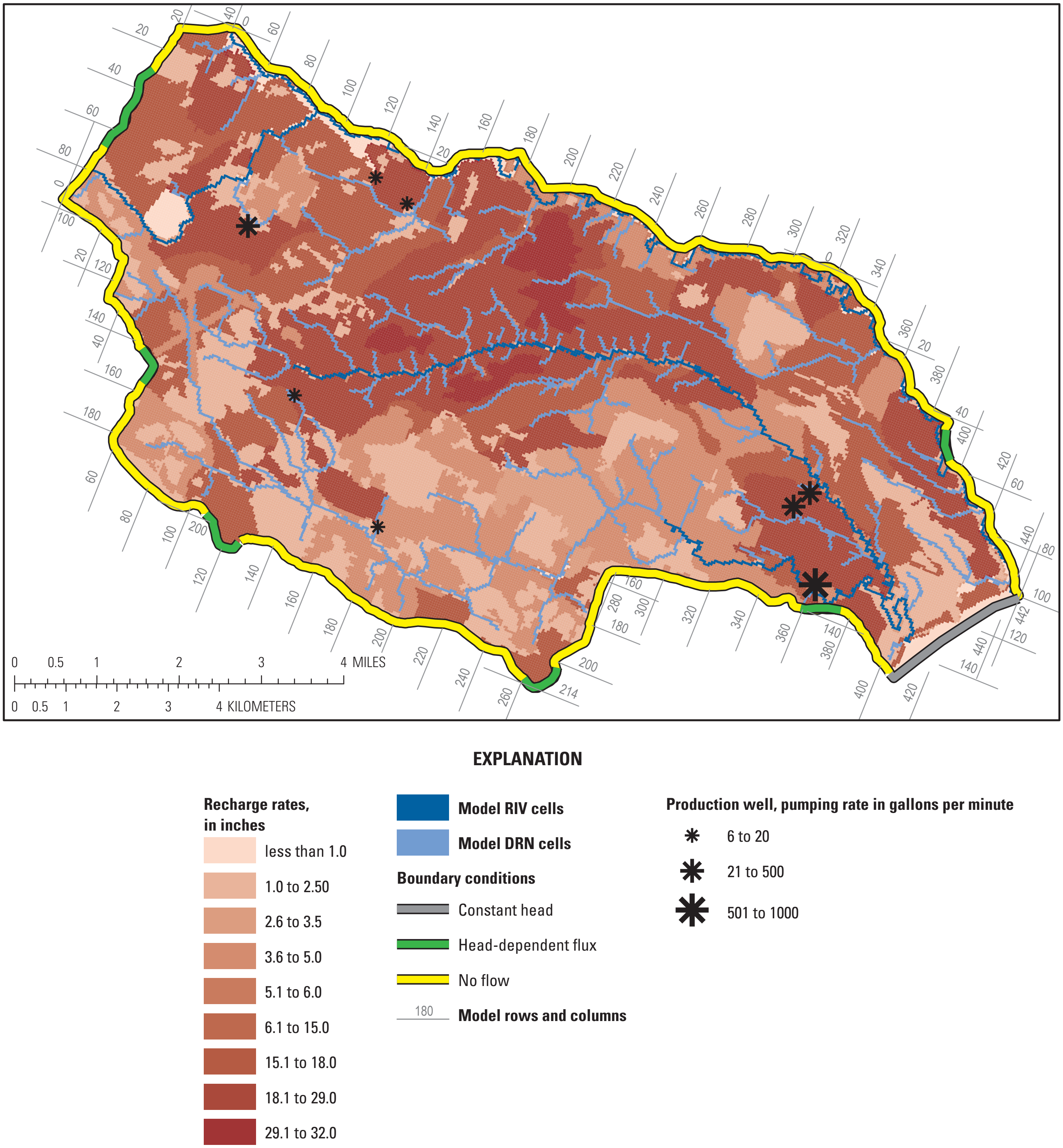


Figure 10. Model grid and boundary conditions for the numerical groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

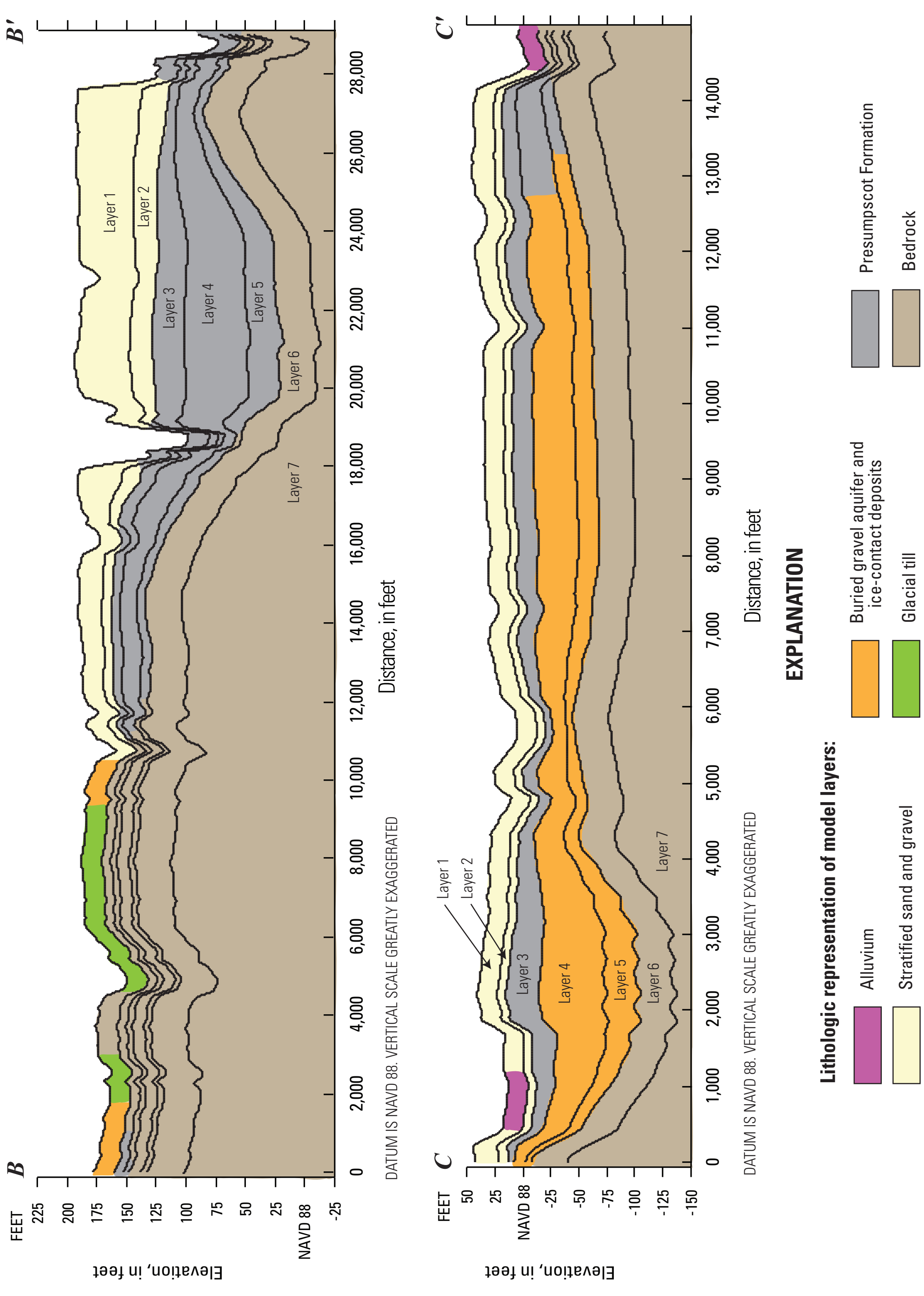


Figure 11. Representation of model layers for cross-sections *B–B′* and *C–C′* in the area in and around the Branch Brook watershed in southern Maine.

remainder of the unconsolidated surficial materials or shallow bedrock where the surficial materials are less than 25 ft thick (fig. 11). Where the Presumpscot Formation is present, it is represented in layers 3 through 5. Figure 11 shows the vertical layering of the model across two of the cross sections illustrated in figure 3. Cross section *B–B′* crosses the model at approximately model column 210, and cross section *C–C′* crosses the model at model column 366. The bottom of layer 5 is the bedrock surface where the bedrock surface is more than 45 ft below land surface or at 45 ft if the surficial units are less than 45 ft thick. Layers 6 and 7 represent 300 ft of bedrock, with layer 6 representing the top 30 ft of this thickness and layer 7 the remainder.

Boundary Conditions

The extent of the groundwater model area is defined as much as possible by inferred groundwater divides (as determined by topographic divides) around the study area, using the bedrock highs of the Merriland River watershed as the southern model edge. The topographic divides are treated as no-flow boundaries, with exceptions as outlined below. The northern model edge is defined by the Mousam River, which is incised into the silt and clay of the Presumpscot Formation along much of its length, which would prevent any appreciable groundwater movement under the river. The Mousam River is modeled as a no-flow boundary. The primary concern of the model on the western edge is in the headwaters of the Merriland River and Branch Brook, but as there is no clear groundwater divide to use in this area, the model boundary was moved inland to include more of the Mousam River watershed so that there would be few (if any) effects of the boundary on the model area of interest.

As shown in figure 1, the watershed boundaries defining the western and southern edge of the area included in the active model area fall across small sections of mapped sand and gravel aquifer. These were defined in the model as head-dependent boundaries (general head boundaries) to account for small amounts of groundwater flow and to reduce any boundary effects they might cause (fig. 10). These general head boundaries (GHBs) are active from the land surface to the bottom of the surficial sand and gravel aquifers. Additionally, as the possible extent of the buried sand and gravel aquifer under the coastal plain became evident, GHBs were added in layers 3 through 5 crossing the model boundary south of the Merriland River and across the Mousam River to allow for inflow to the model from buried sand and gravel outside the model boundaries.

Discharge to rivers and streams was simulated using the Drain (DRN) and River (RIV) packages (Harbaugh, 2005) in MODFLOW. Small streams were simulated using the DRN package (fig. 10), where stream discharge is modeled as a head-dependent flow across the stream bottom, which is one-directional and no water transfer occurs if the simulated head in the aquifer drops below the defined elevation of the stream bottom. As described in the earlier section on groundwater flow, springs are particularly common along some of the short, steep tributaries to Branch Brook, and also to tributaries to the Mousam River. Individual springs were not mapped for the study, being very numerous (Charles Fitz, University of Southern Maine, written commun., 2011). Discharge from stream segments containing springs was handled with a separate leakance value from the other stream segments, although they were both simulated using the DRN package. Larger rivers, including the Mousam River, the main stem of Branch Brook, and the downstream part of the Merriland River (fig. 10), were simulated in the model using the RIV package, in which flux can move in either direction between the aquifer and the river bottom, depending on the head in the aquifer and the river stage.

The ocean is modeled as a constant head boundary. The elevation of the top of the cells that are ocean is derived from the digital elevation model used for the study area. Cells below layer 1 are treated with an equivalent freshwater head approach, in which the constant head is increased as the depth of the cell center increases such that the head is equal to $1 + 0.025*depth$.

Stresses

The stresses applied to the groundwater system in the model include recharge and pumping. Evapotranspiration was not modeled explicitly but is included implicitly in the recharge stress.

Recharge was applied as a constant flux to the top active cell in the model. The spatial variation in recharge rates (fig. 10) was based on a combination of soil drainage classes and surficial geologic units. Recharge rates were treated as model parameters during the optimization phase of model calibration and were adjusted within a range of reasonable values, which were determined on the basis of previous studies and a review of the literature for other recharge rates used in New England groundwater studies. Some of the recharge rates used in the calibrated model are quite high compared to other New England groundwater studies. The high measured base flows in the streams in the study area (Branch Brook, Cold Water Brook, and Perkins Marsh Brook in particular) largely determined the need for high recharge rates in the coarse-grained deposits in the central and western parts of the study area. Previous groundwater modeling efforts in the study area (Robert Gerber, oral commun., 2012) also required unusually high recharge rates, which corroborates this finding. The recharge rates used in the calibrated model are between 5 and 63 percent of total precipitation. A few areas within the sandy part of the central Branch Brook watershed have very sparse vegetation, which limits the evapotranspiration potential of these areas substantially. The recharge rates in those areas were increased to 70 percent of total precipitation.

Because of the small extent of the unsewered residential areas receiving public water supply (approximately 2.7 percent of the study area), the model does not explicitly account for the potential increase in recharge from domestic septic return flow. As most of the private well septic discharge percolates back into the local groundwater system from which it was withdrawn, recharge rates were not altered in the rural residential areas either.

Pumping from the eight water-supply wells in the study area was simulated using the WEL package (Harbaugh, 2005). Pumping for each well location was divided equally between model layers, depending on the screened intervals of the pumping wells. Pumping rates for the four small water-supply wells (table 10) were based on reported withdrawals on file with the Maine Drinking Water Program (Andrews Tolman, written commun., 2010) and were between 3 and 8 gallons per minute (gal/min). These wells were assumed to pump year round. Pumping from the larger municipal pumping wells (table 10) was based on reported pumping rates and data from the water utilities (Scott D. Minor, Assistant Superintendent, Kennebunk, Kennebunkport and Wells Water District, written commun., May 2014; David Parent, Superintendent, Sanford Water District, written commun., September 2013). The Sanford well pumps continuously at about 400 to 450 gal/min. The Harriseckett, Plant, and Merriland River wells pump at rates of 150, 350, and 1,000 gal/min but only during the summer months. The pumping rates used in the model for these wells (table 10) were based on how long they had been pumping at the time of the water-level survey in June 2012. The Merriland River well was simulated using the full 1,000 gal/min pumping rate (192,000 ft^3/d), as it had been pumping for several months at the time of the survey. Lacking data to indicate how long the Plant and Herriseckett wells take to reach steady state with respect to streamflow depletion in the local rivers, these two wells were assigned withdrawal rates in the model that were 70 to 75 percent of their full pumping rates, as they had been turned on within less than a month of the water-level survey.

Hydraulic Properties

Hydraulic properties used in the model included streambed and riverbed hydraulic conductivity, horizontal hydraulic conductivity in the hydrogeologic units, anisotropy, and vertical hydraulic conductivity. These hydraulic properties were represented as parameters and adjusted during the model calibration and parameter estimation within reasonable limits determined by previous investigations and literature surveys. The parameter zones were distributed primarily on the basis of the surficial and bedrock geology and were adjusted and simplified somewhat during calibration. The unconsolidated deposits were simulated using 12 parameter zones representing 11 hydrogeologic units (table 11). These include the nine geologic units shown in figure 2 plus a zone representing the buried gravel aquifer (in layers 4 and 5; see figs. 3 and 11, cross section *C–C′*) under the coastal plain, a zone representing surface-water bodies, and a multiplier zone used for the Presumpscot Formation areas. As described earlier, the Presumpscot Formation is simulated in layers 3 through 5 of the model. However, the transition from coarse sandy material in the western part of the model to the silt and clay of this unit is not abrupt, but occurs gradually. Therefore, a dataset representing this spatially graded hydraulic conductivity distribution was used to represent the Presumpscot Formation and horizontally equivalent unconsolidated deposits in the model (layers 3 through 5). The hydraulic conductivity of this zone ranges from 50 ft/d in the Sanford area to 0.02 ft/d in the Mousam River/Branch Brook area. The multiplier zone was used to adjust the values in this zone up or down during parameter estimation. The vertical anisotropy for the surficial hydraulic conductivity units ranged from 1:10 to 1:200 in the final model. The high degree of anisotropy needed for the model reflects the vertically heterogeneous nature of many of the deposits and the fact that lenses of silt and clay can be found in many of the coarse-grained units.

Model areas used to simulate surface-water bodies (ponds, reservoirs, the Atlantic Ocean; fig. 1) were assigned hydraulic conductivity values of 5,000 ft/d. Using a very high value for hydraulic conductivities in these areas effectively simulates the lack of resistance to water flow and allows the elevation of the water body to be simulated rather than proscribed.

The bedrock is represented by five hydraulic conductivity zones, which range from 8×10^{-4} to 0.35 ft/d (table 11). The uppermost part of the bedrock is reported to be more fractured than the deeper zones (Randall and others, 1988) and is therefore represented with a slightly higher hydraulic conductivity than much of the rest of the bedrock areas. The vertical anisotropy in the bedrock units ranges from 1:1 to 1:10.

Streambed and riverbed conductivities were determined by calibration, within reasonable ranges determined from the literature. The riverbed conductivities used in the RIV package ranged from 0.1 ft/d in the Merriland River to 1.5 ft/d in Branch Brook. Streams and seeps simulated with the DRN package had streambed conductance values of 1.44 and 0.57 ft/d (table 12).

Model Calibration Using Parameter Estimation and Observations

Methods outlined in Hill and Tiedeman (2007) were followed during calibration using the UCODE_2005 software package (Poeter and others, 2008). These methods allow for the explicit accounting for uncertainty in the water levels and streamflows used as calibration targets, documenting the model sensitivity to model variables (parameters) and sensitivity to data used in the model.

Statistics on the fit of the model to the observed values (the ability of the model to reproduce the observations) are used as the dependent variables in the parameter estimation, whereas the model parameters are set up as independent variables through a series of linear and nonlinear regression calculations. The optimization of the parameter values is done using an iterative process, during which the output of each model iteration is used to determine parameters that can be

Table 10. Pumping wells simulated in the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

[fig., figure; ft, feet; gal/min, gallons per minute; ft^3/d, cubic feet per day; R., River; yr, year; approx., approximately]

Well name	Map number (fig. 1)	Watershed	Depth, in ft	Model layers	Pumping regime	Pumping rate, gal/min	Pumping rate in model (ft^3/d)
Sanford well	1	Mousam R.	65	4	365 days/yr	400–450	86,624
Mobile home park “C” well	4	Merriland R.	10	1	365 days/yr	4.5*	1,728
Mobile home park “A” well	2	Mousam R.	64	4, 5, 6	365 days/yr	7.4*	2,972
Mobile home park “D” well	5	Merriland R.	15	1	365 days/yr	5.6*	2,246
Harriseckett well	7	Branch Brook	45	3, 4	Approx. 34 days/yr	150	20,000
Mobile home park “B” well	3	Mousam R.	264	3, 4, 5	365 days/yr	3.0*	1,210
Merriland River well	8	Merriland R.	128	4, 5	6 months/yr	1,000	192,000
Plant well	6	Branch Brook	56	3, 4	Approx. 53 days/yr	350	50,000

*Reported to the State as an annual total volume; rate shown assumes constant (24 hours/day) pumping.

Table 11. Hydrogeologic units and corresponding hydraulic properties.

[ft/d, feet per day; Fm., Formation; NA, not applicable]

Unit	Parameter name	Composite scaled sensitivity	Estimated?	Calibrated value (ft/d)	Vertical anisotropy
Hydraulic properties for unconsolidated units					
Holocene alluvium	HK_Alluvium	1.3	Yes	1.97	1/100
Nearshore marine deposits	HK_MrnSand	2.7	Yes	3.56	1/100
Undifferentiated marine deposits	HK_PmUndiff	0.95	Yes	1.49	1/100
Presumpscot Fm. (in layers 1–2)	HK_Presump	1.9	Yes	0.19	1/100
Ice-frontal delta deposits	HK_Delta1	0.54	Yes	27.9	1/50
Distal delta deposits	HK_Delta2	5.5	Yes	6.30	1/100
Glacial till	HK_Till	0.98	Yes	0.79	1/10
Modern wetlands	HK_Wetland	0.003	No	40	1/10
Buried gravel aquifer in coastal plain	HK_BuriedGrav	2.78	Yes	140	1/200
Coarse-grained distal delta deposits	HK_Coarse	0.7	Yes	41.2	1/10
Multiplier zone for layers 3–5	HK_ClayEXP	1.66	Yes	1.81	NA
Hydraulic properties for bedrock units					
Granite bedrock	HK_Granite	0.29	No	0.1	1/1
Shallow bedrock of all types	HK_L1ROCK	1.0	Yes	1.09	1/10
Metamorphic bedrock	HK_MMRock	0.20	No	0.01	1/1
Shear zone (fault) bedrock	HK_ShearZn	0.04	No	0.5	1/1
Very tight granite bedrock	HK_Special	1.0	No	0.008	1/10

Table 12. Riverbed and streambed hydraulic properties.

[ft/d/ft, feet per day per foot; RIV, MODFLOW-2005 RIVER package; DRN, MODFLOW-2005 DRAIN package]

Unit	Composite scaled sensitivity	Estimated?	Calibrated value (ft/d/ft)
Conductance for RIV cells			
KRIV_BranchBrook	0.20	No	1.5
KRIV_Merriland	0.24	No	0.1
KRIV_Mousam	0.02	No	1.0
Conductance for DRN cells			
KDR_Seeps	5.0	Yes	0.57
KDR_Streams	0.79	Yes	1.44

estimated and if trial-and-error changes to other parameters or changes to the conceptual model are needed. During the optimization process, the sensitivity of the model to each parameter value is determined for each optimization iteration, and only parameters that exceed a threshold sensitivity (and are not highly correlated with each other) are estimated (see Hill and Tiedeman [2007] for further details on the process of parameter estimation).

Table 13. Summary of groundwater level observation points used in calibrating the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

[<, less than; ft, feet; ≥, greater than or equal to]

Observation information	Number of observations
Total number of groundwater level observations	151
Wells	136
Surface-water points	15
Sand and gravel wells	117
Till wells	8
Bedrock wells	11
Wells <50 ft deep	83
Wells ≥50 ft deep	52
Observations in layer 1	72
Observations in layer 2	18
Observations in layer 3	10
Observations in layer 4	17
Observations in layer 5	13
Observations in layer 6	11
Observations in layer 7	10

Observations

Observations used to calibrate the groundwater model included head observations and flux observations. Observations were assigned weights used in the model sensitivity and parameter estimation analysis. The head (groundwater level) observations consisted of the water levels measured during the synoptic groundwater level survey in June 2012 plus 15 surface-water elevation points (these were a mixture of wetlands, reservoirs, and ponds; fig. 6). The flux observations consisted of groundwater discharge (base flow) to streams and rivers in the model area.

Groundwater Level Observations

Head observations used in the calibration consist of the groundwater level measurements collected in 2012 (listed in appendix 1), and the locations are shown in figure 6. Every layer in the model had at least one head observation. There were a total of 151 groundwater level observations used in calibrating the model. Many of these were concentrated in several clusters of monitoring wells installed for previous investigations or for routine monitoring in association with the groundwater withdrawal wells in the study area. The homeowner wells and surface-water points were used to fill in the other areas of the model where monitoring wells did not exist. Although almost one-half of the total observations were shallow wells or surface-water observations in layer 1 (72 points), the distribution of wells in layers 2 through 7 was fairly even, and 52 of the wells were 50 or more feet deep (table 13).

The variances used to calculate weights for the observations for water levels in wells (appendix 1) included a combination of measurement and elevation errors. Most of the water levels were assigned a measurement error of plus or minus 1 ft, which accounted for the changes in water levels in the aquifer during the several days that the water-level survey took place. Some of the monitoring well elevations were determined using global positioning system (GPS) technology or surveying, and these were assigned an elevation error of ±0.1 ft. The other elevations were derived from a digital elevation model of the area. Much of the study area has lidar surface elevation data, and wells in the lidar area were assigned an elevation accuracy of ±1 ft. Wells in the rest of the study area were assigned an elevation accuracy of ±5 ft. The surface-water elevation points were assigned an accuracy equal to the appropriate land-surface elevation accuracy, depending on the location. The variances derived from these errors were summed to calculate the weights on each observation. Additional details on the use of observations and weighting are described in Hill and Tiedeman (2007).

Streamflow Observations

Because the groundwater model was developed to represent a long-term average condition for the early summer time period, the streamflow observations to use as calibration targets represented base-flow conditions from June through July. Base flows (groundwater discharge) are used in the model because the model cannot simulate direct runoff and because base flow is a conservative target for streamflow, as flows are lower than whenever there is runoff. The method used to calculate base-flow values was similar to that used for calculating the monthly mean flows for Branch Brook and the Merriland River using the MOVE.1 technique described earlier in the section on surface-water resources, but the method was applied to all 13 of the streamflow measurement sites in the study area. The index flows in this case were base flows for the Mousam River, Bearcamp River, and Branch Brook gages (stations 01069500, 01064801, and 01069700) during June and July from 2008 through 2012 time period. The PART program (Rutledge, 1998) was used to analyze the hydrographs for these dates to determine average base flows for these months. These base flows were averaged to obtain an index site flow, from which the base-flow observations at each site were calculated (table 14). For context, the base-flow calibration target for Branch Brook at the continuous streamgage (BB#2, station 01069700) is shown in figure 12 with the daily flows during late June when the groundwater observation data were collected. The base flow calculated as the model calibration target (17.2 ft^3/s) is close to the daily streamflow at the end of June 2012, as the streamflows were declining during the groundwater survey. This indicates that the base-flow calibration targets used in the model are a reasonable representation of base flows to use with the groundwater measurements collected in 2012.

After the base flow was calculated for each surface-water site, the base flows were divided into incremental flows for the streamflow reach just above each site. This was done by subtracting the base flow at the site immediately upstream from the base-flow total at that site, if there was an upstream site. This applied just to the observation sites on Branch Brook and the Merriland River.

In the model, the base-flow values, from here on referred to as “base-flow observations” are calculated as the sum of the RIV and DRN drain cells in the watersheds of each of the streamflow measurement sites (fig. 13). Because the model simulates groundwater discharge from both RIV and DRN cells, the observed base-flow amounts in each subwatershed had to be partitioned between RIV cells and DRN cells for the model calibration process. Furthermore, because the model simulates two types of DRN cells (seepage [spring] flow cells and stream cells, which are differentiated by streambed conductance), some of the observed base flows had to be further partitioned into two DRN observations (table 14). The percentages for partitioning the flows were made on the basis of professional judgment, using the number of RIV and DRN cells in each subwatershed as a guide.

The base-flow observations were assigned uncertainty values to use in the model calibration and against which to evaluate the simulated streamflow values from the calibrated model. For the parameter estimation and sensitivity analysis, the uncertainty values were expressed as a standard deviation. For each of the base-flow observations, before apportioning them between RIV and DRN observations, the standard deviation was estimated, which is needed for the calculation weights for parameter estimation. The standard deviation for each subwatershed (table 14) was estimated using the streamflow measurements made in the field at each site. The separating of the observed flow into the RIV and DRN individual observations required doubling the total standard deviation in the observations because the actual division of flow between the two types of discharge cells was unknown. The standard deviations for each partitioned observation used during the model calibration are shown in table 14. The weight of each observation is the inverse of the coefficient of variation, which is the square of the standard deviation. Additional details on the use of observations and weighting are described in Hill and Tiedeman (2007).

Parameters

As stated earlier, the model was calibrated using a combination of parameter estimation and trial-and-error adjustments in the model variables. A “reasonable range” of values for each parameter is input to the process (determined using values from the literature and previous studies [tables 2 and 3]) for comparison with the value output by the parameter estimation routine. Generally, parameters with composite scaled sensitivities greater than 0.5 can be estimated (Hill and Tiedeman, 2007), as long as they are not highly correlated with other estimated parameters. Of the 31 parameters set up for the model, 18 were sensitive enough to estimate. Two of these were not estimated because the estimation arrived at values outside their reasonable ranges (RCH_Sandy1 and RCH_Till). One (HK_Special) was not estimated because it was correlated with another parameter (RCH_Bedrock). Of the final 15 determined by use of parameter estimation, there were 2 recharge parameters, 11 horizontal K parameters, and 2 streambed K parameters (table 15). As the model variables were adjusted and tested for model fit, alternatives to the original conceptual model also were tested to determine if they helped in providing a better model fit. Some adjustments to the original assumptions of the distribution of the geologic units at depth were made in the model to improve the model fit as necessary.

Model Fit to Observations

The overall model fit is assessed by evaluating observations and their simulated equivalents. The model-simulated water levels for the head observations at 134 wells and 15 surface-water points are graphed against the observed values in figure 14 (one well was simulated as dry and could not be plotted). The correlation between observed and simulated heads indicated a very good agreement (R^2=0.99). The weighted residuals (residuals are the observed values minus the simulated values) plotted against the unweighted simulated heads also indicate a slight negative bias in the weighted residuals (fig. 15). The mean difference between the observed and simulated heads (observed minus simulated) is

Table 14. Streamflow observations used in calibrating the Branch Brook area groundwater flow model.

[USGS, U.S. Geological Survey; ID, identification; ft^3/s, cubic feet per second; ft^3/d, cubic feet per day; BB, Branch Brook; --, not applicable]

USGS station number	Local ID	Name of partitioned observations	Total flow this site, ft^3/s	Incremental (subwatershed) observed flow, ft^3/s	Incremental (subwatershed) observed flow, ft^3/d	Standard deviation on incremental flow, ft^3/d	Standard deviation on partitioned flow, ft^3/d	Observation flux, ft^3/d
01069640	BB #7	BB7_Str	0.77	0.77	66,328	15,805	--	66,328
01069645	BB #6	BB6_Str	0.92	0.15	12,869	5,268	--	12,869
01069660	BB #5		5.42	4.50	388,721	52,683	--	--
		BB5_Riv	--	--	--	--	31,113	207,462
		BB5_Seeps	--	--	--	--	47,912	181,259
01069680	BB #4		0.63	0.63	54,057	18,439	--	--
		BB4_Seeps	--	--	--	--	9,167	13,908
		BB4_Str	--	--	--	--	18,492	40,149
01069690	BB #3		13.11	7.07	610,456	26,341	--	--
		BB3_Seeps	--	--	--	--	31,363	502,337
		BB3_Riv	--	--	--	--	8,149	108,118
01069700	BB#2		17.04	3.93	339,824	52,683	--	--
		BB2_Seeps	--	--	--	--	16,486	110,612
		BB2_Str	--	--	--	--	11,588	86,968
		BB2_Riv	--	--	--	--	50,951	142,245
01069720	BB #1		18.13	1.06	91,326	13,171	--	--
		BB1_Seeps	--	--	--	--	6,703	48,302
		BB1_Riv	--	--	--	--	13,053	43,024
01069505	Perkins Marsh	Perkins_Str	2.73	2.73	235,498	18,439	--	235,498
01069515	Cold Water	Cold_Seeps	2.11	2.11	182,156	13,171	--	182,156
01069580	Day Brook		2.13	2.13	183,823	26,341	--	--
		Day_Seeps	--	--	--	--	3,216	2,259
		Day_Str	--	--	--	--	36,296	181,564
01069725	BB# 8	BB8_Str	0.83	0.83	72,021	26,341	--	72,021
01069785	Merri #1		9.31	0.76	65,765	26,341	--	--
		Merri1_Str	--	--	--	--	13,829	30,203
		Merri1_Riv	--	--	--	--	25,683	35,562
01069780	Merri #2		8.55	8.55	739,022	52,683	--	--
		Merri2_Str	--	--	--	--	74,701	722,188
		Merri2_Riv	--	--	--	--	4,323	16,834

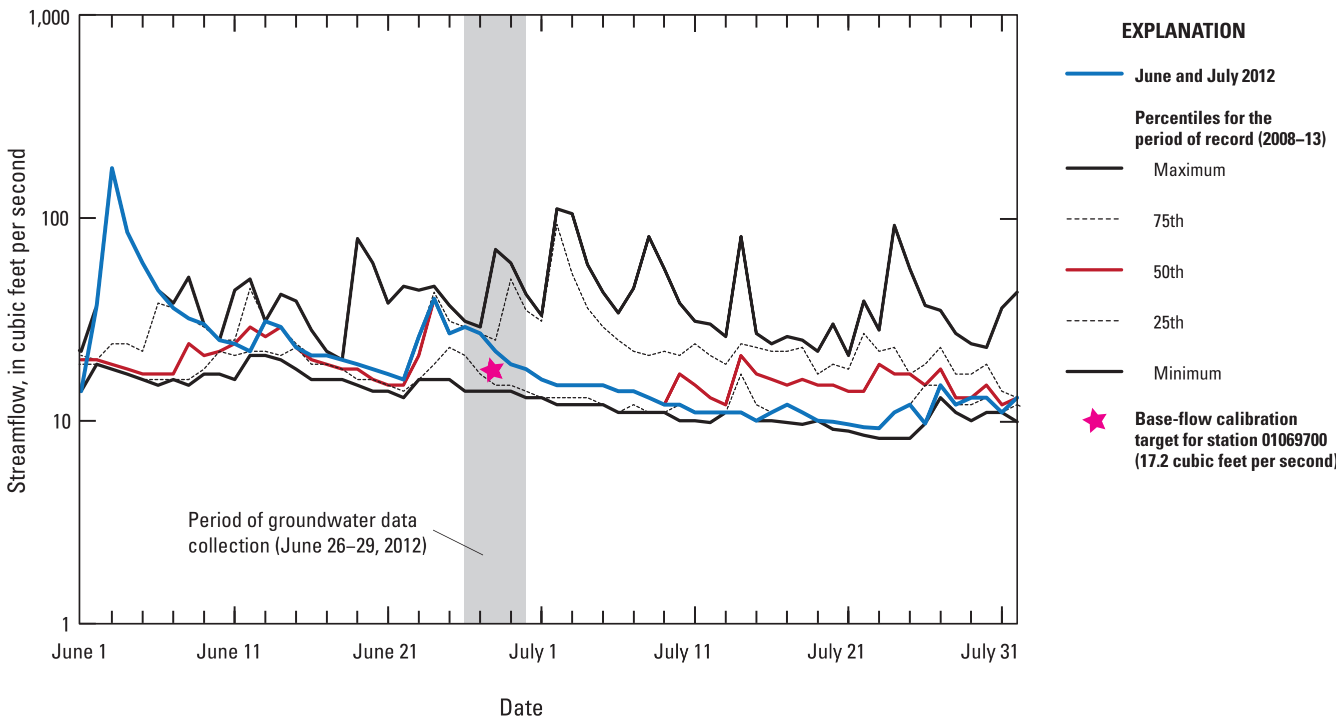


Figure 12. Percentiles of daily streamflow in Branch Brook at station 01069700 for June and July for the period of record, June and July daily streamflows for 2012, and the base-flow calibration target for the groundwater flow model, southern Maine.

1.4 ft, and the mean absolute difference between the observed and simulated heads is 4.0 ft. Given that the range in observed heads for the model area is 282 ft, these errors represent 0.5 and 1.4 percent, respectively, of the total head change across the model. The surface-water points fall very close to the line of equality (fig. 14), whereas the till wells plot slightly above the line of equality, meaning that the simulated heads are slightly lower, on average, than observed. The bedrock wells have water levels that are somewhat over-predicted, especially in the 140- to 175-foot elevation range.

The spatial distribution of the head residuals (observed minus simulated heads) in figure 16 shows that the simulated heads in the areas underlain by till and shallow bedrock (between the coastal plain area and the central part of the study area) are higher than observed. Several of the heads in the Sanford area also are simulated somewhat higher than observed. The heads in the central part of the study area, in the Branch Brook watershed, show the lowest general residuals (both positive and negative) in the model area.

The discrepancy between observed and simulated heads is somewhat worse than average (5.7 ft mean absolute difference between observed and simulated heads) for the sand and gravel wells in the coastal plain section of the model, which are primarily in the vicinity of the pumping wells in that area (fig. 16). The head data in the vicinity of the pumping wells were difficult to fit for two reasons: (1) pumping was not steady and the observation points had not fully equilibrated to the pumping stresses when the water-level survey was conducted, and (2) many of the wells were in the buried gravel aquifer, which appears to have more heterogeneity than was possible to simulate in the model. This lack of fit is evident in the somewhat wide spread in the weighted residuals plot as well (fig. 15).

The observed and simulated base flows in the reaches above the streamflow measurement sites are shown in figure 17. The fit of the base-flow data is very good, and most of the model-simulated flows fall well within the 95-percent confidence intervals of the observations. The primary exceptions to this are for BB#3, for which the confidence interval is relatively narrow and which has a relatively small contributing watershed for the amount of flow that enters the river in this segment. The recharge rate in this contributing watershed is very high already, so there were limits to the amount of water that was available for discharge to Branch Brook. The Merriland #2 site is the other significant observation in which the model-simulated flows are somewhat lower than desired. The contributing watershed to this observation site is large, but consists largely of areas with till and shallow bedrock, which have low recharge rates. Increasing the recharge for these areas beyond what was considered a reasonable range was not a favorable option. The lack of fit with both of these observations may be a result

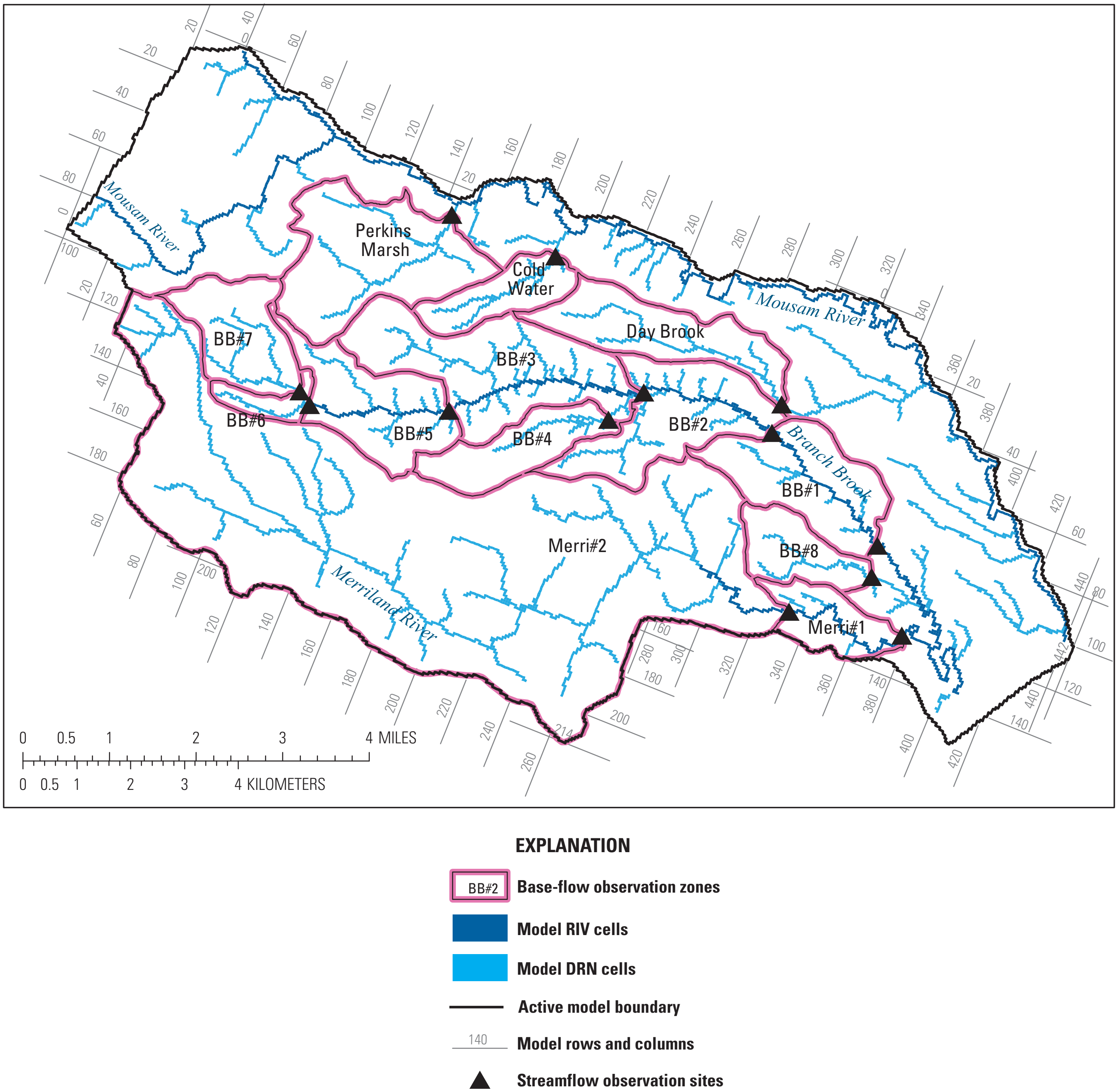


Figure 13. Subwatersheds used as base-flow observation zones in the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

Table 15. Parameters used in the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine, with composite scaled sensitivities and calibrated values.

[RIV, MODFLOW-2005 RIVER package; DRN, MODFLOW-2005 DRAIN package; Calibrated values for conductances are in feet per day; calibrated values for recharge parameters are in inches, calibrated parameters for hydraulic conductivity are in feet per day]

Unit	Composite scaled sensitivity	Estimated?	Calibrated value
Conductances for RIV cells			
KRIV_BranchBrook	0.20	No	1.5
KRIV_Merriland	0.24	No	0.1
KRIV_Mousam	0.02	No	1.0
Conductances for DRN cells			
KDR_Seeps	5.0	Yes	0.57
KDR_Streams	0.79	Yes	1.445
Recharge parameters			
RCH_Alluv_Urb	0.17	No	5.0
RCH_Bedrock	1.2	No	2.3
RCH_Moraine	0.15	No	3
RCH_Sandy_1	15.0	No	29
RCH_Sandy_2	3.9	Yes	15.9
RCH_Till	1.36	Yes	5.0
RCH_Wetlands	0.002	No	2.5
RCH_Water	0.20	No	1.0
RCH_Xtra	0.47	No	3.0
Hydraulic conductivity parameters			
HK_Alluvium	1.3	Yes	1.97
HK_MrnSand	2.7	Yes	3.56
HK_PmUndiff	0.95	Yes	1.5
HK_Presump	1.9	Yes	0.19
HK_Delta1	0.54	Yes	28
HK_Delta2	5.5	Yes	6.3
HK_Till	0.98	Yes	0.79
HK_Wetland	0.003	No	40
HK_BuriedGrav	2.78	Yes	69.8
HK_Coarse	0.7	Yes	41.2
HK_ClayEXP	1.66	Yes	1.81
HK_Granite	0.29	No	0.1
HK_L1ROCK	1.0	Yes	1.09
HK_MMRock	0.20	No	0.01
HK_ShearZn	0.04	No	0.5
HK_Special	1.0	No	0.008

of model error or the range in measurement error. Site BB#8 also is under-simulated in the model, although this site is quite close to the Plant and Herriseckett pumping wells, and the wells were not pumping when many of the streamflow measurements used to determine the base-flow observation were made. The over-simulation of base flows for BB#6, which is in the headwater section of Branch Brook, is not considered significant because of the particularly small contributing area and the lack of detail in the input datasets in this area.

Simulated Groundwater Levels and Flow Under Steady-State Conditions

The simulated steady-state heads and groundwater flow directions in the calibrated model in model layers 1 and 4 are represented in figure 18. Heads range from 0 ft at the Atlantic Ocean to greater than 250 ft at the northwestern edge of the model in the Sanford area. In layer 1, the head contours generally follow the land surface and are most widely spaced where the hydraulic conductivities are highest. Breaks in the contours in the layer 1 map indicate areas where the model cells in layer 1 are dry for this unconfined simulation. Flow directions are towards surface-water features. There is a very small amount of flow between the model and the general head boundaries in layer 1, which are shown on figure 18. In layer 4, the heads range from -10 ft in the vicinity of the largest pumping well near the ocean to 260 ft in bedrock hills in the northwest corner of the model. Although the heads and flow directions in layer 4 are quite similar to those in layer 1, there are some differences. The pumping wells, especially the larger ones, influence the water levels in layer 4 much more than in layer 1, and cones of depression are developed in the Sanford area and near the pumping wells in the coastal plain. The highly conductive buried gravel aquifer in layer 4 and the pumping in that aquifer greatly influence the flow directions in layer 4 in that area. There is more groundwater flow crossing the general head boundaries in layer 4 than in layer 1, especially along the model edge where the gravel aquifer crosses to the south. The vertical head gradients are generally downwards from layer 1 to layer 4 in most of the model area. The exceptions to that are in the major stream and river valleys, where groundwater flow is discharging to the surface-water features.

Model Sensitivity Analysis and Parameter Uncertainty

The parameter estimation process generates data describing the sensitivity between parameters and observations in the model. Dimensionless scaled sensitivities (DSS) indicate the sensitivity of each simulated observation to small changes in parameter values, whereas composite scaled sensitivities (CSS) indicate the composite sensitivity of all the observations to changes in each parameter value. The DSS values (listed in appendix 2) are generated for every parameter and observation

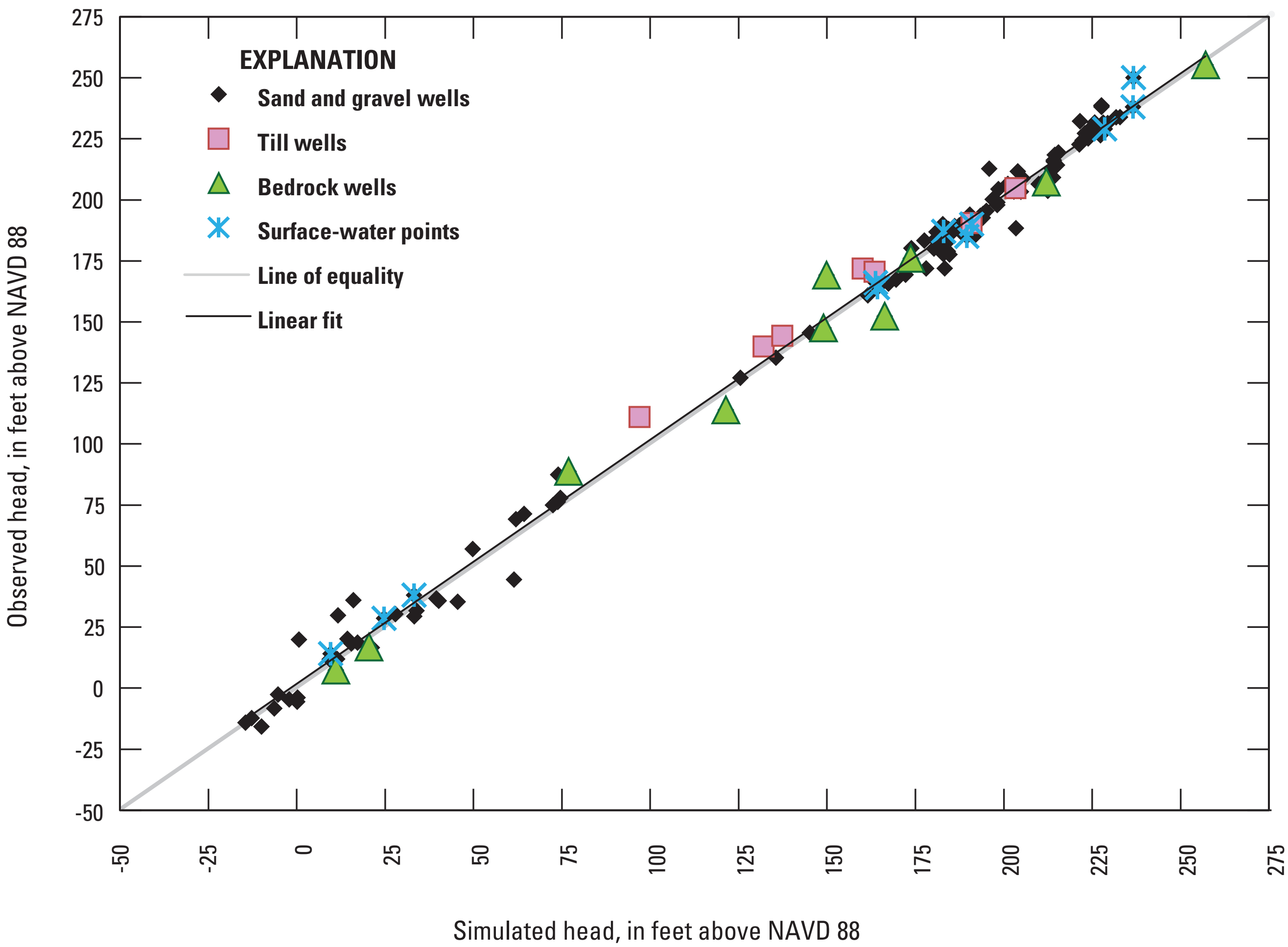


Figure 14. Relation between observed and model-simulated heads for the area in and around the Branch Brook watershed in southern Maine.

and can be used to examine which observations or groups of observations have the most influence on particular parameter estimates in the model. The CSS values, in contrast, reflect overall model sensitivity to each parameter. The model parameters with the greatest sensitivity overall include (with CSS values in parentheses) the RCH_Sandy1 (15.0), HK_Delta2 (5.5), and KDR_Seeps (5.0) parameters (table 15).

The RCH_Sandy1 parameter was particularly influential on the streamflow observations but not the head observations. The HK_Delta2 and KDR_Seeps parameters primarily influenced heads in the central part of the Branch Brook watershed. Simulated heads in this area also were particularly sensitive to the HK_L1ROCK, HK_Alluv, and HK_Presump parameters. Together, these parameters control the supply of water to the sand and gravel aquifer and the rate at which the groundwater discharges to Branch Brook. The model in this area is quite sensitive to the vertical layering setup and how the model simulates discharge to the springs and seeps that feed Branch Brook.

In the coastal plain area, simulated heads were most sensitive to a range of parameters, including the RCH_Sandy1, HK_MrnSand, RCH_Sandy2, HK_BurGrav, and HK_ClayExp parameters. These parameters control the supply of water to this area, and the rate at which flow moves vertically from the surficial units, through the confining Presumpscot Formation, and into the buried gravel aquifer below, as well as the rate at which water in the buried gravel aquifer flows towards the Merriland River pumping well.

Simulated heads in the Sanford area were most sensitive to the HK_Delta2, HK_ClayExp, RCH_Sandy1, and RCH_Sandy2 parameters and were somewhat sensitive to the HK_Coarse and KDR_Stream parameters. This area was surprisingly insensitive to the KRIV_Mous parameter, especially how close many of the wells are to the river in that area. As the HK_ClayExp parameter controls the hydraulic conductivity of the sand and gravel surrounding the pumping well, sensitivity to that parameter is not surprising.

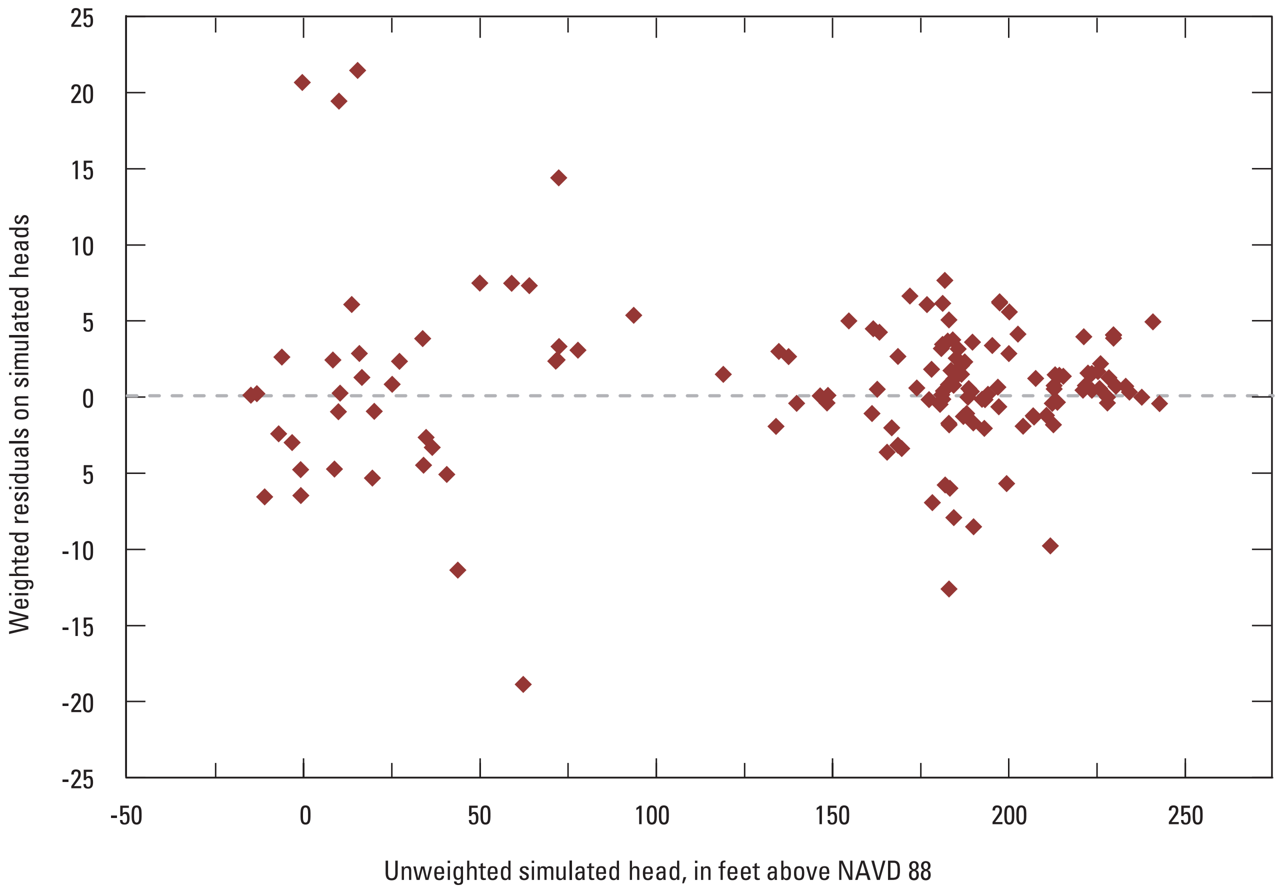
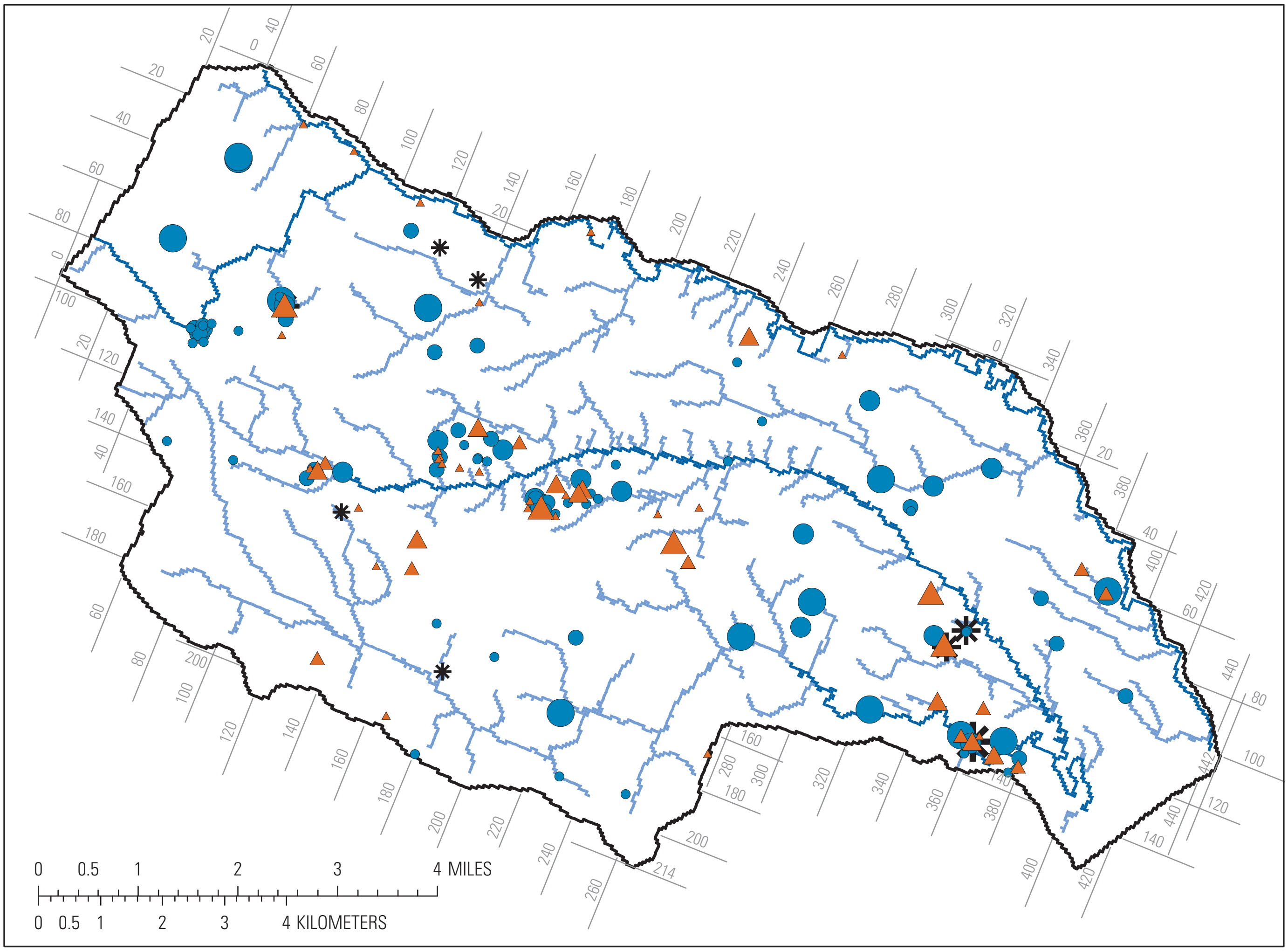


Figure 15. Weighted residuals and unweighted simulated values for heads in the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

The simulated heads in the bedrock and till wells across the study area displayed a mixed degree of sensitivity to the model parameters. Only one bedrock well head simulation (ME_YW_888) was particularly sensitive to the RCH_ Bedrock parameter (the till well heads were much more sensitive to this parameter); in contrast, several of the bedrock wells had heads that were quite sensitive to the RCH_Till parameter. The simulated bedrock well heads were also generally more sensitive to the HK parameters in the adjacent upland areas than to the bedrock HK parameters, probably because the surficial unit HKs control the outflows of water from the bedrock and therefore the heads. The simulated heads in the till wells were sensitive to the RCH_Till and HK_Till parameters in general, although individual till well heads were quite sensitive to HK parameters in nearby sandy areas, and in the RCH_Sandy1 and RCH_Sandy2 parameters.

The 22 individual base-flow simulated values were sensitive to many different parameters. Most of the base-flow simulated values were quite sensitive to the RCH_Sandy1 parameter. The simulated base flows at the Merriland River sites were generally insensitive to the model parameters, but they were sensitive to the layering of the model and spatial distribution of the geologic units. The simulated base flows at the three tributaries to the Mousam River were most sensitive to the HK_Delta2 and RCH_Sandy2 parameters but only mildly sensitive to the KDR parameters. The simulated base flows in the Branch Brook reaches were sensitive to several parameters (besides RCH_Sandy1), including RCH_Sandy2, KDR_Seeps, HK_L1Rock, HK_Presump, and HK_Delta2.

The homeowner dug wells in the sandy units and, to a lesser extent, the till and bedrock wells had some of the greatest individual influence on the model calibration, likely because they were widely distributed across the model area (appendix 2). Monitoring wells that were in some of the clustered areas had less influence in general, except for some of the monitoring wells near the Merriland and Herrisecket pumping wells. The base-flow observations contributed less of an influence on the parameter estimation process than the head observations.



EXPLANATION

Groundwater model

- Model RIV cells
- Model DRN cells
- 120 Model rows and columns
- Active model boundary

Residuals on simulated heads, in feet

- less than 10.0
- -9.9 to -5.0
- -4.9 to -2.5
- -2.4 to 0.0
- 0.1 to 2.5
- 2.51 to 5.0
- 5.1 to 10.0
- greater than 10.0

Production well, pumping rate in gallons per minute

- 6 to 20
- 21 to 500
- 501 to 1000

Figure 16. Spatial distribution of head residuals for the model domain in the area in and around the Branch Brook watershed in southern Maine.

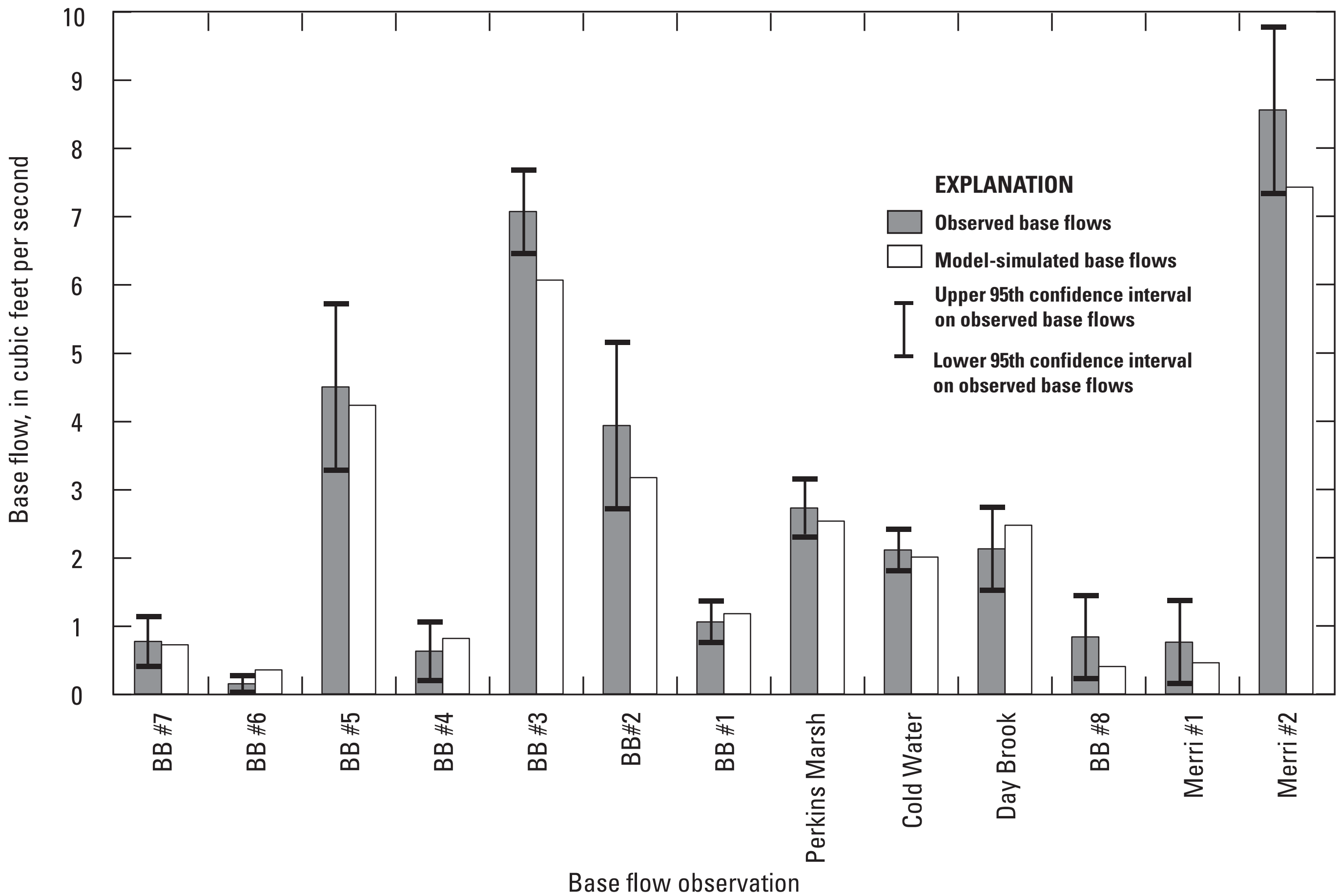


Figure 17. Steady-state observed and model-simulated base flow (groundwater discharge), with confidence intervals on the observed values, for the area in and around the Branch Brook watershed in southern Maine.

The use of parameter estimation also provides information on the confidence intervals of the parameter estimates for model variables determined using this process. The estimates are shown in figure 19 along with the 95-percent confidence intervals and reasonable ranges for the estimated 15 parameters. Ideally, the parameter confidence intervals would be small and would fall entirely within the reasonable ranges. Prior modeling studies have shown, however, that a large degree of uncertainty in most parameter values is quite common (Mary Hill, U.S. Geological Survey, written commun., 2011). Most of the parameters were estimated within their reasonable ranges, and the confidence intervals for nine of them fell entirely within the reasonable ranges. Only one was estimated outside the reasonable range (RCH_Till), although earlier runs of the estimation process attempted to set the RCH_Sandy1 parameter (not shown) far outside its reasonable range, so that parameter was instead set by hand.

Model-Calculated Water Budget for Branch Brook, the Merriland River, and Lower Mousam River

The simulated average annual water budget for the Branch Brook, Merriland River, and lower Mousam River watershed areas in the model were calculated using the MODFLOW supplemental software ZONEBUDGET (Harbaugh, 1990), which is used to calculate internal flows between different zones of the model. This allows for detailed summarizing of the cell-by-cell flows across different parts of the model and interactions with boundaries and stresses. The ZONEBUDGET zones set up for the model followed the watershed boundaries and included the surficial units (layers 1 through 5) in each of the three watersheds. In the areas where bedrock is at or near land surface, the shallow bedrock is included in the surficial ZONEBUDGET zones. The deeper bedrock (layers 6 and 7, and layers 2 through 5 in

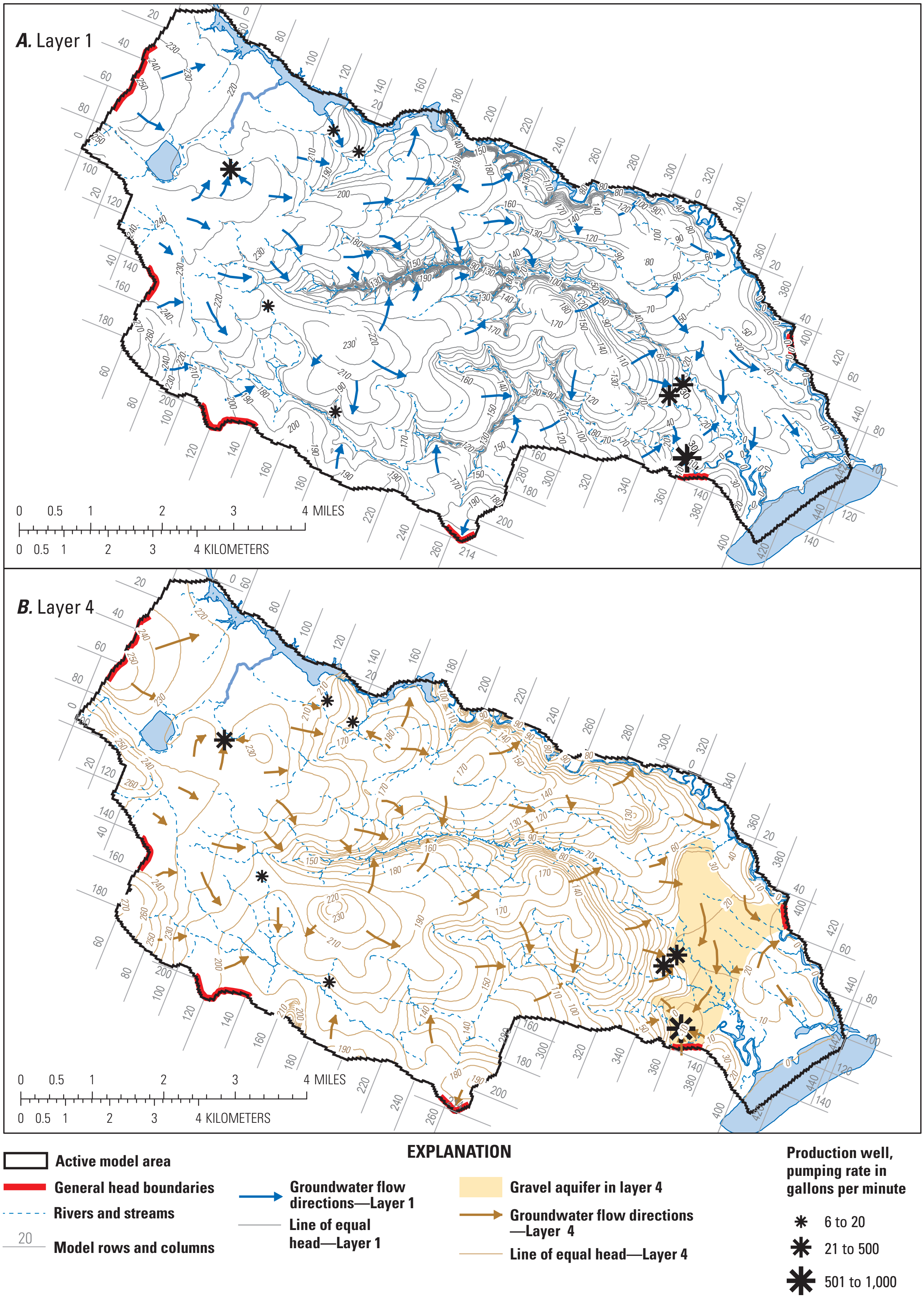


Figure 18. Simulated steady-state groundwater heads and flow directions in *A*, layer 1 and *B*, layer 4 of the groundwater flow model of the area in and around Branch Brook watershed in southern Maine. Contour interval 10 feet.

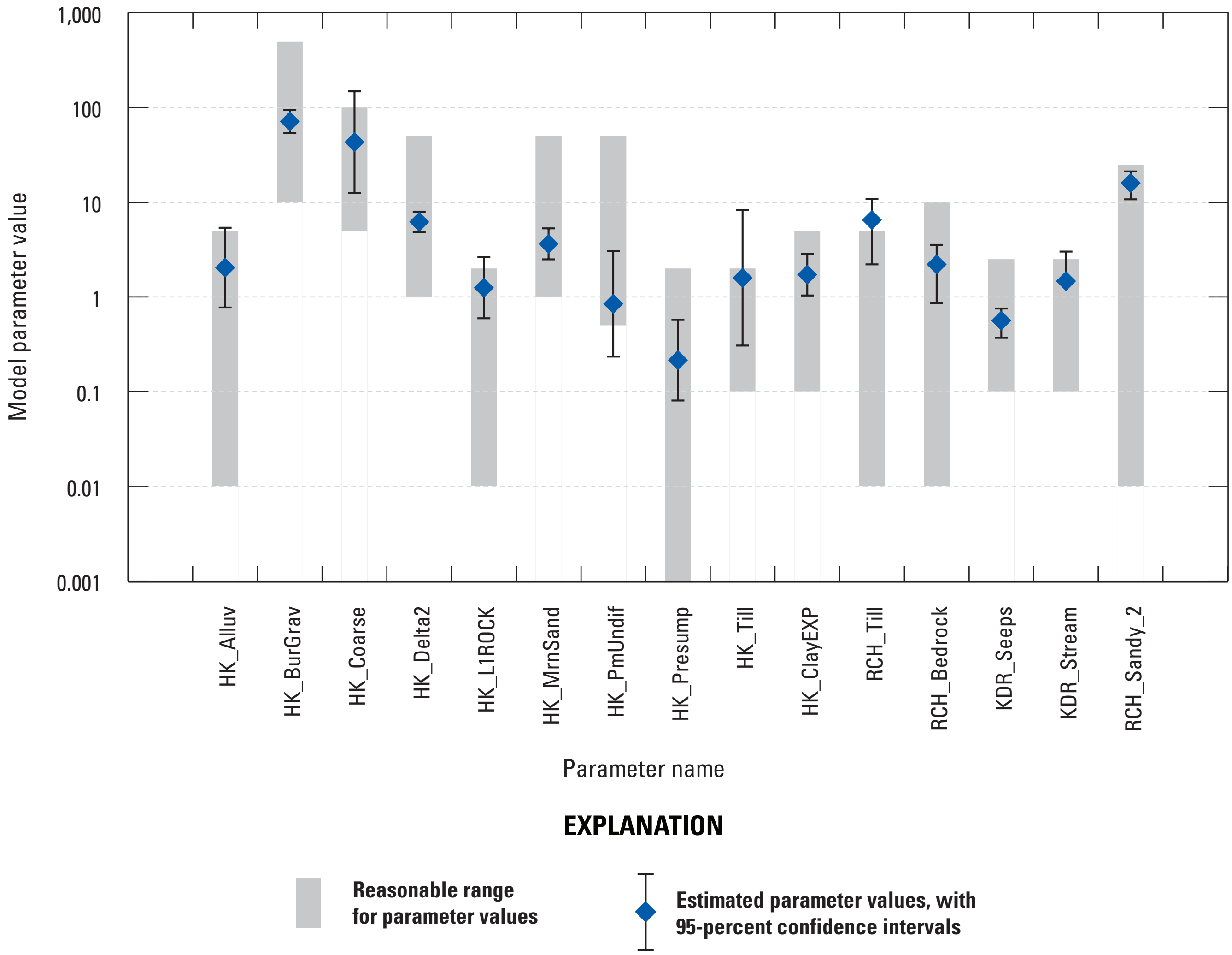


Figure 19. Final calibrated model parameter values, 95-percent confidence intervals, and reasonable ranges for hydraulic conductivity and recharge values for the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

shallow bedrock areas) was set up as a separate zone to test the amount of groundwater interaction with the bedrock units. The constant head in the ocean also was set up as a separate zone. Flows reported here are the net fluxes of water across the boundaries of the various zones. The detailed accounting for fluxes of water between the three watersheds and the boundaries (table 16) indicates that for the model overall, recharge to the surficial units (97 percent) and inflows across the GHB boundaries (3 percent) are the sole inputs to the model. Outflows from the model, as a whole, are to surface-water bodies (89.9 percent), pumping wells (8 percent), GHB boundaries (2.4 percent), and the ocean (less than 0.5 percent).

Flow between the surficial aquifer (or shallow bedrock where the surficial sediments are less than 25 feet thick) and the underlying bedrock accounts for between 7 and 11 percent of total fluxes in and out of the surficial units. The Merriland River and Mousam River watersheds, being on the edges of the model area, had the primary interactions with the GHB boundaries (fig. 18), being approximately 6 and 3 percent of the flux in those watersheds, respectively. Net inflows from GHB boundaries into the Mousam River watershed were split between the GHB boundary on the northwest edge of the model (65 percent of the GHB inflow) and the smaller one that simulates flow within the buried gravel aquifer under the Mousam River (35 percent). The southern edge of the Merriland River watershed is bounded by GHB boundaries in four locations where sand and gravel aquifers cross the topographic divide (figs. 1 and 11). The net total flow across all these GHB boundaries is fairly small (table 16), but the inflows across this watershed occur dominantly in the buried gravel aquifer in the coastal plain (towards the pumping well), whereas the outflows occur along the upland GHB boundaries.

Table 16. Steady-state model calculated water budget fluxes for the Branch Brook area groundwater flow model and three primary watersheds within the model area.

[ft³/d, cubic feet per day; GHB, general head boundary; GW, groundwater; --, not applicable; numbers in parentheses indicate negative flows]

Hydrologic budget component	Rate of flux, in ft³/d			
	Model domain	Branch Brook watershed	Merriland River watershed	Mousam River watershed area
Inflows				
Recharge to surficial units[1]	4,532,656	1,751,205	813,024	1,968,426
Inflows from GHB boundaries	132,749	702	56,372	75,675
Interbasin GW flows	--	223,662	133,100	133,042
Inflows from bedrock units	--	203,830	118,984	166,629
Outflows				
Discharge to surface-water features	(4,077,654)	(1,640,361)	(681,393)	(1,755,900)
Pumping	(359,725)	(70,000)	(195,970)	(93,755)
Discharge to ocean	(1,041)	(2,467)	0	1,425
Interbasin GW flows	--	(266,134)	(61,734)	161,928
Flows to bedrock units	--	(199,979)	(101,949)	(158,918)
Outflows to GHB boundaries	(112,178)	(1,225)	(52,818)	(58,136)
Net GHB flux	20,570	(523)	3,554	17,539
Net bedrock flux	--	3,852	17,035	7,711

[1]Does not include recharge applied to ocean.

There is a notable amount of groundwater flux between the three watersheds within the surficial units, which accounts for about 12 percent of the flows in and out of the surficial units of the Branch Brook aquifer, and about 11 and 7 percent, respectively, for the Mousam and Merriland River watersheds. Much of the flux between the Branch Brook and Merriland River watersheds occurs within the buried gravel aquifer in layers 4 and 5 (fig. 18). The fluxes between the watersheds are combined with the GHB flows in the "GW-surficial" inflow and outflow categories in figure 20. Internal fluxes between the surficial and bedrock units in each watershed area are not shown on figure 20, only the net flows in and out of each watershed. Outflows from bedrock in the Mousam River watershed (fig. 20) discharge to river and drain cells and to the ocean.

Scenario Testing

The groundwater model was used to evaluate several different hydrologic conditions, or scenarios, that could change the amount of groundwater flowing to the rivers and streams in the study area. The scenarios were (a) no pumping from the water-supply wells; (b) current (as of 2013) pumping from the water-supply wells, but simulated drought conditions (25 percent reduction in recharge); (c) current recharge, but with increased pumping from the large water-supply wells; and (d) drought conditions and increased pumping combined. The simulation without any water-supply wells (including the SWD and KKWWD wells) was used as a "natural" flow scenario against which the base flows with the current pumping were compared to derive the base-flow depletion amounts in the rivers. The increased pumping scenarios used pumping rates for the KKWWD wells that were close to the maximum rates that the wells are able to pump. The rate for the SWD wells was 150 percent of its current (2013) pumping rate. The small community water-supply pumping rates were not increased for the scenarios.

Use of the Groundwater Model to Determine Groundwater Divides and Flow Directions

At the beginning of the study, there were uncertainties about the position of the groundwater divides between the Branch Brook, Merriland River, and Mousam River watersheds because of the low-relief topography in the sand plains that separated the watersheds. There were also questions about how pumping in the Sanford area would affect the position of the water table and whether groundwater could flow from the Branch Brook watershed to the Mousam River watershed under pumping or nonpumping conditions. The calibrated groundwater flow model was used to address these questions.

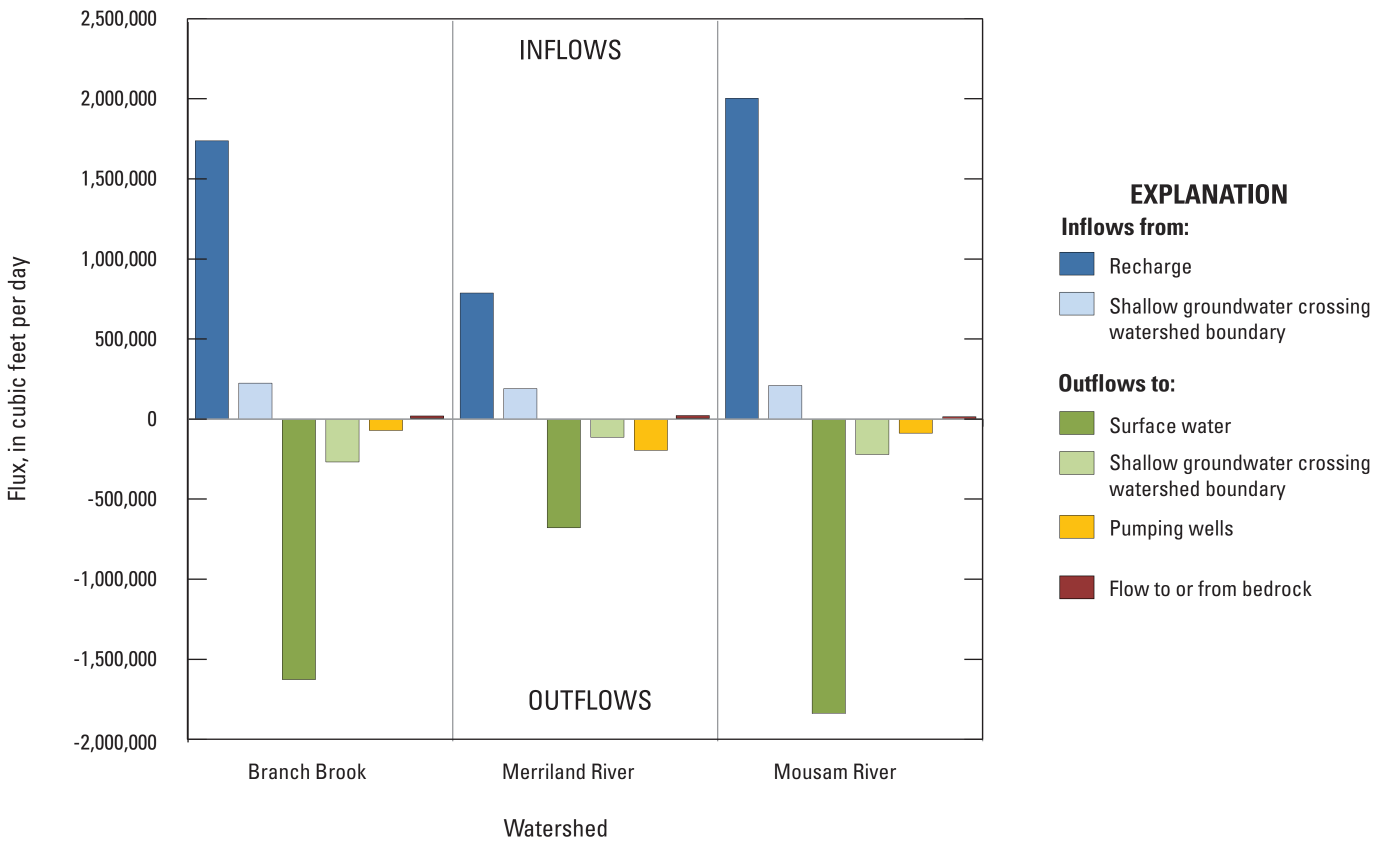


Figure 20. Steady-state simulated inflows and outflows for the Branch Brook, Merriland River, and Mousam River watershed areas in the groundwater flow model of the area in and around the Branch Brook watershed in southern Maine.

The head contours in layer 1 represent the water table and are appropriate for the delineation of groundwater divides and flow directions in relation to the watershed divides in the headwater areas of Branch Brook and the divides between Branch Brook and the Mousam River watershed to the north and the Merriland River watershed to the south (fig. 21*A*). Under the normal (pumping) conditions, the groundwater divide between Branch Brook and the Mousam River is more of a straight line than the topographic divide, and groundwater flow crosses the topographic divide in both directions along this border. The largest difference is in the northwestern most part of the Branch Brook watershed, where the groundwater divide is almost one-half mile farther to the south than the topographic divide, and a significant amount of water flows across the topographic divide north into the Mousam River watershed and towards the Sanford withdrawal well (fig. 21*A*). However, under the no-pumping scenario, the groundwater divide still falls to the south of the topographic divide (fig. 21*A*). The pumping well in Sanford therefore has a small effect on the flow directions and groundwater flow divides under the current pumping rates and captures a small amount of groundwater from the Branch Brook watershed. The water-budget analysis concluded that from 7 to 12 percent of the entire water budgets of the three watersheds consisted of groundwater flows across watershed boundaries but that most of this flow crosses the watershed boundaries in the vicinity of the Merriland River pumping well, within the buried gravel aquifer. The amount crossing the watershed boundaries in the headwater areas is correspondingly a small portion of the total.

The movement of the groundwater divide under drought conditions with additional pumping is illustrated in figure 21*B*. Under this scenario, there is a significant further deflection of the groundwater divide towards Branch Brook with more groundwater flowing to the north and the Mousam River watershed. Under this scenario, the groundwater divide is deflected about three-quarters of a mile south of the topographic divide. The changes in the groundwater divide between this scenario and the base case shown in figure 21*A* are primarily because of the reduction in recharge, especially in areas not immediately adjacent to the Sanford pumping wells.

The differences between the groundwater divide and the topographic divide in the area that separates Branch Brook from the Merriland River to the south are somewhat less pronounced and do not indicate any significant deviation between the pumping and no pumping scenarios.

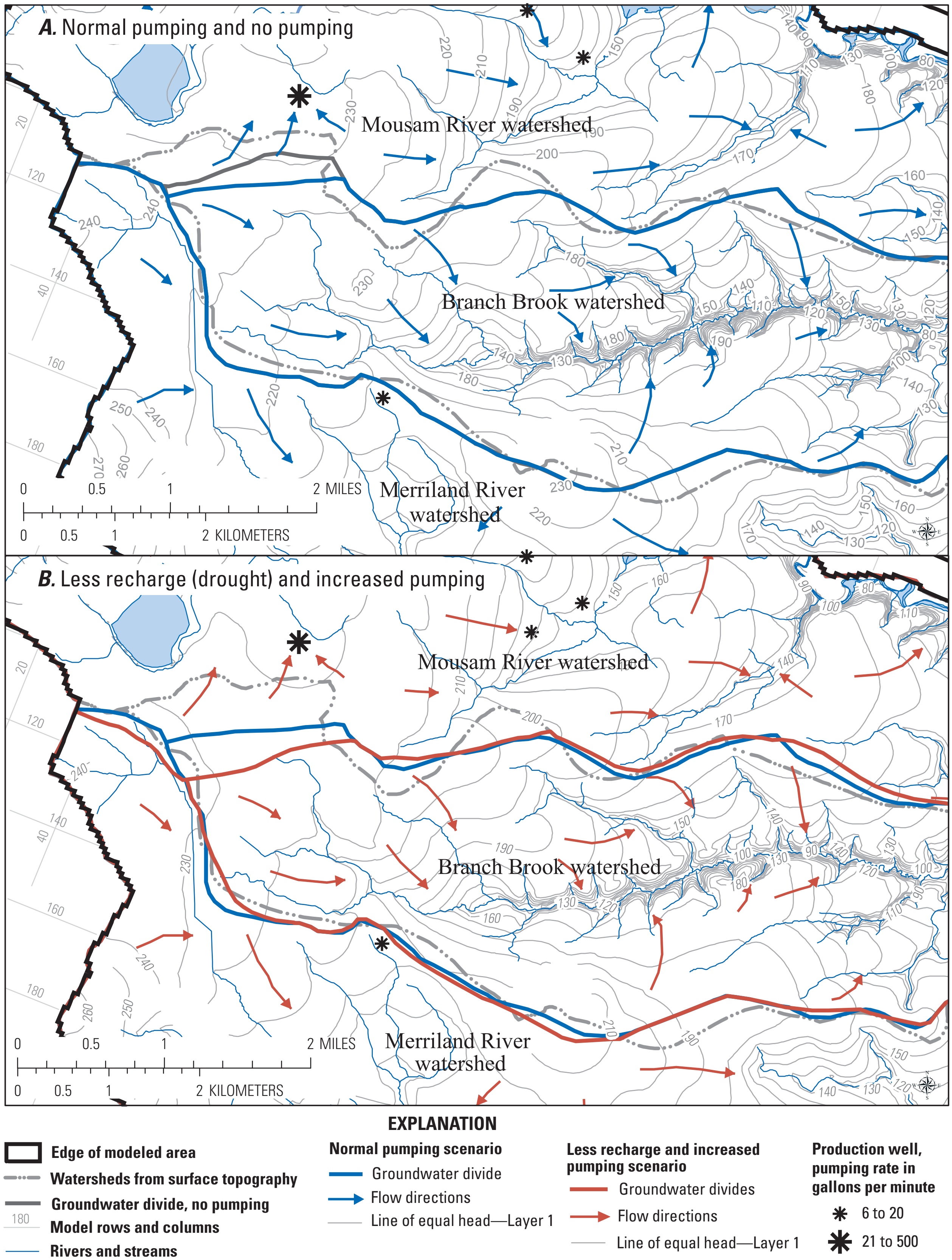


Figure 21. Groundwater divides and flow directions from simulated heads compared to topography-based watershed divides in the headwaters of the Branch Brook watershed in southern Maine: *A*, normal pumping and no pumping scenario and *B*, less recharge (drought) and increased pumping scenario.

Evaluation of Streamflow Depletion in Branch Brook and the Merriland River

A reduction in streamflow resulting from a groundwater withdrawal is known as streamflow depletion. Estimating the amount of streamflow depletion at a particular location caused by a groundwater withdrawal requires knowing how that withdrawal propagates through an aquifer to the river or stream. The cumulative effect of groundwater pumping by wells in the headwaters and near the mouths of Branch Brook and the Merriland River was calculated using the groundwater flow model.

Simulation of Streamflow Depletion Using the Groundwater Flow Model

Streamflow depletion resulting from pumping was calculated as the difference between streamflow (discharge to RIV and DRN cells) with no pumping (no simulated withdrawals from the calibrated model) and streamflow with pumping (the base-case calibrated model). Streamflow depletion was calculated for three of the streamflow measurement and streamflow observation locations: BB#6 (station 01069645), which represents the headwaters of Branch Brook; BB#1 (station 01069725), which is the farthest downstream site on Branch Brook and is near several withdrawal wells; and Merri#1 (station 01069780), which is the farthest downstream site on the Merriland River and is downstream from the withdrawal wells. In addition to the streamflow depletion using the base pumping rates, the streamflows with no pumping were compared to streamflows under drought conditions, with increases in pumping, and with drought and increased pumping combined.

The streamflow depletion calculations derived from the steady-state model assume that the pumping is constant, which is not the case for all the wells. The wells in the headwaters of Branch Brook pump year round, so the calculation of streamflow depletion for the headwater site is assumed to be valid for the entire year. The wells in the coastal plain, however, do not pump year round. Streamflow depletions may last well beyond the period of pumping in many situations (Barlow and Leake, 2012), but given the short distances between the wells in the coastal plain area and the rivers (less than ½ mile) and the fast rebound of streamflows after the cessation of pumping in wells near rivers in similar settings in Maine (Dudley and Stewart, 2006), the streamflows may return to their natural state shortly after the withdrawals end for the season. Therefore, the depletion calculations apply primarily to the pumping months, which are primarily April through November for the Merriland River wells and June through August for the wells closer to Branch Brook. Transient simulations of the groundwater, streamflow, and pumping in the study area would be useful to indicate more precisely how long the streamflow depletion is likely to last in Branch Brook and the Merriland River after pumping ceases. The streamflow depletion simulated with the groundwater model is considered to represent a maximum expected amount of depletion for the June base flows simulated in the model.

Streamflow depletion in the headwaters of Branch Brook at site BB#6 was 0.12 ft^3/s for the steady-state simulation, or about 10 percent of the total simulated base flow at that location (table 17). This is consistent with the finding that the Sanford pumping well had a small effect on the location of the groundwater divide, moving it farther south and capturing some of the flow in the Branch Brook watershed area. Downstream on Branch Brook at BB#1, the total streamflow depletion from all the wells was 0.59 ft^3/s, or 3 percent of the total simulated base flow at that location (although the simulated base flow, at 18.1 ft^3/s, is higher than the estimated August median flow of 11.8 ft^3/s). Most of that depletion was the result of pumping in the wells near Branch Brook, as model simulations without the Merriland River wells did not change the amount of depletion in Branch Brook. In the Merriland River at Merri#1, the total amount of streamflow depletion was 0.6 ft^3/s, or about 7 percent of simulated base flow (table 17). This amount of streamflow depletion is caused by pumping in the Merriland River well, as simulations without the wells near Branch Brook did not alter this amount.

The model was run with simulated increases in the pumping rates in each of the wells, as described in the section on scenario testing. The streamflow depletion by pumping in the headwaters at BB#6 increased to 0.19 ft^3/s, or 16 percent of the flow at that site (table 17). Increases in the pumping in the coastal plain wells increased the amount of streamflow depletion to 1.0 ft^3/s at BB#1 (6 percent of the flow) and to 0.72 ft^3/s at Merri#1 (8 percent of the flow).

The additional stress of a drought imposed on the model (25 percent less recharge) had a significant effect on streamflows, as would be expected. The reduction in streamflows from the simulated drought (not streamflow depletion) was 0.42 ft^3/s (38 percent reduction) at BB#6, 3.8 ft^3/s (23 percent reduction) at BB#1, and 2.1 ft^3/s (27 percent reduction) at Merri#1. It is interesting to note that the reduction in recharge had a disproportionately large effect on streamflows in the headwaters and a somewhat disproportionately large effect in the Merriland River. When compared to the normal recharge simulation without pumping, the streamflow in these river reaches was reduced by 34, 23, and 25 percent, respectively.

If the simulated drought occurred simultaneously with an increase in pumping, the simulated declines in streamflows would be 0.58 ft^3/s (a 48-percent reduction in flow from the no-pumping scenario) in the headwaters at BB#6. Downstream in Branch Brook at BB#1, the total reduction in flow would be 4.9 ft^3/s, which is 29 percent less than the no-pumping scenario. In the Merriland River, the reduction would be 2.8 ft^3/s, or a 33-percent reduction from the no-pumping scenario (table 17).

Because the groundwater model simulates streamflow (base flow) at all the Branch Brook streamflow sites, the differing effects of pumping and drought can be graphed going

Table 17. Model-calculated streamflow depletion in Branch Brook and the Merriland River.

[ft^3/s, cubic feet per second]

Scenario	Streamflow site		
	Branch Brook headwaters (BB#6)	Branch Brook at intake (BB#1)	Merriland River near mouth (Merri#1)
Total streamflow (in ft^3/s)			
Model-calculated steady-state with existing pumping	1.1	16.5	7.9
Predicted steady-state without pumping	1.2	17.1	8.5
Predicted with pumping increased	1.0	16.1	7.8
Predicted with 25 percent less recharge, existing pumping	0.68	12.7	5.8
Predicted with increased pumping and 25 percent less recharge	0.62	12.2	5.7
Streamflow depletion[1]			
Model-calculated steady-state with existing pumping	0.12	0.59	0.60
Predicted with pumping increased	0.19	1.0	0.72
Predicted with 25 percent less recharge, existing pumping	0.52	4.5	2.7
Predicted with increased pumping and 25 percent less recharge	0.58	4.9	2.8

[1]Difference between no pumping and the other scenarios (in ft^3/s).

downstream from the headwaters to the station at BB#1 (fig. 22). It is clear that in terms of magnitude of effect, the reduction of recharge (drought) has a much greater influence on streamflow than does pumping, suggesting that base flows in Branch Brook are sensitive to drought. The effect of groundwater withdrawals is evident primarily in the river reach between the USGS streamgage (station 01069700 at BB#2) and downstream at site BB#1 (station 01069720). Under the maximum pumping and drought scenario, the line between those two stations is almost flat (fig. 22), indicating that groundwater discharge (base flow) along that reach would almost cease.

Comparison of Streamflow Depletion Estimates to In-stream Flow Requirements

The water resources of Branch Brook have been used as a drinking-water source for many years, as described in the introduction. The groundwater model was used to put those withdrawals into context with the monthly in-stream flow requirements, monthly estimated flows, and streamflow depletion from groundwater pumping.

Figure 23 illustrates the combined effects of simulated pumping, direct withdrawals from Branch Brook, and simulated drought as applied to the monthly median estimates of streamflow in Branch Brook throughout the course of a year, in comparison with the State in-stream flow requirements. The monthly median flows in Branch Brook estimated using the MOVE.1 regression technique are shown, along with estimates of streamflow if there had been no groundwater pumping. The effect of drought on the streamflows is added to show how that might change the hydrograph throughout the year (assuming that the effect does not vary by month). The effect of the direct withdrawals downstream from the public supply intake at BB#1 is shown as well, and during the summer months, the flows below the intake can be a fraction of the unaffected flows. Because this effect has been directly observed by the water district in the past, they are actively seeking out alternative sources of water to use during the summer months (Scott D. Minor, Assistant Superintendent, Kennebunk, Kennebunkport and Wells Water District, oral commun., 2012).

As noted earlier in the section on the calculation of in-stream flow requirements, the two methods of determining in-stream flow requirements (based on August median flows) differ widely, with the MOVE.1 regression resulting in more realistic estimates than using the statewide flow equations. The streamflow depletion in Branch Brook simulated by the model would be 5 percent of the MOVE.1 August median (11.8 ft^3/s). In the Merriland River, the simulated streamflow depletion of 0.6 ft^3/s is approximately 20 percent of the MOVE.1 August median (3.07 ft^3/s).

Limitations of the Model

The groundwater flow model simulates groundwater levels, flow, and discharge in the study area. This model is not designed to simulate chemical transport, although it could be

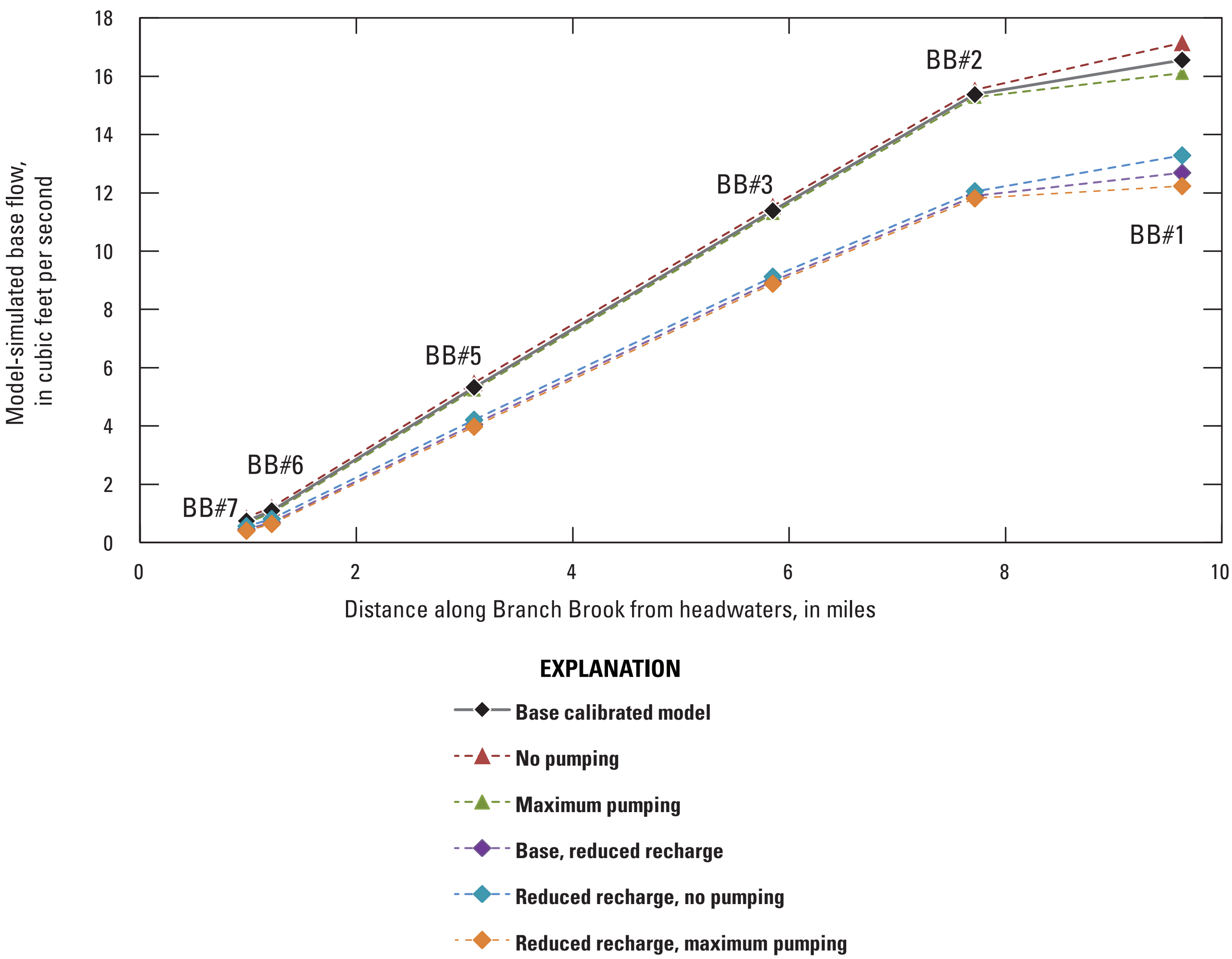


Figure 22. Model-simulated base flow in Branch Brook from the headwaters to the end, showing the effects of pumping and drought, southern Maine.

adapted for that purpose. As with any numerical simulation of a natural system, the model incorporates simplifications and assumptions about the natural system that create uncertainty in model results. Some of the simplifications include the assumption that the water levels and base flows represent true steady-state conditions and that geology is adequately represented by parameter values in the assigned zones.

The river and stream network is simplified from reality, and the modeled streambed conductance and riverbed conductance incorporate highly simplified representations of the width of each stream segment. The discretization of the stream network also assumes a straight-line segment in each model cell, which may differ significantly from reality. The water-level elevations in each model cell are interpolated from the topography in a way that may not represent each individual stream segment accurately. Most importantly, the known quantities for the base-flow observations (total flows at the 13 monitoring locations) had to be divided into individual DRN and RIV observations in the model. This was done using the modeler's best judgment for each segment but not by any measurements. Although the uncertainties of each of these individual DRN and RIV observations was adjusted upwards significantly to account for this, they still remained arbitrary divisions. The parameter estimation, therefore, may have given individual DRN or RIV observations more weight than warranted in determining the best fit between the observations and parameter estimates.

Additional stratigraphic data would have helped to make the movement of water more certain, particularly in the coastal plain area of the model. The extent of the buried gravel

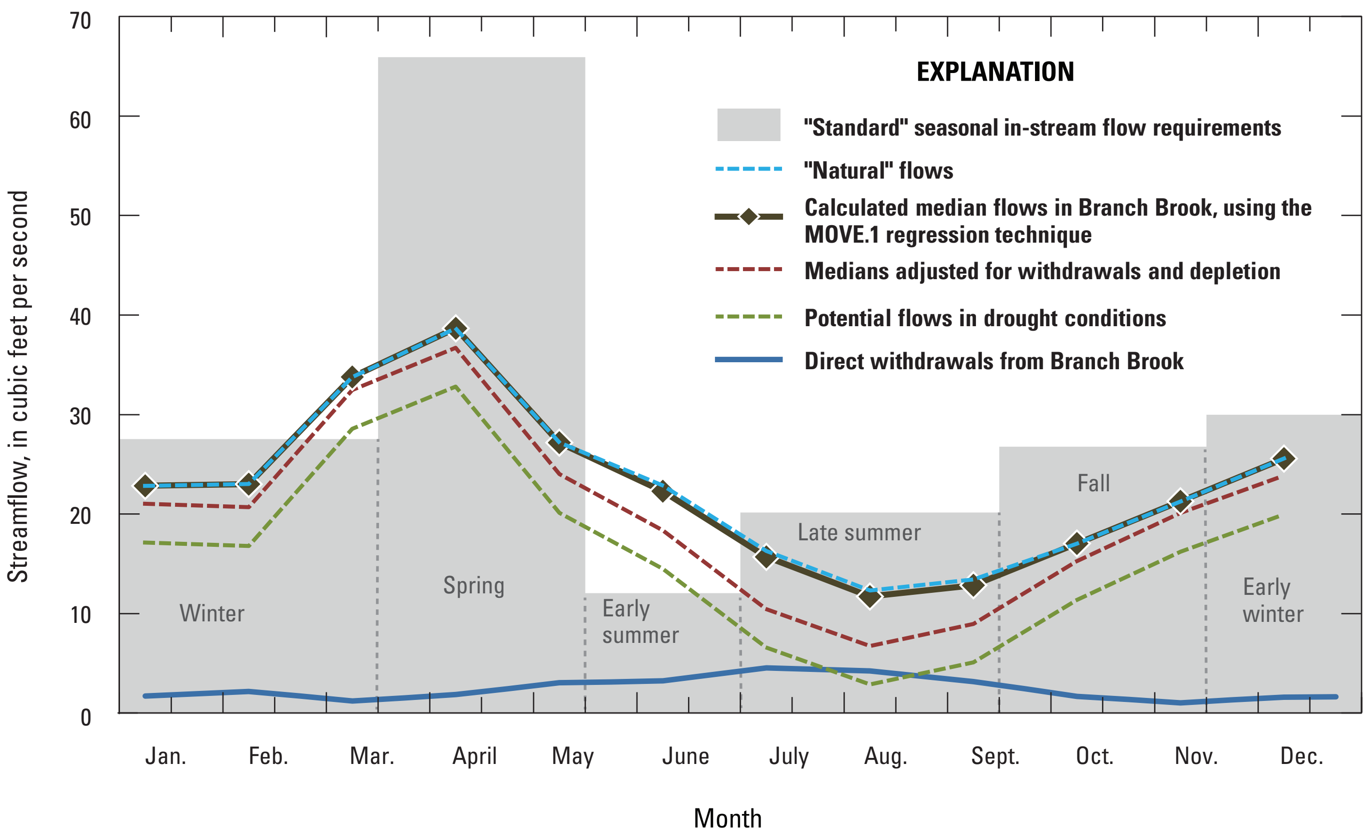


Figure 23. Calculated monthly streamflows in Branch Brook and projections of streamflows accounting for direct withdrawals, streamflow depletion from pumping, and drought, southern Maine.

aquifer in the coastal section is largely based on a geometry that provided the best fit between the observed and simulated water levels, rather than on actual boring or well data (all the well data that did exist were used in the delineation of this aquifer area). Also, the fact that this aquifer apparently extends beyond the model boundary to the south limits the accuracy of the model with respect to predictions of changes in water levels and fluxes to changes in stresses (pumping) so close to this model boundary.

There is other evidence of some model error in the central part of the Branch Brook watershed. The base-flow observations in this part of the model are extremely sensitive to several recharge parameters, but the recharge parameter with the greatest model sensitivity had to be constrained within the reasonable bounds as determined from prior information and could not be estimated. If the model construction perfectly matched the physical reality, the parameter estimation would derive best estimates for the recharge rates that fell within a reasonable range. This error could be either because of some undetected geologic factor that was not accounted for in the model or because of errors in the method used to calculate the base-flow observations.

The analysis of the model sensitivities noted earlier suggests that improvements to the model could be made with some additional data collection. This could include additional drilling to determine the extent and geologic nature of the buried gravel aquifer in the coastal plain area; collecting independent measurements of recharge in the study area, particularly in the Branch Brook, Cold Water Brook, and Day Brook watersheds; and additional drilling between Day Brook and Branch Brook to better determine the stratigraphy and extent of the Presumpscot Formation in that area.

The use of a steady-state model to simulate processes that change with the seasons, and pumping rates that are not constant, presents some limitations to the final results, as the streamflow depletion amounts that would be obtained from a transient model would likely differ somewhat from the steady-state streamflow depletion described in this report. A transient model also would be more suited to understanding the temporal effects of pumping on the rivers and stream and would be able to determine how long the streamflow depletion lingers after pumping ceases.

Summary and Conclusions

The Branch Brook watershed area in the towns of Kennebunk, Wells, and Sanford, Maine, was investigated in 2010 and 2013 under a cooperative project between the U.S. Geological Survey (USGS) and the Maine Geological Survey to investigate the effect of water withdrawals on watersheds having a large amount of permitted withdrawals relative to their size. The study area, located in southern coastal Maine, includes the Branch Brook watershed, the adjacent Merriland River watershed to the south, and extends north to the Mousam River, which forms the northern boundary of the study area. This investigation provides an illustration of the effects that large withdrawals can have on hydrologic processes in Maine watersheds and evaluates the cumulative effect of several withdrawals on a relatively complex sand and gravel aquifer system. A steady-state groundwater flow model was used to evaluate the water budget, to understand the movement of water within the system, and to assess the effect that groundwater withdrawals have on streamflows. This study, like an earlier study under the cooperative project, is intended to provide insight into the effect of withdrawals on streamflows under a certain set of conditions (that is, the aquifer geometry presented by the specific study area) and to help understand streamflow depletion in light of the State requirements to maintain in-stream flows for habitat protection. The groundwater flow model was used to simulate the present (2013) withdrawal situation as well as scenarios that included drought conditions and future increased pumping.

There are four large water-supply wells in the study area, four small water-supply wells, and 1,751 self-supplied domestic wells. The large water-supply wells in the study area withdraw a total of 658.8 million gallons per year (Mgal/yr), and a surface-water withdrawal in Branch Brook withdraws 590 Mgal/yr. One of the largest groundwater withdrawals is located just outside the Branch Brook watershed boundary, and one objective of the study was to understand if and how much effect that well has on the location of the groundwater divide and flow in Branch Brook.

The geologic units in the study area include fractured crystalline bedrock and stratified, unconsolidated glacial and post-glacial deposits that are draped over the bedrock. The glacial deposits include till (in moraines and as a blanket deposit), stratified marine sand and gravel, marine silt and clay, beach and nearshore sand and gravel deposits, and sandy deltaic deposits.

The surficial deposits provide most of the available groundwater resource for human use. The hydrogeologic units supplying groundwater to the public supply wells, irrigation wells, and to a lesser extent, domestic wells, are primarily sands and gravels of a large set of ice-contact and marine deltaic deposits and nearshore marine deposits. A previously unmapped buried gravel aquifer that appears to supply most of the water to the Merriland River well trends northeast-southwest under the coastal plain, and crosses the model boundary to the south. In the central and western part of the study area, the topography is very flat, and the relative positions of the groundwater and surface-water divides between the headwaters of Branch Brook, the Mousam River watershed, and the headwaters of the Merriland River are difficult to ascertain. Groundwater levels were measured in 130 wells in the study area in June 2012. The wells were a mix of monitoring wells and homeowner wells. One long-term groundwater monitoring well operated by the USGS since 1988 provided context for the hydrologic conditions during the water-level survey.

Streamflow was measured at 13 locations in the study area from June 2010 to April 2012, including 5 sites on the main stem of Branch Brook. Estimates of long-term monthly flows were made using the MOVE.1 record-extension techniques on 16 to 17 measurements at each location.

Surface-water withdrawals in the study area in 2010 were primarily withdrawals from Branch Brook, in the amount of 590 million gallons (Mgal). Agricultural irrigation from surface-water ponds was estimated to be about 9 Mgal. Permitted groundwater withdrawals totaled 384.3 Mgal in the Merriland River watershed, 231.5 Mgal in the Mousam River watershed, and 32.2 Mgal in the Branch Brook watershed. Domestic withdrawals from private wells were split fairly evenly between the watersheds and were 90 Mgal in total. Commercial and industrial water use in the study area is small in relation to these other uses and was estimated to total 2.3 Mgal.

The groundwater modeling component of the study was used to better understand groundwater flow and the interaction of groundwater with streamflow in the study area. A steady-state groundwater model was constructed using the three-dimensional, finite-difference groundwater flow modeling code, MODFLOW–2005. This model was used to simulate flow in the unconsolidated glacial deposits and shallow bedrock units.

The model area was discretized into a grid of 443 rows and 214 columns of cells with uniform 150-foot (ft) spacing. The seven-layer model was used to simulate flow in the bedrock under the glacial deposits (two layers), a middle zone including productive aquifers in the eastern and western parts of the study area and a confining unit in the central and eastern parts of the study area (three layers), and an upper zone consisting of the shallowest sand and gravel deposits, till, and shallow bedrock in upland areas with thin unconsolidated materials over bedrock (two layers). The upper two layers were modeled as unconfined. The land surface was set as the top of the uppermost layer (layer 1). The lateral model boundaries were primarily no-flow boundaries on upland surface-water divides. The Atlantic Ocean was modeled as a constant-head boundary on the eastern edge. Although the watershed boundary was used for most of the groundwater model boundary, significant sand and gravel aquifers are mapped crossing the watershed boundary in several locations, where a general head boundary (GHB) was used instead of a no-flow boundary. The southern end of the buried gravel aquifer in the coastal plain area also was modeled with a GHB boundary.

Data from monitoring wells and surface-water bodies were used to set the heads at these boundaries.

Recharge was applied in the model to the top active cell. Recharge rates ranged from less than 3 inches/year (in/yr) in the shallow bedrock and wetland settings to approximately 30 in/yr in the very coarse-grained soils that cover much of the study area. Although this is considered a relatively high recharge rate for southern Maine, other investigators have corroborated this high rate in the study area. Pumping was simulated in the model for all the water-supply wells. The surface-water system was modeled using both the Drain package and River package in MODFLOW.

The model was calibrated using a mix of parameter estimation of hydraulic properties and recharge rates and trial-and-error adjustments to the conceptual model of the groundwater system, as well as some of the hydraulic properties and recharge rates. Groundwater level observations were acquired from the water-level survey of June 2012 and surface-water elevations in wetlands and ponds. Stream- and river-flow observations were mid-summer (June and July) base flows in the 13 streamflow measurement sites, determined by use of record-extension techniques. Hydraulic properties and recharge rates were set within a reasonable range established by prior studies and literature values.

The mean difference between the observed and simulated heads is 1.4 ft, and the mean absolute difference between the observed and simulated heads is 4.0 ft. Given the range in observed heads over the model area of 282 ft, these errors represent 0.5 and 1.4 percent, respectively, of the total head change across the model. The simulated streamflows at the 13 observation sites were almost all within the 95-percent confidence intervals of the observation target flows.

The simulated average annual water budget for the Branch Brook, Merriland River, and lower Mousam River watershed areas in the model were calculated using the MODFLOW supplemental software ZONEBUDGET. Flow across the surface-water divides between the headwaters of Branch Brook, the Mousam River watershed, and the headwaters of the Merriland River accounted for between 7 and 12 percent of the overall budgets of the watersheds. Mapping of the simulated water-table divides compared to the surface-water divides confirmed that the groundwater divides in this area of low topography do not exactly correspond to the surface-water divides.

The groundwater model was used to evaluate several different scenarios that could change the amount of groundwater flowing to the rivers and streams in the study area. The scenarios were (1) no pumping from the water-supply wells; (2) current (as of 2013) pumping from the water-supply wells, but simulated drought conditions (25 percent reduction in recharge); (3) current recharge, but with increased pumping from the large water-supply wells; and (4) drought conditions and increased pumping combined. The simulation without pumping water-supply wells was used as a "natural" flow scenario against which the streamflows with the current pumping were compared to derive the streamflow depletion amounts in the rivers.

Streamflow depletion resulting from pumping was calculated as the difference between discharge to river and drain cells in the calibrated model with the no pumping scenario. Streamflow depletion was calculated for three of the streamflow measurement locations: the first represents the headwaters of Branch Brook (site BB#6), the second is the furthest downstream site on Branch Brook and is near several withdrawal wells (site BB#1), and the third is the furthest downstream site on the Merriland River and is downstream from the Merriland River withdrawal well (site Merri#1).

Streamflow depletion in the headwaters of Branch Brook at site BB#6 was 0.12 cubic feet per second (ft^3/s) for the steady-state simulation, or about 10 percent of the simulated base flow at that location. Downstream on Branch Brook at BB#1, the total streamflow depletion from all the wells was 0.59 ft^3/s, or 3 percent of the simulated base flow at that location. In the Merriland River at Merri#1, the total amount of streamflow depletion was 0.6 ft^3/s, or about 7 percent of the simulated base flow. Under simulations of increased pumping, streamflow depletion in the headwaters at BB#6 increased to 0.19 ft^3/s, or 16 percent of the simulated base flow at that site. Increases in the pumping in the coastal plain wells increased the amount of streamflow depletion to 1.0 ft^3/s at BB#1 and to 0.72 ft^3/s at Merri#1. The additional stress of a drought imposed on the model (25 percent less recharge) had a significant effect on streamflows, as expected. The reduction in streamflows from the simulated drought (not streamflow depletion) was 0.42 ft^3/s (37 percent reduction) at BB#6, 3.8 ft^3/s (23 percent reduction) at BB#1, and 2.1 ft^3/s (27 percent reduction) at Merri#1. If the simulated drought occurred simultaneously with an increase in pumping, the simulated declines in streamflows would be 0.58 ft^3/s (a 48-percent reduction in flow from the no-pumping scenario) in the headwaters at BB#6. Downstream in Branch Brook at BB#1, the total reduction in flow would be 4.9 ft^3/s, which is 29 percent less than the no-pumping scenario. In the Merriland River, the reduction would be 2.8 ft^3/s, or a 33 percent reduction from the no-pumping scenario.

The pumping from the groundwater-supply wells in the coastal plain area is not year round. The streamflow depletion estimates for the Merriland River generally apply for the primary pumping season for that well, or April through November. The pumping wells are pumped for a shorter amount of time during the summer months, so the streamflow depletion estimates for the downstream Branch Brook site generally apply to June through September, although the exact period varies from year to year. The pumping in the headwaters of Branch Brook is year round, so the headwaters streamflow depletion estimates are assumed to be constant.

The August median in-stream flow requirement in the Merriland River was calculated as 7.18 ft^3/s using the statewide equations but was 3.07 ft^3/s using the MOVE.1 analysis. In Branch Brook, the August median in-stream flow requirements were calculated as 20.3 ft^3/s using the statewide equations and 11.8 ft^3/s using the MOVE.1 analysis. In each case, analysis of site-specific data yields target median flows that are closer to actual conditions in the local streams than what the statewide equations provide, and which would therefore be easier for a regulated utility to maintain for meeting in-stream flow requirements. The State Chapter 587 requirements for in-stream flows does allow for using a third possible method of calculating in-stream flows using a geomorphic analysis, but doing so was not an objective of this study.

An analysis of summertime base flows in Branch Brook with the permitted surface-water withdrawals and simulated declines in flows under drought conditions indicates that the amount of water flowing in Branch Brook downstream from the withdrawal site could be about 23 to 29 percent less than the natural flows under normal conditions. The water utility in this area is already planning for increases in groundwater withdrawals in the greater region so that the surface-water withdrawals might be reduced.

The use of the groundwater flow model to map the groundwater divides and flow directions in the flat headwaters section has helped to understand the groundwater resources in these watersheds and can be used to better manage the resource. The scenario simulations run with the model indicated that the pumping well in the Mousam River watershed, near the headwaters of Branch Brook, does shift the groundwater divide towards the south several hundred feet, capturing a small amount (less than 0.2 ft^3/s) of groundwater from the Branch Brook watershed. The simulations of streamflow depletion in Branch Brook and the Merriland River indicate that the cumulative effects of pumping should be considered together to evaluate the overall effect on a given river or stream location.

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Appendix 1. Groundwater Observation Information

Table 1–1. Groundwater observation information, including well names, well depths, land surface altitude, and variances and weights used in the model.

[ft, feet; NAVD 88, North American Vertical Datum of 1988; σ^2, variance]

Well name	Model observation name	Observation group	Well depth, in ft	Land surface altitude, in ft above NAVD 88	Model layer	Measured water level, in ft above NAVD 88	Total variance (σ^2), in ft	Weight, $1/\sigma^2$
ME-YW 985 KKW MW-02	KKW_MW02	BB-North	23	211	1	196.8	0.263	3.804
ME-YW 986 KKW MW-07A	KKW_MW07A	BB-North	54	210	2	193.2	0.263	3.804
ME-YW 987 KKW MW-15	KKW_MW15	BB-North	36	181	2	166.3	0.263	3.804
ME-YW 988 KKW MW-23	KKW_MW23	BB-North	54	208	2	188.7	0.263	3.804
ME-YW 989 KKW MW-26	KKW_MW26	BB-North	38	211	1	194.4	0.263	3.804
ME-YW 990 KKW MW-30	KKW_MW30	BB-North	35	207	1	191.6	0.263	3.804
ME-YW 991 KKW MW-35	KKW_MW35	BB-North	35	207	1	182.1	0.263	3.804
ME-YW 992 KKW MW-48	KKW_MW48	BB-North	38	212	1	184.7	0.263	3.804
ME-YW 933 Nestle MW-01	Nestle_MW01	BB-North	20	199	1	192.4	0.521	1.921
ME-YW 934 Nestle MW-06	Nestle_MW06	BB-North	73	214	4	203.3	0.521	1.921
ME-YW 935 Nestle MW-13	Nestle_MW13	BB-North	81	210	5	192.9	0.521	1.921
ME-YW 936 Nestle MW-14	Nestle_MW14	BB-North	85	205	4	188.4	0.521	1.921
ME-YW 937 Nestle MW-16	Nestle_MW16	BB-North	64	205	3	164.7	0.521	1.921
ME-YW 938 Nestle MW-24	Nestle_MW24	BB-North	60	205	4	184	0.521	1.921
ME-YW 939 Nestle MW-33	Nestle_MW33	BB-North	64	208	3	189.7	0.521	1.921
ME-YW 940 Nestle MW-41	Nestle_MW41	BB-North	49	203	3	180.7	0.521	1.921
ME-YW 941 Nestle MW-44	Nestle_MW44	BB-North	55	203	2	186.6	0.521	1.921
ME-YW 942 Nestle MW-45	Nestle_MW45	BB-North	64	206	3	182.3	0.521	1.921
ME-YW 943 Nestle MW-46	Nestle_MW46	BB-North	41	211	1	197.9	0.521	1.921
ME-YW 944 Nestle MW-47	Nestle_MW47	BB-North	44	211	2	199.1	0.521	1.921
ME-YW 1002 TNC MW-101	TNC_MW101	BB-South	50	197	2	170.8	0.521	1.921
ME-YW 946 TNC MW-103	TNC_MW103	BB-South	50	191	4	170.9	0.521	1.921
ME-YW 1003 TNC MW-105	TNC_MW105	BB-South	25	196	1	181.2	0.521	1.921
ME-YW 1004 TNC MW-106	TNC_MW106	BB-South	25	192	2	185.6	0.521	1.921
ME-YW 947 TNC MW-107	TNC_MW107	BB-South	25	188	2	176.6	0.521	1.921
ME-YW 948 TNC MW-109	TNC_MW109	BB-South	15	191	1	185.8	0.521	1.921
ME-YW 949 TNC MW-110	TNC_MW110	BB-South	30	186	3	176.8	0.521	1.921
ME-YW 1000 TNC MW-202	TNC_MW202	BB-South	29.5	193	2	185.5	0.521	1.921
ME-YW 1001 TNC MW-204	TNC_MW204	BB-South	25	191	2	183.9	0.521	1.921
ME-YW 951 TNC MW-304	TNC_MW304	BB-South	19	195	1	189	0.521	1.921
ME-YW 953 TNC MW-308	TNC_MW308	BB-South	30	196	2	187.8	0.521	1.921
ME-YW 954 TNC MW-310	TNC_MW310	BB-South	30	197	2	185.8	0.521	1.921
ME-YW 999 TNC MW-315	TNC_MW315	BB-South	26	197	2	188.2	0.521	1.921
ME-YW 956 TNC MW-401	TNC_MW401	BB-South	30	198	1	187	0.521	1.921
ME-YW 993 TNC MW-403	TNC_MW403	BB-South	29	199	1	179	0.521	1.921
ME-YW 994 TNC MW-404	TNC_MW404	BB-South	39	198	3	180.6	0.521	1.921
ME-YW 957 TNC MW-410	TNC_MW410	BB-South	36	198	2	186.9	0.521	1.921
ME-YW 995 TNC MW-415	TNC_MW415	BB-South	30	199	2	182.6	0.521	1.921
ME-YW 959 TNC MW-422	TNC_MW422	BB-South	30	200	1	182.7	0.521	1.921

Table 1–1. Groundwater observation information, including well names, well depths, land surface altitude, and variances and weights used in the model.—Continued

[ft, feet; NAVD 88, North American Vertical Datum of 1988; σ^2, variance]

Well name	Model observation name	Observation group	Well depth, in ft	Land surface altitude, in ft above NAVD 88	Model layer	Measured water level, in ft above NAVD 88	Total variance (σ^2), in ft	Weight, $1/\sigma^2$
ME-YW 996 TNC MW-425	TNC_MW425	BB-South	28	194	1	177.8	0.521	1.921
ME-YW 962 TNC MW-430	TNC_MW430	BB-South	30	195	1	179.1	0.521	1.921
ME-YW 997 TNC MW-433	TNC_MW433	BB-South	21	198	1	187.4	0.521	1.921
ME-YW 998 TNC MW-440	TNC_MW440	BB-South	20	195	1	184.5	0.521	1.921
ME-YW 870	ME_YW_870	Bedrock	260	161	7	112.9	0.521	1.921
ME-YW 878	ME_YW_878	Bedrock	73	159	6	146.5	0.521	1.921
ME-YW 882	ME_YW_882	Bedrock	75	208	4	206.2	0.521	1.921
ME-YW 883	ME_YW_883	Bedrock	700	179	7	175	0.521	1.921
ME-YW 888	ME_YW_888	Bedrock	300	273	7	254.2	0.521	1.921
ME-YW 891	ME_YW_891	Bedrock	244	36	7	6.3	0.521	1.921
ME-YW 894	ME_YW_894	Bedrock	300	31	7	15.7	0.521	1.921
ME-YW 895	ME_YW_895	Bedrock	300	122	7	108.8	0.521	1.921
ME-YW 896	ME_YW_896	Bedrock	300	95	7	87.7	0.521	1.921
ME-YW 897	ME_YW_897	Bedrock	500	173	7	168.1	0.521	1.921
ME-YW 901	ME_YW_901	Bedrock	200	175	7	151.3	0.521	1.921
ME-YW 871	ME_YW_871	Coastal sands dug	5	78	1	75.2	0.521	1.921
ME-YW 872	ME_YW_872	Coastal sands dug	10.6	81	1	76.8	0.521	1.921
ME-YW 873	ME_YW_873	Coastal sands dug	18.1	71	1	70.3	0.521	1.921
ME-YW 890	ME_YW_890	Coastal sands dug	9.8	34	1	28.7	0.521	1.921
ME-YW 892	ME_YW_892	Coastal sands dug	9.1	38	1	35.6	0.521	1.921
ME-YW 893	ME_YW_893	Coastal sands dug	10	33	1	29.2	0.521	1.921
ME-YW 906	ME_YW_906	Coastal sands dug	7.8	61	1	55.9	0.521	1.921
ME-YW 874	ME_YW_874	Delta sands dug	10.5	141	1	134.3	0.521	1.921
ME-YW 875	ME_YW_875	Delta sands dug	18	171	1	164.7	0.521	1.921
ME-YW 876	ME_YW_876	Delta sands dug	13.5	214	1	204.8	0.521	1.921
ME-YW 884	ME_YW_884	Delta sands dug	16	205	1	202.6	0.521	1.921
ME-YW 885	ME_YW_885	Delta sands dug	14.1	210	1	202.3	0.521	1.921
ME-YW 886	ME_YW_886	Delta sands dug	15	209	1	202.3	0.521	1.921
ME-YW 900	ME_YW_900	Delta sands dug	15	175	1	168.3	0.521	1.921
ME-YW 902	ME_YW_902	Delta sands dug	9.5	216	1	211.7	6.768	0.148
ME-YW 903	ME_YW_903	Delta sands dug	20	133	1	126	0.521	1.921
ME-YW 905	ME_YW_905	Delta sands dug	10.9	223	1	218	6.768	0.148
ME-YW 907	ME_YW_907	Delta sands dug	10.5	148	1	144.5	0.521	1.921
ME-YW 908	ME_YW_908	Delta sands dug	9.2	160	1	159.8	0.521	1.921
ME-YW 909	ME_YW_909	Delta sands dug	9.5	210	1	207.8	6.768	0.148
ME-YW 963	ME_YW_963	Delta sands dug	11	89	1	86.4	0.521	1.921
ME-YW 965	ME_YW_965	Delta sands dug	10	210	1	205.5	0.521	1.921
ME-YW 966	ME_YW_966	Delta sands dug	9	79	1	73.9	0.521	1.921
ME-YW 967 Genest 33-81	Genest_33_81	Genest	45	211	5	208	6.768	0.148

Table 1–1. Groundwater observation information, including well names, well depths, land surface altitude, and variances and weights used in the model.—Continued

[ft, feet; NAVD 88, North American Vertical Datum of 1988; σ^2, variance]

Well name	Model observation name	Observation group	Well depth, in ft	Land surface altitude, in ft above NAVD 88	Model layer	Measured water level, in ft above NAVD 88	Total variance (σ^2), in ft	Weight, $1/\sigma^2$
ME-YW 971 Genest 34-81	Genest_34_81	Genest	116	219	6	215.2	6.768	0.148
ME-YW 970 Genest 34A-81	Genest_34A	Genest	116	218	6	214.6	6.768	0.148
ME-YW 969 Genest 34B	Genest_34B	Genest	116	218	6	208.1	6.768	0.148
ME-YW 972 Genest 34C	Genest_34C	Genest	94	221	5	217.4	6.768	0.148
ME-YW 968 Genest 34D	Genest_34D	Genest	74	219	4	211.6	6.768	0.148
ME-YW 973 Genest 34E	Genest_34E	Genest	118	246	5	213.2	6.768	0.148
ME-YW 974 Genest 59-81	Genest_59_81	Genest	70	236	4	218.3	6.768	0.148
ME-YW 1020 MWHR 1	KKW_MWHR1	Herrisecket Rd.	55	68	4	28.3	0.521	1.921
ME-YW 1009 KKW MWHR 11	KKW_MWHR11	Herrisecket Rd.	53	51	6	10.8	0.521	1.921
ME-YW 917 KKW-MWHR 12	KKW_MWHR12	Herrisecket Rd.	51	51	5	10.8	0.521	1.921
ME-YW 910 KKW-MWHR 3	KKW_MWHR3	Herrisecket Rd.	69	68.	5	30.6	0.521	1.921
ME-YW 1008 KKW MWHR 4	KKW_MWHR4	Herrisecket Rd.	45	69.5	3	34.7	0.521	1.921
ME-YW 912 KKW-MWHR 6	KKW_MWHR6	Herrisecket Rd.	35	64.9	2	34.3	0.521	1.921
ME-YW 913 KKW-MWHR 7	KKW_MWHR7	Herrisecket Rd.	40	75.7	2	43.4	0.521	1.921
ME-YW 914 KKW-MWHR 8	KKW_MWHR8	Herrisecket Rd.	15	79.2	1	68.1	0.521	1.921
ME-YW 926 KKW-DPMR 1	KKW_DPMR1	Merriland	11	19.8	1	19.1	0.521	1.921
ME-YW 923 KKW-DPMR 3	KKW_DPMR3	Merriland	12	38.2	1	34.9	0.521	1.921
ME-YW 925 KKW-MWMR 1	KKW_MWMR1	Merriland	108	22.4	6	-15.2	0.521	1.921
ME-YW 921 KKW-MWMR 10	KKW_MWMR10	Merriland	73	72.7	6	15.5	0.521	1.921
ME-YW 929 KKW-MWMR 11	KKW_MWMR11	Merriland	66	31.2	5	-3.7	0.521	1.921
ME-YW 1006 KKW MWMR 13	KKW_MWMR13	Merriland	53	34.3	4	18.8	0.521	1.921
ME-YW 931 KKW-MWMR 14	KKW_MWMR14	Merriland	73	17.3	4	-6.6	0.521	1.921
ME-YW 928 KKW-MWMR 15	KKW_MWMR15	Merriland	42	39.8	5	17.2	0.521	1.921
ME-YW 927 KKW-MWMR 16	KKW_MWMR16	Merriland	45	30	6	17.6	0.521	1.921
ME-YW 1007 KKW MWMR 18	KKW_MWMR18	Merriland	100	31	4	-16.8	0.521	1.921
ME-YW 932 KKW-MWMR 5	KKW_MWMR5	Merriland	197	40.1	5	-9.4	0.521	1.921
ME-YW 924 KKW-MWMR 6	KKW_MWMR6	Merriland	134	33.7	6	-13.4	0.521	1.921
ME-YW 930 KKW-MWMR 8	KKW_MWMR8	Merriland	70	38.2	5	-5.7	0.521	1.921
ME-YW 922 KKW-MWMR 9	KKW_MWMR9	Merriland	91	53.1	4	-5	0.521	1.921
ME-YW 980 SWD Eagle 1	SWD_Eagle_1	Sanford	35	227	3	221.6	6.768	0.148
ME-YW 981 SWD Eagle 2	SWD_Eagle_2	Sanford	65	227	4	187.3	6.768	0.148
ME-YW 977 SWD Eagle #6	SWD_Eagle_6	Sanford	91	226	4	205.4	6.768	0.148
ME-YW 978 SWD Eagle #6a	SWD_Eagle_6a	Sanford	68	227	4	210.6	6.768	0.148
ME-YW 979 SWD Eagle #7	SWD_Eagle_7	Sanford		233	3	231.2	6.768	0.148
ME-YW 975 SWD IDC M1	SWD_IDC_M1	Sanford	130	259	6	226.8	6.768	0.148
ME-YW 976 SWD IDC M4	SWD_IDC_M4	Sanford	93	250	6	225.4	6.768	0.148
ME-YW 982 SWD ND-1	SWD_ND_1	Sanford	65	250	5	237.6	6.768	0.148
ME-YW 983 SWD ND-4	SWD_ND_4	Sanford	50	251	4	237	6.768	0.148
ME-YW 984 SWD ND GP	SWD_ND_GP	Sanford	65	250	5	237.6	6.768	0.148

Table 1–1. Groundwater observation information, including well names, well depths, land surface altitude, and variances and weights used in the model.—Continued

[ft, feet; NAVD 88, North American Vertical Datum of 1988; σ^2, variance]

Well name	Model observation name	Observation group	Well depth, in ft	Land surface altitude, in ft above NAVD 88	Model layer	Measured water level, in ft above NAVD 88	Total variance (σ^2), in ft	Weight, $1/\sigma^2$
ME-YW 1010 DEP MW03-02	DEP_MW03_02	Sanford-Cyro	25	232	1	226.2	6.768	0.148
ME-YW 1011 DEP MW-101A	DEP_MW101A	Sanford-Cyro	19	248.5	1	232.8	6.768	0.148
ME-YW 1012 DEP MW-104A	DEP_MW104A	Sanford-Cyro	20	242	1	230.6	6.768	0.148
ME-YW 1013 DEP MW-104BR	DEP_MW104BR	Sanford-Cyro	48	242	5	230.6	6.768	0.148
ME-YW 1014 DEP MW-201A	DEP_MW201A	Sanford-Cyro	20	244.5	1	232.8	6.768	0.148
ME-YW 1015 DEP MW-204A	DEP_MW204A	Sanford-Cyro	15	232	1	224.1	6.768	0.148
ME-YW 1016 DEP MW-204B	DEP_MW204B	Sanford-Cyro	33	232	3	226.2	6.768	0.148
ME-YW 1017 DEP MW-205B	DEP_MW205B	Sanford-Cyro	38	240.5	4	228.6	6.768	0.148
ME-YW 1018 DEP MW-209A	DEP_MW209A	Sanford-Cyro	15	232	1	226.3	6.768	0.148
ME-YW 1019 DEP MW-702B	DEP_MW702B	Sanford-Cyro	13	226	1	223.3	6.768	0.148
ME-YW 1005 DEP Cyro X-2	DEPCyro_X2	Sanford-Cyro	35	250	2	230.4	6.768	0.148
Airport wetland S[1]	Airport_S	SW points	2	228	1	228	6.7	0.15
Airport wetland SW[1]	Airport_SW	SW points	2	237	1	237	6.7	0.15
Estes Lake 1[1]	Estes_Lake_1	SW points	5	213	1	213	6.7	0.15
Estes Lake 2[1]	Estes_Lake_2	SW points	5	213	1	213	6.7	0.15
Estes Lake 3[1]	Estes_Lake_3	SW points	5	213	1	213	6.7	0.15
Merriland headwaters wetland[1]	Merri_head	SW points	2	184	1	184	1	1
Merriland wetland south[1]	Merri_S_wet	SW points	2	165	1	165	6.7	0.15
Ocean wetland[1]	Ocean_wet	SW points	2	13	1	13	1	1
Old Falls Pond[1]	OldFallsPond	SW points	5	5	1	0	0.52	1.9
Perkins Marsh wetland[1]	Perkins_Msh	SW points	2	163	1	163	1	1
Railroad wetland N[1]	RR_wet_N	SW points	2	37	1	37	1	1
Railroad wetland S[1]	RR_wet_S	SW points	2	27	1	27.5	1	1
Sanford wetland 1[1]	Sanford_wet1	SW points	2	249	1	249	6.7	0.15
Saywards Corner wetland[1]	Saywards_Wet	SW points	2	189	1	189	1	1
Till uplands wetland[1]	Till_up_wet	SW points	2	186	1	186	1	1
ME-YW 869	ME_YW_869	Till dug	13.9	142.8	1	138.9	0.521	1.921
ME-YW 877	ME_YW_877	Till dug	18	191.2	1	189.4	0.521	1.921
ME-YW 880	ME_YW_880	Till dug	9	170.8	1	170.8	0.521	1.921
ME-YW 881	ME_YW_881	Till dug	15.1	209.8	1	203.7	0.521	1.921
ME-YW 887	ME_YW_887	Till dug	15	269.8	7	265.1	0.521	1.921
ME-YW 899	ME_YW_899	Till dug	17.6	114.5	1	110	0.521	1.921
ME-YW 904	ME_YW_904	Till dug	12.7	175.3	1	169.5	0.521	1.921
ME-YW 964	ME_YW_964	Till dug	7	144.1	1	143.3	0.521	1.921

[1]Surface-water and wetland points used as groundwater level observations.

Appendix 2. Dimensionless Scaled Sensitivities for Parameters

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Horizontal K parameters											
		HK_Alluv	HK_BurGrav	HK_Coarse	HK_Delta1	HK_Delta2	HK_Granite	HK_L1ROCK	HK_MMRock	HK_MrnSand	HK_PmUndif	HK_Presump	HK_Special
Nestle_MW01	BB-North	-1.23	0.00	-0.91	-0.03	-11.11	-0.18	-0.93	0.00	0.00	0.00	-1.76	0.00
Nestle_MW06	BB-North	-1.42	0.00	-1.13	-0.04	-14.49	-0.68	-0.89	0.00	0.00	0.00	-1.31	0.00
Nestle_MW13	BB-North	-1.37	0.00	-0.95	-0.03	-11.12	-0.91	-1.07	0.00	0.00	0.00	-1.91	0.00
Nestle_MW14	BB-North	-2.66	0.00	-0.39	-0.01	-10.69	-0.78	-1.39	0.00	0.00	-0.00	-3.16	0.00
Nestle_MW16	BB-North	-6.00	0.00	-0.20	-0.00	-3.49	-0.22	-1.73	0.00	0.00	-0.00	-3.51	0.00
Nestle_MW24	BB-North	-1.04	0.00	-0.77	-0.03	-5.06	-0.02	-1.11	0.00	0.00	-0.00	-2.20	0.00
Nestle_MW33	BB-North	-2.79	0.00	-0.39	-0.01	-11.28	-0.45	-1.36	0.00	0.00	0.00	-3.09	0.00
Nestle_MW41	BB-North	-2.08	0.00	-0.28	-0.01	-5.26	-0.12	-1.76	0.00	0.00	0.00	-4.42	0.00
Nestle_MW44	BB-North	-4.27	0.00	-0.32	-0.01	-8.89	-0.26	-1.07	0.00	0.00	-0.00	-2.28	0.00
Nestle_MW45	BB-North	-4.43	0.00	-0.25	-0.01	-7.63	-0.36	-1.54	0.00	0.00	-0.00	-3.26	0.00
Nestle_MW46	BB-North	-2.77	0.00	-0.55	-0.02	-15.40	-0.32	-1.10	0.00	-0.00	-0.00	-2.23	0.00
Nestle_MW47	BB-North	-2.58	0.00	-0.56	-0.02	-12.28	-0.33	-0.74	0.00	0.00	0.00	-1.38	0.00
KKW_MW02	BB-North	-1.64	0.00	-1.32	-0.04	-16.99	-0.30	-1.13	0.00	0.00	-0.00	-1.86	0.00
KKW_MW07A	BB-North	-1.64	0.00	-1.13	-0.04	-15.11	-0.27	-1.22	0.00	0.00	0.00	-2.25	0.00
KKW_MW15	BB-North	-7.49	0.00	-0.21	-0.00	-4.65	-0.11	-1.80	0.00	0.00	-0.00	-3.82	0.00
KKW_MW23	BB-North	-1.50	0.00	-0.88	-0.03	-11.97	-0.21	-1.23	0.00	0.00	0.00	-2.67	0.00
KKW_MW26	BB-North	-1.51	0.00	-1.29	-0.04	-14.76	-0.24	-1.10	0.00	0.00	0.00	-1.90	0.00
KKW_MW30	BB-North	-2.17	0.00	-0.62	-0.02	-14.63	-0.26	-1.70	0.00	0.00	0.00	-4.69	0.00
KKW_MW35	BB-North	-3.40	0.00	-0.27	-0.01	-7.56	-0.19	-1.49	0.00	0.00	-0.00	-3.53	0.00
KKW_MW48	BB-North	-6.72	0.00	-0.47	-0.01	-10.90	-0.34	-0.89	0.00	-0.00	-0.00	-1.89	0.00
TNC_MW202	BB-South	-0.24	0.00	-0.44	-0.01	-5.98	-0.38	-0.92	-0.01	0.00	-0.13	-2.71	0.00
TNC_MW204	BB-South	-0.16	0.00	-0.05	-0.01	-5.66	-0.30	-0.65	-0.01	0.00	-0.10	-1.96	0.00
TNC_MW101	BB-South	-0.32	0.00	3.11	-0.01	-4.22	-0.45	-1.54	-0.00	0.00	-0.19	-3.29	0.00
TNC_MW105	BB-South	-0.31	0.00	0.17	-0.01	-4.75	-0.46	-1.23	-0.01	-0.00	-0.19	-2.62	0.00
TNC_MW106	BB-South	-0.18	0.00	-0.73	-0.01	-5.12	-0.35	-0.78	-0.01	-0.00	-0.14	-1.94	0.00
TNC_MW103	BB-South	-0.22	0.00	-1.91	-0.02	-4.55	-1.12	-1.54	-0.00	-0.00	-0.28	-2.64	0.00
TNC_MW107	BB-South	-0.21	0.00	-2.12	-0.02	-4.63	-0.48	-1.55	-0.00	0.00	-0.28	-2.68	0.00
TNC_MW109	BB-South	-0.27	0.00	0.59	-0.02	-4.44	-0.43	-1.73	-0.00	-0.00	-0.25	-3.02	0.00
TNC_MW110	BB-South	-0.31	0.00	0.26	-0.01	-5.31	-0.63	-1.09	-0.01	-0.00	-0.15	-2.97	0.00
TNC_MW304	BB-South	-0.44	0.00	1.46	-0.01	-5.32	-0.43	-1.21	-0.01	-0.00	-0.14	-3.56	0.00
TNC_MW308	BB-South	-0.19	0.00	-2.89	-0.02	-4.84	-0.46	-1.21	-0.00	-0.00	-0.26	-2.19	0.00
TNC_MW310	BB-South	-0.18	0.00	-3.20	-0.02	-4.86	-0.46	-1.17	-0.00	0.00	-0.27	-2.08	0.00
TNC_MW401	BB-South	-0.23	0.00	-0.92	-0.02	-4.70	-0.46	-1.50	-0.00	-0.00	-0.24	-2.74	0.00
TNC_MW410	BB-South	-0.23	0.00	-0.83	-0.02	-4.54	-0.46	-1.56	-0.00	-0.00	-0.25	-2.80	0.00
TNC_MW422	BB-South	-0.11	0.00	-0.01	-0.00	-13.28	-0.16	-0.63	-0.03	-0.00	-0.05	-9.37	0.00
TNC_MW430	BB-South	-0.04	0.00	-0.05	-0.00	-6.90	-0.10	-0.23	-0.01	-0.00	-0.02	-2.47	0.00
TNC_MW403	BB-South	-0.26	0.00	0.37	-0.02	-4.21	-0.43	-1.73	-0.00	0.00	-0.26	-2.93	0.00
TNC_MW404	BB-South	-0.21	0.00	-1.94	-0.03	-4.43	-0.54	-1.70	-0.00	-0.00	-0.32	-2.80	0.00
TNC_MW415	BB-South	-0.25	0.00	0.46	-0.02	-4.29	-0.44	-1.73	-0.00	-0.00	-0.25	-3.01	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Horizontal K parameters											
		HK_Alluv	HK_BurGrav	HK_Coarse	HK_Delta1	HK_Delta2	HK_Granite	HK_L1ROCK	HK_MMRock	HK_MrnSand	HK_PmUndif	HK_Presump	HK_Special
TNC_MW425	BB-South	-0.32	0.00	0.04	-0.01	-5.08	-0.43	-1.07	-0.01	0.00	-0.16	-2.70	0.00
TNC_MW433	BB-South	-0.23	0.00	-1.04	-0.01	-4.95	-0.44	-1.14	-0.00	0.00	-0.20	-2.37	0.00
TNC_MW440	BB-South	-0.21	0.00	-1.93	-0.02	-4.55	-0.47	-1.61	-0.00	-0.00	-0.29	-2.74	0.00
TNC_MW315	BB-South	-0.20	0.00	-2.82	-0.02	-4.75	-0.48	-1.43	-0.00	-0.00	-0.29	-2.50	0.00
ME_YW_870	Bedrock	-0.14	0.00	-0.00	0.00	0.13	0.00	-0.97	-0.77	-0.02	-0.30	-1.24	0.00
ME_YW_878	Bedrock	0.00	0.00	-0.00	0.00	-0.00	-0.04	-0.07	0.00	-1.26	-0.00	-0.38	0.00
ME_YW_882	Bedrock	-0.07	0.00	-0.06	-0.28	-3.22	-0.64	-0.45	0.00	0.00	-0.35	-0.09	0.00
ME_YW_883	Bedrock	-0.00	0.00	0.00	-0.01	-0.00	-0.01	-0.48	0.00	-0.85	-0.07	-0.03	0.00
ME_YW_888	Bedrock	-0.00	0.00	-0.00	-0.00	0.00	-1.65	-0.76	0.00	-0.00	-0.47	-0.00	-12.69
ME_YW_891	Bedrock	-0.00	-0.34	0.00	0.00	-0.00	0.00	-0.00	0.03	-0.32	0.00	-0.02	0.00
ME_YW_894	Bedrock	-0.58	0.03	0.00	0.00	0.00	0.00	-0.23	-0.49	-2.29	0.00	-0.00	0.00
ME_YW_896	Bedrock	-0.02	-0.00	0.00	0.00	0.00	0.02	-0.56	0.53	-0.34	0.00	-0.32	0.00
ME_YW_897	Bedrock	-0.00	-0.00	0.00	0.00	-0.01	-0.17	-3.11	-0.92	-0.97	0.00	-0.72	0.00
ME_YW_901	Bedrock	-0.01	0.00	-0.03	-0.00	-1.81	-0.12	-0.11	-0.01	-0.01	-0.00	-0.33	0.00
ME_YW_871	Coastal sands dug	-0.02	-1.07	0.00	0.00	-0.15	0.01	-0.04	-0.07	-11.37	-0.00	-4.39	0.00
ME_YW_872	Coastal sands dug	-0.02	-0.91	0.00	0.00	-0.16	0.01	-0.03	-0.06	-11.52	-0.00	-3.80	0.00
ME_YW_873	Coastal sands dug	-0.00	-0.61	0.00	0.00	-0.02	0.01	0.00	-0.04	-6.67	-0.00	-0.48	0.00
ME_YW_890	Coastal sands dug	-0.00	-0.36	0.00	0.00	-0.00	0.00	-0.00	0.00	-2.18	0.00	-0.02	0.00
ME_YW_892	Coastal sands dug	-0.01	-0.86	0.00	0.00	-0.00	0.00	-0.10	-0.02	-15.60	0.00	-0.03	0.00
ME_YW_893	Coastal sands dug	-3.45	0.05	0.00	0.00	0.00	0.00	-0.65	-0.32	-11.83	0.00	-0.00	0.00
ME_YW_906	Coastal sands dug	-0.01	-1.14	0.00	0.00	-0.00	0.00	-0.00	0.00	-3.12	0.00	-0.06	0.00
ME_YW_874	Delta sands dug	-4.64	0.00	0.00	0.00	-20.77	-0.01	-6.14	-0.93	-0.53	-1.72	-8.40	0.00
ME_YW_875	Delta sands dug	-0.15	0.00	-0.00	0.00	-0.41	-0.00	-0.97	-0.27	-0.19	-10.71	-1.96	0.00
ME_YW_876	Delta sands dug	-0.48	0.00	-1.18	-0.01	-19.90	-0.18	-0.37	0.00	-0.00	-0.00	-0.12	0.00
ME_YW_884	Delta sands dug	-0.60	0.00	-0.36	-0.38	-25.95	-0.69	-1.73	0.00	0.00	-0.43	-0.70	0.00
ME_YW_885	Delta sands dug	-0.12	0.00	-0.07	-1.13	-9.07	-0.02	-0.39	0.00	0.00	-0.06	-0.05	0.00
ME_YW_886	Delta sands dug	-0.01	0.00	-0.05	-6.85	-0.41	-0.12	-0.02	0.00	0.00	-4.70	-0.03	0.00
ME_YW_900	Delta sands dug	-0.01	0.00	-0.08	0.00	-10.54	-0.85	-1.43	-0.01	-0.04	-0.01	-1.51	0.00
ME_YW_902	Delta sands dug	-0.01	0.00	-0.71	-0.01	-2.38	0.02	-0.02	0.00	0.00	0.00	-0.00	0.00
ME_YW_903	Delta sands dug	-0.29	0.00	0.00	0.00	-2.26	0.00	-0.19	0.01	-4.37	-1.24	-0.15	0.00
ME_YW_905	Delta sands dug	-0.00	0.00	-0.40	-0.00	-0.98	-0.02	-0.02	0.00	0.00	0.00	-0.00	0.00
ME_YW_907	Delta sands dug	-0.53	0.00	-0.02	0.00	-7.26	0.40	-0.74	-0.16	-0.16	-0.00	-5.02	0.00
ME_YW_908	Delta sands dug	-0.05	0.00	-0.10	-0.00	-4.01	-0.01	-0.06	-0.05	-0.02	-0.01	-1.76	0.00
ME_YW_909	Delta sands dug	-0.10	0.00	-0.23	-0.01	-6.29	-0.16	-0.14	0.00	0.00	-0.00	-0.02	0.00
ME_YW_963	Delta sands dug	-0.07	-0.03	0.00	0.00	-1.32	0.00	0.02	0.05	-2.62	-0.00	-0.65	0.00
ME_YW_965	Delta sands dug	-0.02	0.00	-0.16	-0.02	-4.76	0.01	-0.09	0.00	0.00	-0.00	-0.01	0.00
ME_YW_966	Delta sands dug	-0.19	0.00	0.00	0.00	0.01	0.00	-0.14	0.05	-0.03	-0.00	-2.50	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Horizontal K parameters											
		HK_Alluv	HK_BurGrav	HK_Coarse	HK_Delta1	HK_Delta2	HK_Granite	HK_L1ROCK	HK_MMRock	HK_MrnSand	HK_PmUndif	HK_Presump	HK_Special
ME_YW_869	Till dug	-1.59	-0.00	0.00	0.00	-6.75	-0.04	-1.99	-0.61	-0.32	-0.29	-0.45	0.00
ME_YW_877	Till dug	0.00	0.00	0.00	-0.03	0.00	-0.07	-0.14	0.00	-0.00	-1.69	0.00	0.01
ME_YW_880	Till dug	-0.02	0.00	-0.00	-0.01	-0.01	0.15	-1.27	0.00	-0.01	-0.01	-0.13	0.00
ME_YW_881	Till dug	-0.00	0.00	-0.03	-0.14	-0.10	-0.25	-0.29	0.00	-0.00	-2.63	-0.02	0.00
ME_YW_899	Till dug	0.00	0.00	-0.00	0.00	-0.00	0.05	0.10	0.00	0.00	0.00	-0.06	0.00
ME_YW_904	Till dug	-0.07	-0.00	-0.00	0.00	-0.03	-0.05	-5.05	-1.64	-7.01	-0.00	-0.76	0.00
ME_YW_964	Till dug	-0.00	-0.00	0.00	0.00	-0.01	-0.60	-2.03	-0.00	-0.33	0.00	-2.27	0.00
Genest_33_81	Genest	-0.00	0.00	-0.03	0.05	-0.88	0.00	0.00	0.00	0.00	-0.00	-0.00	0.00
Genest_34D	Genest	-0.00	0.00	-0.03	-0.02	-0.88	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
Genest_34B	Genest	-0.00	0.00	-0.03	-0.06	-0.87	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
Genest_34A	Genest	-0.00	0.00	-0.03	-0.07	-0.86	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
Genest_34_81	Genest	-0.00	0.00	-0.03	-0.07	-0.86	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
Genest_34C	Genest	-0.00	0.00	-0.03	-0.08	-0.83	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
Genest_34E	Genest	-0.00	0.00	-0.03	-0.12	-0.78	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
Genest_59_81	Genest	-0.00	0.00	-0.02	-0.16	-0.81	0.00	-0.01	0.00	0.00	-0.00	-0.00	0.00
KKW_MWHR4	Herrisecket Rd.	-0.06	-0.48	0.00	0.00	-0.00	-0.00	0.15	-0.05	-2.64	0.00	-0.54	0.00
KKW_MWHR11	Herrisecket Rd.	-0.03	4.06	0.00	0.00	-0.00	-0.00	0.04	0.21	0.12	0.00	-0.41	0.00
KKW_MWHR1	Herrisecket Rd.	-0.06	-0.48	0.00	0.00	-0.00	-0.00	0.14	-0.04	-2.87	0.00	-0.54	0.00
KKW_MWHR3	Herrisecket Rd.	-0.06	-0.49	0.00	0.00	-0.00	-0.00	0.14	-0.04	-2.90	0.00	-0.54	0.00
KKW_MWHR6	Herrisecket Rd.	-0.06	-0.48	0.00	0.00	-0.00	-0.00	0.13	-0.05	-1.89	0.00	-0.57	0.00
KKW_MWHR7	Herrisecket Rd.	-0.02	-0.64	0.00	0.00	-0.00	-0.00	-0.36	-0.23	-16.85	0.00	-3.11	0.00
KKW_MWHR8	Herrisecket Rd.	-0.05	-0.57	0.00	0.00	-0.00	-0.00	0.05	-0.11	-8.07	0.00	-0.91	0.00
KKW_MWHR12	Herrisecket Rd.	-0.03	5.94	0.00	0.00	-0.00	0.00	0.04	0.04	0.19	0.00	-0.40	0.00
KKW_MWMR13	Merriland	-0.13	4.11	0.00	0.00	-0.00	0.00	0.05	0.04	-0.62	0.00	-0.03	0.00
KKW_MWMR18	Merriland	-0.12	15.73	0.00	0.00	-0.00	0.00	0.08	0.06	-0.53	0.00	-0.03	0.00
KKW_MWMR10	Merriland	-0.56	-7.92	0.00	0.00	0.00	0.00	0.11	0.33	-1.35	0.00	-0.17	0.00
KKW_MWMR9	Merriland	-0.15	5.23	0.00	0.00	-0.00	0.00	0.08	0.06	-0.67	0.00	-0.04	0.00
KKW_DPMR3	Merriland	-0.49	1.91	0.00	0.00	-0.00	0.00	0.04	0.02	-0.36	0.00	-0.04	0.00
KKW_MWMR6	Merriland	-0.11	17.03	0.00	0.00	-0.00	0.00	0.07	0.23	-0.52	0.00	-0.03	0.00
KKW_MWMR1	Merriland	-0.11	18.75	0.00	0.00	0.00	0.00	0.07	0.34	-0.51	0.00	-0.03	0.00
KKW_DPMR1	Merriland	-0.97	0.87	0.00	0.00	0.00	0.00	0.01	0.01	-0.07	0.00	-0.01	0.00
KKW_MWMR16	Merriland	-2.45	0.09	0.00	0.00	0.00	0.00	-0.04	-0.38	-5.88	0.00	-0.00	0.00
KKW_MWMR15	Merriland	-2.04	0.03	0.00	0.00	0.00	0.00	-0.81	-0.17	-5.14	0.00	-0.00	0.00
KKW_MWMR11	Merriland	-0.06	9.29	0.00	0.00	-0.00	0.00	0.09	0.06	-0.36	0.00	-0.03	0.00
KKW_MWMR8	Merriland	-0.10	6.95	0.00	0.00	-0.00	0.00	0.12	0.08	-0.55	0.00	-0.04	0.00
KKW_MWMR14	Merriland	-0.08	3.79	0.00	0.00	-0.00	0.00	0.03	0.03	-0.35	0.00	-0.02	0.00
KKW_MWMR5	Merriland	-0.12	10.78	0.00	0.00	-0.00	0.00	0.07	0.06	-0.55	0.00	-0.03	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Horizontal K parameters											
		HK_Alluv	HK_BurGrav	HK_Coarse	HK_Delta1	HK_Delta2	HK_Granite	HK_L1ROCK	HK_MMRock	HK_MrnSand	HK_PmUndif	HK_Presump	HK_Special
DEPCyro_X2	Sanford-Cyro	-0.00	0.00	-0.30	-0.45	-0.74	-0.03	-0.03	0.00	0.00	-0.00	-0.00	0.00
DEP_MW03_02	Sanford-Cyro	-0.00	0.00	-0.02	-0.02	-0.12	-0.00	-0.00	0.00	0.00	0.00	0.00	0.00
DEP_MW101A	Sanford-Cyro	-0.00	0.00	-0.09	-0.11	-2.16	-0.08	-0.10	0.00	0.00	0.00	-0.00	0.00
DEP_MW104A	Sanford-Cyro	-0.00	0.00	-0.07	-0.08	-0.80	-0.02	-0.02	0.00	0.00	0.00	-0.00	0.00
DEP_MW104BR	Sanford-Cyro	-0.00	0.00	-0.08	-0.09	-0.60	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
DEP_MW201A	Sanford-Cyro	-0.00	0.00	-0.13	-0.15	-1.40	-0.04	-0.06	0.00	0.00	0.00	-0.00	0.00
DEP_MW204A	Sanford-Cyro	-0.00	0.00	-0.04	-0.04	-0.20	-0.00	-0.00	0.00	0.00	0.00	-0.00	0.00
DEP_MW204B	Sanford-Cyro	-0.00	0.00	-0.04	-0.05	-0.22	-0.00	-0.00	0.00	0.00	0.00	-0.00	0.00
DEP_MW205B	Sanford-Cyro	-0.00	0.00	-0.08	-0.09	-0.47	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
DEP_MW209A	Sanford-Cyro	-0.00	0.00	-0.09	-0.07	-0.37	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
DEP_MW702B	Sanford-Cyro	0.00	0.00	-0.01	-0.01	-0.07	-0.00	-0.00	0.00	0.00	0.00	0.00	0.00
SWD_IDC_M1	Sanford	-0.00	0.00	-0.43	-0.08	-0.67	0.01	-0.03	0.00	0.00	0.00	-0.00	0.00
SWD_IDC_M4	Sanford	-0.00	0.00	-0.51	-0.30	-0.76	-0.04	-0.03	0.00	0.00	0.00	-0.00	0.00
SWD_Eagle_6	Sanford	-0.00	0.00	-0.30	0.16	-0.50	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
SWD_Eagle_6a	Sanford	-0.00	0.00	-0.31	0.15	-0.51	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
SWD_Eagle_7	Sanford	-0.00	0.00	-0.25	0.42	-0.43	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
SWD_Eagle_1	Sanford	-0.00	0.00	-0.21	0.37	-0.37	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
SWD_Eagle_2	Sanford	-0.00	0.00	-0.31	0.15	-0.51	-0.01	-0.01	0.00	0.00	0.00	-0.00	0.00
SWD_ND_1	Sanford	-0.00	0.00	-0.00	-0.23	-0.45	-0.02	-0.01	0.00	0.00	0.00	0.00	0.00
SWD_ND_4	Sanford	0.00	0.00	-0.00	-0.23	-0.46	-0.02	-0.01	0.00	0.00	0.00	0.00	0.00
SWD_ND_GP	Sanford	0.00	0.00	-0.00	-0.23	-0.45	-0.02	-0.01	0.00	0.00	0.00	0.00	0.00
Sanford_wet1	SW points	-0.00	0.00	-0.00	-0.94	-1.07	-0.09	-0.09	0.00	0.00	0.00	0.00	0.00
Saywards_Wet	SW points	-0.03	0.00	-0.02	-0.13	-0.45	-0.02	-0.04	0.00	0.00	-0.30	-0.02	0.00
Airport_S	SW points	-0.00	0.00	-0.02	-0.02	-0.39	0.00	-0.00	0.00	0.00	-0.00	0.00	0.00
Airport_SW	SW points	-0.00	0.00	-0.01	-0.01	-0.76	-0.01	-0.02	0.00	0.00	-0.00	-0.00	0.00
Merri_head	SW points	-0.00	0.00	-0.00	-0.10	0.44	-0.02	-0.00	0.00	0.00	-0.21	-0.00	-0.00
Till_up_wet	SW points	-0.02	0.00	-0.53	-0.02	-1.58	-0.60	-1.06	-0.00	-0.01	-0.37	-0.35	0.00
Merri_S_wet	SW points	0.00	0.00	0.00	-0.05	0.00	0.00	-0.01	0.00	-0.02	0.05	-0.00	0.00
Ocean_wet	SW points	-0.01	-0.00	0.00	0.00	0.00	0.00	0.02	-0.00	0.00	0.00	-0.00	0.00
RR_wet_N	SW points	-0.01	-0.60	0.00	0.00	0.00	0.00	-0.00	0.01	-1.11	0.00	-0.04	0.00
RR_wet_S	SW points	-0.04	-0.66	0.00	0.00	-0.00	0.00	-0.01	-0.02	-5.72	0.00	-0.03	0.00
Perkins_Msh	SW points	-0.01	0.00	0.05	-0.00	0.05	0.01	-0.00	0.00	0.00	-0.00	-0.00	0.00
Estes_Lake_1	SW points	0.00	0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estes_Lake_2	SW points	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estes_Lake_3	SW points	0.00	0.00	-0.00	0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00	0.00
OldFallsPond	SW points	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Horizontal K parameters											
		HK_Alluv	HK_BurGrav	HK_Coarse	HK_Delta1	HK_Delta2	HK_Granite	HK_L1ROCK	HK_MMRock	HK_MrnSand	HK_PmUndif	HK_Presump	HK_Special
Merri2_Str_1	Baseflows	0.01	0.00	0.04	0.03	0.07	0.00	0.05	0.01	0.06	-0.04	0.03	0.00
Merri1_Str_1	Baseflows	-0.00	0.13	0.00	0.00	0.00	-0.00	-0.00	-0.01	-0.05	0.00	0.03	0.00
Perkins_st_1	Baseflows	0.05	0.00	0.39	0.11	-0.28	0.02	0.03	-0.00	0.00	0.00	0.03	0.00
Cold_seeps_1	Baseflows	0.42	0.00	0.23	0.00	0.36	0.15	0.08	0.01	0.00	0.03	0.32	0.00
BB7_Str_1	Baseflows	0.01	0.00	0.59	0.15	0.56	0.04	0.03	0.00	0.00	0.00	0.00	0.00
BB6_Str_1	Baseflows	0.01	0.00	0.09	0.33	0.98	-0.00	0.04	0.00	0.00	0.01	0.00	0.00
BB5_Seeps_1	Baseflows	0.03	0.00	0.11	0.03	0.36	0.02	0.19	0.00	0.00	-0.00	0.20	0.00
BB4_Seeps_1	Baseflows	0.01	0.00	0.01	0.00	-0.00	-0.00	0.01	0.00	0.00	0.00	0.20	0.00
BB4_Str_1	Baseflows	0.03	0.00	0.50	0.00	0.65	0.10	0.19	0.00	0.00	0.05	0.53	0.00
BB3_Seeps_1	Baseflows	-0.42	0.00	-0.22	0.00	-0.80	0.00	0.24	-0.00	0.06	0.04	0.60	0.00
BB2_Seeps_1	Baseflows	0.39	0.00	0.00	0.00	-0.46	0.00	0.28	0.02	-0.05	0.07	0.23	0.00
BB2_Str_1	Baseflows	0.03	0.00	0.08	0.00	0.34	0.05	0.21	0.04	-0.01	0.01	0.28	0.00
BB1_Seeps_1	Baseflows	0.01	0.52	0.00	0.00	0.00	0.00	-0.11	-0.01	0.45	0.00	0.72	0.00
BB8_Str_1	Baseflows	0.01	0.06	0.00	0.00	0.00	-0.00	0.04	0.03	0.59	0.00	0.04	0.00
Day_Seeps_1	Baseflows	0.12	0.00	0.00	0.00	1.21	0.01	0.12	0.05	0.13	0.06	0.07	0.00
Day_Str_1	Baseflows	0.17	0.00	0.00	0.00	0.70	0.00	0.10	0.03	0.75	-0.15	0.34	0.00
Merri2_Riv_1	Baseflows	0.01	-0.00	0.00	0.00	0.00	-0.18	-0.53	-0.06	0.10	0.00	-0.18	0.00
Merri1_Riv_1	Baseflows	-0.10	-0.40	0.00	0.00	0.00	-0.00	0.00	0.00	0.01	0.00	-0.02	0.00
BB5_Riv_1	Baseflows	-0.01	0.00	-1.13	0.04	-1.68	-0.06	-0.38	0.00	0.00	0.00	-0.37	0.00
BB3_Riv_1	Baseflows	0.21	0.00	-1.20	0.00	-0.41	-0.26	-1.50	-0.05	0.02	0.01	-4.59	0.00
BB2_Riv_1	Baseflows	-0.18	0.00	0.00	0.00	-0.06	0.00	-0.13	-0.02	-0.71	0.00	-0.08	0.00
BB1_Riv_1	Baseflows	0.01	1.22	0.00	0.00	0.01	-0.00	-0.06	-0.04	-0.33	0.00	-0.84	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	HK_Till	HK_wetland	HK_ShearZn	HK_ClayEXP	Recharge parameters							
						Moraines	Sandy_1	Till	Wetlands	Bedrock	Alluv_Urb	Sandy_2	RCH_Xtra
Nestle_MW01	BB-North	-0.00	-0.02	-0.00	-0.48	0.00	25.94	0.02	0.08	0.02	0.03	0.84	0.82
Nestle_MW06	BB-North	-0.01	-0.03	-0.00	-0.55	0.00	26.89	0.02	0.13	0.03	0.03	1.40	0.85
Nestle_MW13	BB-North	-0.01	-0.03	-0.00	-0.88	0.00	24.47	0.04	0.09	0.02	0.03	1.00	0.75
Nestle_MW14	BB-North	-0.00	-0.03	-0.00	-0.92	0.00	29.50	0.02	0.04	0.01	0.06	0.59	0.98
Nestle_MW16	BB-North	-0.00	-0.03	0.00	-0.46	0.00	26.88	0.01	0.02	0.01	0.12	0.30	0.49
Nestle_MW24	BB-North	-0.01	-0.02	-0.00	-0.59	0.00	18.92	0.03	0.06	0.02	0.03	0.67	0.47
Nestle_MW33	BB-North	-0.00	-0.02	0.00	-0.77	0.00	30.20	0.02	0.04	0.01	0.06	0.57	1.02
Nestle_MW41	BB-North	-0.00	-0.02	-0.00	-1.20	0.00	26.48	0.03	0.03	0.01	0.07	0.47	0.76
Nestle_MW44	BB-North	-0.00	-0.03	-0.00	-0.44	0.00	28.54	0.01	0.03	0.01	0.07	0.51	0.88
Nestle_MW45	BB-North	-0.00	-0.03	0.00	-0.56	0.00	28.74	0.01	0.02	0.01	0.09	0.39	0.78
Nestle_MW46	BB-North	-0.00	-0.03	-0.00	-0.56	0.00	34.58	0.01	0.06	0.02	0.04	0.79	1.49
Nestle_MW47	BB-North	-0.00	-0.04	0.00	-0.39	0.00	28.37	0.01	0.07	0.02	0.03	0.97	1.05
KKW_MW02	BB-North	-0.01	-0.03	-0.00	-0.54	0.00	35.16	0.03	0.13	0.03	0.04	1.33	1.31
KKW_MW07A	BB-North	-0.01	-0.03	-0.00	-0.63	0.00	32.44	0.03	0.10	0.03	0.04	1.09	1.09
KKW_MW15	BB-North	-0.00	-0.03	0.00	-0.49	0.00	32.98	0.01	0.02	0.01	0.15	0.34	0.62
KKW_MW23	BB-North	-0.00	-0.02	-0.00	-0.71	0.00	29.62	0.02	0.08	0.02	0.04	0.85	0.91
KKW_MW26	BB-North	-0.01	-0.03	-0.00	-0.54	0.00	32.58	0.03	0.11	0.03	0.04	1.18	1.08
KKW_MW30	BB-North	-0.00	-0.02	-0.00	-1.10	0.00	39.00	0.02	0.06	0.02	0.05	0.75	1.19
KKW_MW35	BB-North	-0.00	-0.02	-0.00	-0.62	0.00	32.25	0.01	0.03	0.01	0.07	0.44	0.99
KKW_MW48	BB-North	-0.00	-0.04	-0.00	-0.46	0.00	35.89	0.01	0.05	0.01	0.05	0.83	1.10
TNC_MW202	BB-South	-0.09	-0.17	0.00	-0.23	0.04	18.28	0.52	0.16	0.09	0.05	3.67	0.98
TNC_MW204	BB-South	-0.07	-0.15	0.00	-0.17	0.03	14.13	0.41	0.12	0.07	0.04	3.34	0.72
TNC_MW101	BB-South	-0.12	-0.19	-0.00	-0.20	0.04	19.31	0.79	0.22	0.14	0.08	3.91	0.83
TNC_MW105	BB-South	-0.12	-0.21	-0.00	-0.18	0.05	19.52	0.78	0.22	0.14	0.07	4.25	0.94
TNC_MW106	BB-South	-0.10	-0.20	-0.00	-0.16	0.04	14.87	0.56	0.17	0.09	0.04	4.08	0.74
TNC_MW103	BB-South	-0.17	-0.25	-0.00	-0.22	0.06	19.23	1.18	0.32	0.21	0.05	5.08	0.73
TNC_MW107	BB-South	-0.17	-0.25	-0.00	-0.17	0.06	20.46	1.21	0.32	0.22	0.05	5.10	0.82
TNC_MW109	BB-South	-0.15	-0.22	-0.00	-0.17	0.05	20.82	1.07	0.28	0.20	0.06	4.52	0.86
TNC_MW110	BB-South	-0.10	-0.18	-0.00	-0.26	0.04	19.11	0.59	0.17	0.10	0.07	3.75	0.96
TNC_MW304	BB-South	-0.09	-0.17	-0.00	-0.28	0.04	21.67	0.57	0.17	0.10	0.08	3.52	1.12
TNC_MW308	BB-South	-0.16	-0.27	-0.00	-0.15	0.06	18.31	1.07	0.30	0.18	0.05	5.21	0.80
TNC_MW310	BB-South	-0.16	-0.28	-0.00	-0.15	0.07	17.87	1.10	0.31	0.19	0.04	5.35	0.76
TNC_MW401	BB-South	-0.15	-0.24	-0.00	-0.17	0.06	20.79	1.03	0.28	0.18	0.06	4.72	0.96
TNC_MW410	BB-South	-0.15	-0.23	-0.00	-0.17	0.05	20.21	1.06	0.29	0.19	0.06	4.72	0.87
TNC_MW422	BB-South	-0.04	-0.07	0.00	-0.83	0.01	32.69	0.20	0.06	0.03	0.03	1.78	1.76
TNC_MW430	BB-South	-0.02	-0.04	0.00	-0.22	0.01	13.73	0.10	0.03	0.02	0.01	1.60	0.60
TNC_MW403	BB-South	-0.16	-0.22	-0.00	-0.17	0.05	20.42	1.14	0.30	0.21	0.05	4.59	0.73
TNC_MW404	BB-South	-0.18	-0.24	-0.00	-0.19	0.06	20.67	1.36	0.35	0.25	0.05	5.23	0.67
TNC_MW415	BB-South	-0.15	-0.22	-0.00	-0.17	0.05	20.20	1.08	0.29	0.20	0.06	4.55	0.81

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group					Recharge parameters							
		HK_Till	HK_wetland	HK_ShearZn	HK_ClayEXP	Moraines	Sandy_1	Till	Wetlands	Bedrock	Alluv_Urb	Sandy_2	RCH_Xtra
TNC_MW425	BB-South	-0.10	-0.19	-0.00	-0.21	0.04	19.24	0.64	0.19	0.11	0.06	3.94	0.95
TNC_MW433	BB-South	-0.13	-0.23	-0.00	-0.17	0.05	18.97	0.81	0.23	0.14	0.06	4.51	0.95
TNC_MW440	BB-South	-0.17	-0.24	-0.00	-0.17	0.06	21.22	1.26	0.33	0.23	0.05	5.12	0.81
TNC_MW315	BB-South	-0.17	-0.26	-0.00	-0.17	0.06	19.99	1.21	0.33	0.22	0.05	5.25	0.82
ME_YW_870	Bedrock	-0.00	-0.00	0.00	-0.01	0.00	1.50	0.41	0.00	0.00	0.50	1.61	0.05
ME_YW_878	Bedrock	-0.06	-0.37	0.00	-0.00	0.21	0.00	0.40	0.10	0.34	0.00	1.89	0.00
ME_YW_882	Bedrock	-0.76	-0.23	-0.12	-0.36	0.00	5.16	1.62	0.09	0.34	0.00	0.32	0.00
ME_YW_883	Bedrock	-0.71	-0.29	0.00	0.00	0.00	0.00	0.97	0.28	0.43	0.00	2.01	0.00
ME_YW_888	Bedrock	-0.84	-0.07	0.02	-0.02	0.00	0.08	1.72	0.14	15.58	0.00	0.04	0.00
ME_YW_891	Bedrock	-0.00	-0.00	0.00	0.03	0.00	0.47	0.01	0.02	0.00	0.00	0.40	0.00
ME_YW_894	Bedrock	-0.00	-0.01	0.00	-0.95	0.00	4.12	0.00	0.03	0.00	0.01	0.01	0.00
ME_YW_896	Bedrock	-0.56	0.00	0.00	-0.01	0.00	0.31	1.55	0.00	0.10	0.00	0.11	0.00
ME_YW_897	Bedrock	-2.80	-0.01	0.00	-0.03	0.01	0.52	6.33	0.02	0.13	0.33	1.91	0.00
ME_YW_901	Bedrock	-0.57	-0.09	0.00	-0.06	0.06	3.38	0.36	0.02	0.06	0.02	0.81	0.00
ME_YW_871	Coastal sands dug	-0.01	-0.00	0.00	-1.32	0.00	7.65	3.51	0.59	0.12	0.72	11.31	0.00
ME_YW_872	Coastal sands dug	-0.00	-0.00	0.00	-1.23	0.00	7.67	2.98	0.50	0.13	0.58	11.24	0.00
ME_YW_873	Coastal sands dug	-0.00	-0.00	0.00	-0.41	0.00	0.76	0.59	0.27	0.10	0.10	9.31	0.00
ME_YW_890	Coastal sands dug	-0.00	-0.02	0.00	-0.03	0.00	5.57	0.02	0.03	0.00	0.00	0.43	0.00
ME_YW_892	Coastal sands dug	-0.00	-0.11	0.00	-0.14	0.00	22.80	0.20	0.07	0.00	0.01	2.11	0.00
ME_YW_893	Coastal sands dug	-0.00	-0.03	0.00	-4.51	0.00	24.84	0.00	0.14	0.00	0.05	0.04	0.00
ME_YW_906	Coastal sands dug	-0.00	-0.01	0.00	-0.08	0.00	0.28	0.10	0.13	0.01	0.01	7.09	0.00
ME_YW_874	Delta sands dug	-0.54	-0.13	0.00	-1.40	0.00	45.89	1.08	0.58	0.13	1.31	2.44	0.00
ME_YW_875	Delta sands dug	-0.01	-0.00	0.00	-0.07	0.00	6.99	0.39	0.03	0.00	0.68	12.84	0.20
ME_YW_876	Delta sands dug	-0.01	-1.47	0.00	-0.31	0.00	22.59	0.00	0.09	0.02	0.01	10.39	0.03
ME_YW_884	Delta sands dug	-1.02	-0.67	-0.20	-0.50	0.00	36.66	2.27	0.16	0.26	0.02	1.30	0.02
ME_YW_885	Delta sands dug	-0.06	-0.28	-0.22	0.32	0.00	13.81	0.14	0.10	0.02	0.00	1.35	0.00
ME_YW_886	Delta sands dug	0.09	-0.42	0.05	-0.06	0.00	12.55	2.01	0.52	0.70	0.00	0.24	0.00
ME_YW_900	Delta sands dug	-5.99	-0.32	0.00	-0.33	0.37	23.43	2.80	0.10	0.57	0.10	1.52	0.01
ME_YW_902	Delta sands dug	-0.00	-0.54	0.00	-0.09	0.00	0.42	0.02	0.03	0.00	0.00	5.11	0.00
ME_YW_903	Delta sands dug	-0.01	-0.00	0.00	-0.06	0.00	13.03	0.02	0.01	0.00	0.03	0.99	0.02
ME_YW_905	Delta sands dug	-0.00	-0.02	0.00	-0.08	0.00	0.21	0.02	0.03	0.00	0.00	1.88	0.00
ME_YW_907	Delta sands dug	-0.35	-0.03	0.00	0.01	0.02	2.19	0.71	0.01	0.07	0.16	19.45	0.01
ME_YW_908	Delta sands dug	-0.24	-0.10	0.00	-0.10	0.03	3.06	0.24	0.02	0.03	0.07	11.00	0.03
ME_YW_909	Delta sands dug	-0.00	-0.21	0.00	-0.10	0.00	3.92	0.00	0.04	0.01	0.00	5.82	0.01
ME_YW_963	Delta sands dug	-0.01	-0.00	0.00	-0.30	0.00	6.39	0.25	0.02	0.11	0.03	0.41	0.00
ME_YW_965	Delta sands dug	0.07	-0.01	-0.02	0.63	0.00	6.33	0.06	0.06	0.00	0.00	0.29	0.00
ME_YW_966	Delta sands dug	-0.01	0.00	0.00	0.00	0.00	0.20	0.02	0.00	0.00	0.00	3.23	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	HK_Till	HK_wetland	HK_ShearZn	HK_ClayEXP	Recharge parameters							
						Moraines	Sandy_1	Till	Wetlands	Bedrock	Alluv_Urb	Sandy_2	RCH_Xtra
ME_YW_869	Till dug	-1.60	-0.05	0.00	-0.16	0.00	10.53	3.46	0.12	0.47	0.12	0.52	0.00
ME_YW_877	Till dug	-0.10	-0.14	0.00	-0.00	0.00	0.01	1.99	0.02	0.44	0.00	0.12	0.00
ME_YW_880	Till dug	-0.70	-0.01	0.00	-0.00	0.02	0.02	1.40	0.05	1.56	0.00	0.08	0.00
ME_YW_881	Till dug	-0.54	-0.11	0.00	-0.00	0.01	0.77	3.31	0.38	0.39	0.00	0.10	0.00
ME_YW_899	Till dug	-0.30	-0.00	0.00	0.00	0.03	0.01	0.21	0.00	0.01	0.00	0.00	0.00
ME_YW_904	Till dug	-9.86	-0.00	0.00	-0.14	0.01	10.78	8.20	0.05	1.03	0.14	7.37	0.00
ME_YW_964	Till dug	-3.38	-0.01	0.00	-0.01	0.02	0.22	8.84	0.02	0.11	1.02	0.59	0.00
Genest_33_81	Genest	0.01	-0.01	-0.03	0.54	0.00	1.49	0.02	0.06	0.00	0.01	0.25	0.00
Genest_34D	Genest	0.00	-0.01	-0.05	0.31	0.00	1.50	0.01	0.07	0.00	0.01	0.33	0.00
Genest_34B	Genest	0.00	-0.01	-0.05	0.28	0.00	1.50	0.01	0.08	0.00	0.01	0.37	0.00
Genest_34A	Genest	0.00	-0.01	-0.05	0.26	0.00	1.49	0.01	0.08	0.00	0.01	0.37	0.00
Genest_34_81	Genest	0.00	-0.01	-0.05	0.27	0.00	1.49	0.01	0.08	0.00	0.01	0.37	0.00
Genest_34C	Genest	0.00	-0.01	-0.05	0.24	0.00	1.48	0.01	0.08	0.00	0.01	0.36	0.00
Genest_34E	Genest	0.00	-0.01	-0.05	0.22	0.00	1.45	0.01	0.08	0.00	0.01	0.36	0.00
Genest_59_81	Genest	0.00	-0.02	-0.06	0.07	0.00	1.46	0.01	0.10	0.00	0.01	0.44	0.00
KKW_MWHR4	Herrisecket Rd.	-0.44	-0.00	0.00	-4.35	0.00	20.15	0.36	0.05	0.03	0.04	4.82	0.00
KKW_MWHR11	Herrisecket Rd.	-0.13	-0.00	0.00	6.68	0.00	8.37	0.19	0.10	0.01	0.06	3.84	0.00
KKW_MWHR1	Herrisecket Rd.	-0.39	-0.00	0.00	-0.39	0.00	18.68	0.35	0.06	0.02	0.05	4.79	0.00
KKW_MWHR3	Herrisecket Rd.	-0.40	-0.00	0.00	-0.32	0.00	18.71	0.35	0.06	0.02	0.05	4.82	0.00
KKW_MWHR6	Herrisecket Rd.	-0.47	-0.00	0.00	-4.87	0.00	23.58	0.38	0.05	0.03	0.05	5.10	0.00
KKW_MWHR7	Herrisecket Rd.	-0.54	0.00	0.00	-4.20	0.00	15.07	1.46	0.06	0.06	0.17	18.43	0.00
KKW_MWHR8	Herrisecket Rd.	-0.84	0.00	0.00	-8.29	0.00	31.74	0.68	0.06	0.05	0.06	8.26	0.00
KKW_MWHR12	Herrisecket Rd.	-0.12	-0.00	0.00	6.59	0.00	7.90	0.18	0.10	0.01	0.06	3.79	0.00
KKW_MWMR13	Merriland	0.00	-0.01	0.00	0.36	0.00	3.16	0.03	0.01	0.00	0.02	0.41	0.00
KKW_MWMR18	Merriland	0.01	-0.00	0.00	0.52	0.00	3.72	0.04	0.01	0.00	0.02	0.46	0.00
KKW_MWMR10	Merriland	-0.04	-0.00	0.00	2.00	0.00	10.35	0.08	0.01	0.00	0.02	0.58	0.00
KKW_MWMR9	Merriland	0.00	-0.00	0.00	0.60	0.00	4.56	0.04	0.02	0.00	0.02	0.54	0.00
KKW_DPMR3	Merriland	0.03	-0.00	0.00	0.13	0.00	10.56	0.03	0.00	0.00	0.07	0.29	0.00
KKW_MWMR6	Merriland	0.01	-0.00	0.00	0.52	0.00	3.71	0.05	0.01	0.00	0.02	0.46	0.00
KKW_MWMR1	Merriland	0.01	-0.00	0.00	0.51	0.00	3.66	0.05	0.01	0.00	0.02	0.46	0.00
KKW_DPMR1	Merriland	0.00	-0.00	0.00	0.02	0.00	5.25	0.01	0.00	0.00	0.36	0.09	0.00
KKW_MWMR16	Merriland	-0.00	-0.01	0.00	-6.09	0.00	13.65	0.00	0.07	0.00	0.05	0.04	0.00
KKW_MWMR15	Merriland	-0.00	-0.02	0.00	-2.29	0.00	11.44	0.00	0.08	0.00	0.03	0.02	0.00
KKW_MWMR11	Merriland	0.03	-0.00	0.00	0.42	0.00	3.03	0.08	0.01	0.00	0.02	0.49	0.00
KKW_MWMR8	Merriland	0.00	-0.00	0.00	0.67	0.00	4.46	0.05	0.01	0.00	0.03	0.50	0.00
KKW_MWMR14	Merriland	0.00	-0.00	0.00	0.27	0.00	2.02	0.02	0.01	0.00	0.02	0.25	0.00
KKW_MWMR5	Merriland	0.00	-0.00	0.00	0.50	0.00	3.74	0.04	0.01	0.00	0.02	0.46	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group					Recharge parameters							
		HK_Till	HK_wetland	HK_ShearZn	HK_ClayEXP	Moraines	Sandy_1	Till	Wetlands	Bedrock	Alluv_Urb	Sandy_2	RCH_Xtra
DEPCyro_X2	Sanford-Cyro	-0.01	-0.06	-0.00	-1.83	0.00	3.40	0.06	0.06	0.01	0.13	1.76	0.00
DEP_MW03_02	Sanford-Cyro	-0.00	-0.00	0.00	-0.30	0.00	0.57	0.02	0.01	0.01	0.01	0.24	0.00
DEP_MW101A	Sanford-Cyro	-0.01	-0.02	0.00	-1.24	0.00	2.73	0.22	0.02	0.09	0.12	2.30	0.00
DEP_MW104A	Sanford-Cyro	-0.00	-0.01	0.00	-1.00	0.00	2.15	0.07	0.02	0.03	0.07	1.03	0.00
DEP_MW104BR	Sanford-Cyro	-0.00	-0.01	-0.00	-1.07	0.00	1.37	0.07	0.02	0.02	0.06	0.92	0.00
DEP_MW201A	Sanford-Cyro	-0.01	-0.02	0.00	-1.55	0.00	2.62	0.12	0.03	0.05	0.14	2.36	0.00
DEP_MW204A	Sanford-Cyro	-0.00	-0.01	-0.00	-0.56	0.00	1.04	0.02	0.01	0.01	0.03	0.39	0.00
DEP_MW204B	Sanford-Cyro	-0.00	-0.01	-0.00	-0.58	0.00	0.81	0.02	0.01	0.01	0.03	0.44	0.00
DEP_MW205B	Sanford-Cyro	-0.00	-0.02	-0.00	-1.00	0.00	1.36	0.04	0.02	0.02	0.06	0.80	0.00
DEP_MW209A	Sanford-Cyro	-0.00	-0.02	-0.00	-1.06	0.00	1.94	0.03	0.02	0.01	0.05	0.68	0.00
DEP_MW702B	Sanford-Cyro	-0.00	-0.00	0.00	-0.19	0.00	0.36	0.02	0.01	0.01	0.01	0.16	0.00
SWD_IDC_M1	Sanford	-0.02	-0.10	-0.00	-0.32	0.00	3.17	0.07	0.08	0.01	0.07	1.64	0.00
SWD_IDC_M4	Sanford	-0.02	-0.09	-0.00	-1.37	0.00	3.48	0.07	0.08	0.01	0.09	1.95	0.00
SWD_Eagle_6	Sanford	-0.01	-0.09	-0.00	4.03	0.00	2.54	0.08	0.07	0.00	0.05	1.19	0.00
SWD_Eagle_6a	Sanford	-0.01	-0.09	-0.00	6.61	0.00	2.62	0.08	0.07	0.00	0.06	1.24	0.00
SWD_Eagle_7	Sanford	-0.01	-0.10	-0.00	0.18	0.00	2.38	0.07	0.07	0.00	0.05	1.03	0.00
SWD_Eagle_1	Sanford	-0.01	-0.10	0.00	0.01	0.00	2.05	0.07	0.07	0.00	0.04	0.87	0.00
SWD_Eagle_2	Sanford	-0.01	-0.09	0.00	6.84	0.00	2.62	0.08	0.07	0.00	0.06	1.24	0.00
SWD_ND_1	Sanford	-0.00	-0.06	0.00	-3.48	0.00	2.35	0.00	0.10	0.00	0.00	2.14	0.00
SWD_ND_4	Sanford	-0.00	-0.06	0.00	-3.45	0.00	2.37	0.00	0.10	0.00	0.00	2.13	0.00
SWD_ND_GP	Sanford	-0.00	-0.06	0.00	-3.48	0.00	2.35	0.00	0.10	0.00	0.00	2.15	0.00
Sanford_wet1	SW points	-0.05	-1.51	0.00	-2.82	0.00	1.29	0.02	0.35	0.02	0.00	5.54	0.00
Saywards_Wet	SW points	0.02	-0.89	0.05	0.06	0.00	4.02	0.19	0.29	0.03	0.00	0.24	0.00
Airport_S	SW points	-0.01	-0.00	-0.00	-0.10	0.00	0.15	0.02	0.21	0.01	0.11	0.71	0.00
Airport_SW	SW points	-0.01	-0.00	-0.00	-1.29	0.00	0.05	0.03	0.02	0.04	0.12	2.53	0.00
Merri_head	SW points	-0.01	-1.79	0.27	0.09	0.00	0.31	0.11	0.95	0.04	0.00	1.22	0.00
Till_up_wet	SW points	-1.71	-2.28	-0.00	-0.03	1.88	2.70	4.34	1.07	0.61	0.00	1.64	0.04
Merri_S_wet	SW points	-0.02	0.10	0.00	0.00	0.00	0.00	0.06	0.10	0.04	0.00	0.49	0.00
Ocean_wet	SW points	0.04	-0.83	0.00	-0.00	0.00	0.31	0.00	0.40	0.03	0.00	0.57	0.00
RR_wet_N	SW points	-0.00	-0.00	0.00	0.05	0.00	0.46	0.02	0.39	0.00	0.01	3.33	0.00
RR_wet_S	SW points	-0.00	-0.20	0.00	-0.02	0.00	0.90	0.02	0.66	0.10	0.01	9.41	0.00
Perkins_Msh	SW points	-0.00	0.15	0.00	0.01	0.00	0.27	0.00	0.06	0.00	0.00	0.24	0.00
Estes_Lake_1	SW points	0.00	0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estes_Lake_2	SW points	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estes_Lake_3	SW points	0.00	-0.00	0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
OldFallsPond	SW points	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group					Recharge parameters							
		HK_Till	HK_wetland	HK_ShearZn	HK_ClayEXP	Moraines	Sandy_1	Till	Wetlands	Bedrock	Alluv_Urb	Sandy_2	RCH_Xtra
Merri2_Str_1	Baseflows	-0.02	-0.35	-0.04	0.10	-0.23	-2.68	-1.64	-0.54	-0.36	-0.12	-2.87	-0.00
Merri1_Str_1	Baseflows	0.01	0.00	0.00	0.10	0.00	-1.61	-0.12	-0.00	-0.00	-0.00	-0.28	0.00
Perkins_st_1	Baseflows	0.01	-0.13	0.00	0.31	0.00	-5.31	-0.12	-0.27	-0.03	-0.01	-9.23	-0.01
Cold_seeps_1	Baseflows	0.02	0.08	0.00	0.05	0.00	-13.77	-0.00	-0.05	-0.02	-0.04	-1.38	-0.23
BB7_Str_1	Baseflows	0.01	0.04	0.02	0.59	0.00	-3.44	-0.05	-0.34	-0.01	-0.31	-3.27	-0.00
BB6_Str_1	Baseflows	-0.01	0.05	0.16	-0.55	0.00	-5.24	-0.06	-0.68	-0.01	-0.08	-1.79	-0.00
BB5_Seeps_1	Baseflows	0.01	0.01	0.00	0.06	-0.00	-3.47	-0.07	-0.04	-0.01	-0.02	-0.50	-0.03
BB4_Seeps_1	Baseflows	0.01	0.01	0.00	0.02	-0.00	-1.43	-0.02	-0.00	-0.00	-0.03	-0.93	-0.02
BB4_Str_1	Baseflows	0.04	0.08	0.00	0.05	-0.02	-4.47	-0.21	-0.07	-0.03	-0.02	-2.02	-0.16
BB3_Seeps_1	Baseflows	0.01	0.03	0.00	0.07	-0.00	-9.89	-0.05	-0.03	-0.01	-0.09	-0.68	-0.18
BB2_Seeps_1	Baseflows	-0.03	0.00	0.00	0.08	-0.00	-4.62	-0.17	-0.00	-0.02	-0.02	-0.52	-0.01
BB2_Str_1	Baseflows	0.11	0.12	0.00	0.03	-0.04	-3.41	-0.63	-0.04	-0.08	-0.09	-3.24	-0.01
BB1_Seeps_1	Baseflows	-0.02	0.00	0.00	0.14	-0.00	-3.70	-1.36	-0.05	-0.03	-0.07	-3.57	0.00
BB8_Str_1	Baseflows	-0.07	-0.01	0.00	0.43	-0.00	-3.01	-0.15	-0.00	-0.05	-0.00	-0.39	0.00
Day_Seeps_1	Baseflows	-0.26	0.00	0.00	0.13	0.00	-2.26	-0.43	-0.03	-0.08	-0.02	-0.09	-0.00
Day_Str_1	Baseflows	0.01	0.00	0.00	0.14	0.00	-7.18	-0.08	-0.03	-0.02	-0.07	-1.70	-0.18
Merri2_Riv_1	Baseflows	-0.17	0.00	0.00	-0.01	-0.00	-0.09	-2.23	-0.00	-0.30	-0.01	-0.11	0.00
Merri1_Riv_1	Baseflows	-0.01	0.00	0.00	-0.02	0.00	-1.84	-0.13	-0.01	-0.00	-0.09	-0.61	0.00
BB5_Riv_1	Baseflows	0.01	0.02	0.01	-0.13	-0.00	-3.07	-0.04	-0.02	-0.01	-0.05	-0.16	-0.01
BB3_Riv_1	Baseflows	0.01	0.01	0.00	-0.43	-0.00	-5.78	-0.03	-0.09	-0.00	-0.22	-0.37	-0.06
BB2_Riv_1	Baseflows	-0.00	0.00	0.00	-0.10	0.00	-0.96	-0.03	-0.00	-0.00	-0.04	-0.16	-0.00
BB1_Riv_1	Baseflows	0.03	0.00	0.00	-0.48	0.00	-2.49	-0.37	-0.11	-0.01	-0.26	-2.93	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Stream and river conductance parameters				
		KDR_ Seeps	KDR_ Stream	KRIV_BB	KRIV_ Merri	KRIV_ Mous
Nestle_MW01	BB-North	-7.72	-0.09	-0.69	0.00	-0.00
Nestle_MW06	BB-North	-8.08	-0.14	-0.54	0.00	-0.00
Nestle_MW13	BB-North	-7.76	-0.11	-0.71	0.00	-0.00
Nestle_MW14	BB-North	-10.14	-0.07	-0.26	0.00	-0.00
Nestle_MW16	BB-North	-9.99	-0.05	-0.13	0.00	0.00
Nestle_MW24	BB-North	-7.28	-0.08	-0.95	0.00	-0.00
Nestle_MW33	BB-North	-10.25	-0.06	-0.25	0.00	0.00
Nestle_MW41	BB-North	-10.69	-0.05	-0.24	0.00	0.00
Nestle_MW44	BB-North	-10.26	-0.06	-0.16	0.00	-0.00
Nestle_MW45	BB-North	-10.27	-0.05	-0.15	0.00	0.00
Nestle_MW46	BB-North	-9.56	-0.08	-0.31	0.00	-0.00
Nestle_MW47	BB-North	-9.61	-0.09	-0.25	0.00	0.00
KKW_MW02	BB-North	-9.49	-0.14	-0.79	0.00	-0.00
KKW_MW07A	BB-North	-9.52	-0.12	-0.80	0.00	-0.00
KKW_MW15	BB-North	-12.15	-0.05	-0.14	0.00	0.00
KKW_MW23	BB-North	-9.57	-0.09	-0.74	0.00	-0.00
KKW_MW26	BB-North	-9.22	-0.13	-0.89	0.00	-0.00
KKW_MW30	BB-North	-10.97	-0.08	-0.49	0.00	0.00
KKW_MW35	BB-North	-13.60	-0.05	-0.19	0.00	-0.00
KKW_MW48	BB-North	-12.02	-0.08	-0.21	0.00	-0.00
TNC_MW202	BB-South	-7.63	-1.68	-0.03	0.00	0.00
TNC_MW204	BB-South	-5.34	-1.90	-0.02	0.00	0.00
TNC_MW101	BB-South	-12.85	-1.20	-0.04	0.00	0.00
TNC_MW105	BB-South	-10.44	-1.43	-0.03	0.00	0.00
TNC_MW106	BB-South	-6.28	-1.85	-0.02	0.00	0.00
TNC_MW103	BB-South	-10.48	-1.25	-0.04	0.00	0.00
TNC_MW107	BB-South	-10.75	-1.24	-0.04	0.00	0.00
TNC_MW109	BB-South	-12.29	-1.10	-0.04	0.00	0.00
TNC_MW110	BB-South	-9.44	-1.53	-0.04	0.00	0.00
TNC_MW304	BB-South	-10.74	-1.42	-0.04	0.00	0.00
TNC_MW308	BB-South	-8.58	-1.49	-0.03	0.00	0.00
TNC_MW310	BB-South	-8.17	-1.51	-0.03	0.00	0.00
TNC_MW401	BB-South	-10.84	-1.28	-0.04	0.00	0.00
TNC_MW410	BB-South	-11.14	-1.24	-0.04	0.00	0.00
TNC_MW422	BB-South	-6.31	-1.15	-0.07	0.00	0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Stream and river conductance parameters				
		KDR_ Seeps	KDR_ Stream	KRIV_BB	KRIV_ Merri	KRIV_ Mous
TNC_MW430	BB-South	-2.59	-1.60	-0.02	0.00	0.00
TNC_MW403	BB-South	-12.70	-1.04	-0.05	0.00	0.00
TNC_MW404	BB-South	-11.57	-1.09	-0.05	0.00	0.00
TNC_MW415	BB-South	-12.18	-1.11	-0.05	0.00	0.00
TNC_MW425	BB-South	-9.39	-1.55	-0.03	0.00	0.00
TNC_MW433	BB-South	-9.09	-1.54	-0.03	0.00	0.00
TNC_MW440	BB-South	-11.14	-1.18	-0.04	0.00	0.00
TNC_MW315	BB-South	-9.96	-1.32	-0.04	0.00	0.00
ME_YW_870	Bedrock	-0.81	-0.21	-0.00	0.00	-0.00
ME_YW_878	Bedrock	-0.00	-0.46	0.00	0.00	0.00
ME_YW_882	Bedrock	-0.30	-0.47	-0.06	0.00	0.00
ME_YW_883	Bedrock	0.00	-0.54	0.00	0.00	0.00
ME_YW_888	Bedrock	-0.00	-0.37	-0.00	0.00	0.00
ME_YW_891	Bedrock	-0.05	-0.03	-0.02	-0.03	-0.01
ME_YW_894	Bedrock	-0.00	-0.01	-0.01	-0.08	-0.00
ME_YW_896	Bedrock	-0.00	-0.06	0.00	-0.00	-0.01
ME_YW_897	Bedrock	-0.10	-0.18	-0.00	-0.01	-0.00
ME_YW_901	Bedrock	-0.18	-0.78	-0.00	0.00	0.00
ME_YW_871	Coastal sands dug	-0.15	-0.36	-0.04	-0.68	-0.00
ME_YW_872	Coastal sands dug	-0.14	-0.39	-0.04	-0.57	-0.00
ME_YW_873	Coastal sands dug	-0.08	-0.56	-0.01	-0.11	-0.00
ME_YW_890	Coastal sands dug	-2.34	-0.20	-0.02	-0.03	-0.02
ME_YW_892	Coastal sands dug	-1.74	-0.61	-0.03	-0.06	-0.02
ME_YW_893	Coastal sands dug	-0.00	-0.03	-0.02	-0.39	0.00
ME_YW_906	Coastal sands dug	-0.04	-0.48	-0.01	-0.05	-0.00
ME_YW_874	Delta sands dug	-1.04	-0.86	-0.00	-0.00	-0.04
ME_YW_875	Delta sands dug	-1.89	-1.77	-0.00	0.00	-0.00
ME_YW_876	Delta sands dug	-3.76	-1.01	-0.03	0.00	-0.00
ME_YW_884	Delta sands dug	-2.45	-1.22	-0.56	0.00	0.00
ME_YW_885	Delta sands dug	-0.20	-1.67	-0.32	0.00	0.00
ME_YW_886	Delta sands dug	-0.11	-2.29	-0.01	0.00	0.00
ME_YW_900	Delta sands dug	-0.31	-3.59	-0.00	0.00	0.00
ME_YW_902	Delta sands dug	-0.04	-0.69	-0.00	0.00	-0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Stream and river conductance parameters				
		KDR_ Seeps	KDR_ Stream	KRIV_BB	KRIV_ Merri	KRIV_ Mous
ME_YW_903	Delta sands dug	-2.30	-1.14	-0.01	0.00	0.00
ME_YW_905	Delta sands dug	-0.00	-0.18	0.00	0.00	-0.00
ME_YW_907	Delta sands dug	-3.57	-1.70	-0.01	0.00	0.00
ME_YW_908	Delta sands dug	-4.29	-1.99	-0.00	0.00	0.00
ME_YW_909	Delta sands dug	-0.93	-0.52	-0.01	0.00	-0.00
ME_YW_963	Delta sands dug	-0.07	-0.53	-0.04	-0.07	-0.00
ME_YW_965	Delta sands dug	-0.35	-0.62	-0.70	0.00	0.00
ME_YW_966	Delta sands dug	-0.03	-0.04	-0.06	0.00	0.00
ME_YW_869	Till dug	-0.18	-0.33	-0.00	-0.00	-0.02
ME_YW_877	Till dug	0.00	-0.16	0.00	0.00	0.00
ME_YW_880	Till dug	-0.00	-0.18	0.00	0.00	0.00
ME_YW_881	Till dug	-0.04	-0.47	-0.00	0.00	0.00
ME_YW_899	Till dug	0.00	-0.09	0.00	0.00	0.00
ME_YW_904	Till dug	-1.24	-0.13	-0.02	-0.01	0.00
ME_YW_964	Till dug	-0.03	-0.18	-0.00	-0.00	-0.00
Genest_33_81	Genest	-0.03	-0.58	-0.03	0.00	-0.00
Genest_34D	Genest	-0.02	-0.61	-0.02	0.00	0.00
Genest_34B	Genest	-0.02	-0.61	-0.02	0.00	-0.00
Genest_34A	Genest	-0.02	-0.61	-0.02	0.00	-0.00
Genest_34_81	Genest	-0.02	-0.61	-0.02	0.00	-0.00
Genest_34C	Genest	-0.02	-0.62	-0.02	0.00	-0.00
Genest_34E	Genest	-0.02	-0.62	-0.02	0.00	-0.00
Genest_59_81	Genest	-0.02	-0.59	-0.02	0.00	-0.00
KKW_MWHR4	Herrisecket Rd.	-0.34	-0.38	-0.08	-0.57	-0.00
KKW_MWHR11	Herrisecket Rd.	-0.32	-0.14	-0.16	-1.04	-0.00
KKW_MWHR1	Herrisecket Rd.	-0.35	-0.35	-0.09	-0.61	-0.00
KKW_MWHR3	Herrisecket Rd.	-0.35	-0.35	-0.09	-0.61	-0.00
KKW_MWHR6	Herrisecket Rd.	-0.36	-0.37	-0.08	-0.59	-0.00
KKW_MWHR7	Herrisecket Rd.	-1.86	-0.17	-0.04	-1.41	-0.00
KKW_MWHR8	Herrisecket Rd.	-0.55	-0.39	-0.07	-0.68	-0.00
KKW_MWHR12	Herrisecket Rd.	-0.32	-0.14	-0.16	-1.05	-0.00

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Stream and river conductance parameters				
		KDR_ Seeps	KDR_ Stream	KRIV_BB	KRIV_ Merri	KRIV_ Mous
KKW_MWMR13	Merriland	-0.06	-0.05	-0.09	0.31	-0.00
KKW_MWMR18	Merriland	-0.05	-0.06	-0.08	0.55	-0.00
KKW_MWMR10	Merriland	-0.05	-0.41	-0.06	0.15	-0.00
KKW_MWMR9	Merriland	-0.06	-0.08	-0.11	0.38	-0.00
KKW_DPMR3	Merriland	-0.03	-0.03	-0.03	-0.11	-0.00
KKW_MWMR6	Merriland	-0.05	-0.06	-0.08	0.53	-0.00
KKW_MWMR1	Merriland	-0.05	-0.06	-0.08	0.54	-0.00
KKW_DPMR1	Merriland	-0.02	-0.01	-0.01	-0.60	-0.00
KKW_MWMR16	Merriland	-0.00	-0.02	-0.01	-0.22	0.00
KKW_MWMR15	Merriland	-0.00	-0.01	-0.02	-0.66	-0.00
KKW_MWMR11	Merriland	-0.04	-0.05	-0.06	0.61	-0.00
KKW_MWMR8	Merriland	-0.05	-0.07	-0.09	0.79	-0.00
KKW_MWMR14	Merriland	-0.03	-0.03	-0.05	0.25	-0.00
KKW_MWMR5	Merriland	-0.05	-0.06	-0.09	0.45	-0.00
DEPCyro_X2	Sanford-Cyro	-0.07	-0.23	-0.00	0.00	-0.05
DEP_MW03_02	Sanford-Cyro	-0.00	-0.02	-0.00	0.00	-0.08
DEP_MW101A	Sanford-Cyro	-0.02	-0.09	-0.00	0.00	-0.08
DEP_MW104A	Sanford-Cyro	-0.02	-0.06	-0.00	0.00	-0.09
DEP_MW104BR	Sanford-Cyro	-0.02	-0.07	-0.00	0.00	-0.10
DEP_MW201A	Sanford-Cyro	-0.03	-0.12	-0.00	0.00	-0.08
DEP_MW204A	Sanford-Cyro	-0.01	-0.03	-0.00	0.00	-0.09
DEP_MW204B	Sanford-Cyro	-0.01	-0.04	-0.00	0.00	-0.11
DEP_MW205B	Sanford-Cyro	-0.02	-0.07	-0.00	0.00	-0.10
DEP_MW209A	Sanford-Cyro	-0.02	-0.07	-0.00	0.00	-0.09
DEP_MW702B	Sanford-Cyro	-0.00	-0.01	0.00	0.00	-0.08
SWD_IDC_M1	Sanford	-0.11	-0.31	-0.01	0.00	-0.03
SWD_IDC_M4	Sanford	-0.13	-0.32	-0.01	0.00	-0.03
SWD_Eagle_6	Sanford	-0.07	-0.28	-0.00	0.00	-0.03
SWD_Eagle_6a	Sanford	-0.08	-0.29	-0.00	0.00	-0.03
SWD_Eagle_7	Sanford	-0.06	-0.28	-0.00	0.00	-0.03
SWD_Eagle_1	Sanford	-0.05	-0.27	-0.00	0.00	-0.02
SWD_Eagle_2	Sanford	-0.08	-0.29	-0.00	0.00	-0.03
SWD_ND_1	Sanford	0.00	-0.13	0.00	0.00	-0.02
SWD_ND_4	Sanford	-0.00	-0.13	0.00	0.00	-0.02
SWD_ND_GP	Sanford	0.00	-0.13	0.00	0.00	-0.02

Table 2–1. Dimensionless scaled sensitivities for parameters, by observation groups.—Continued

[Parameters defined in text and tables 11, 12, and 15; K, hydraulic conductivity]

Observation name	Observation group	Stream and river conductance parameters				
		KDR_ Seeps	KDR_ Stream	KRIV_BB	KRIV_ Merri	KRIV_ Mous
Sanford_wet1	SW points	-0.00	-0.07	0.00	0.00	-0.08
Saywards_Wet	SW points	-0.09	-2.71	-0.03	0.00	0.00
Airport_S	SW points	-0.01	-0.37	-0.00	0.00	-0.00
Airport_SW	SW points	-0.00	-0.26	-0.00	0.00	-0.00
Merri_head	SW points	-0.00	-1.31	-0.00	0.00	0.00
Till_up_wet	SW points	-0.60	-2.22	-0.00	0.00	0.00
Merri_S_wet	SW points	0.00	-0.71	0.00	0.00	0.00
Ocean_wet	SW points	-0.00	-0.52	-0.00	-0.00	0.00
RR_wet_N	SW points	-0.03	-0.34	-0.03	-0.05	-0.00
RR_wet_S	SW points	-0.03	-0.74	-0.06	-0.05	-0.00
Perkins_Msh	SW points	-0.04	-0.80	-0.00	0.00	-0.00
Estes_Lake_1	SW points	0.00	-0.01	0.00	0.00	0.00
Estes_Lake_2	SW points	0.00	0.00	0.00	0.00	0.00
Estes_Lake_3	SW points	0.00	-0.00	0.00	0.00	0.00
OldFallsPond	SW points	0.00	0.00	0.00	0.00	0.00
Merri2_Str_1	Baseflows	0.07	-0.19	0.01	0.00	0.00
Merri1_Str_1	Baseflows	0.00	-0.12	0.00	0.09	0.00
Perkins_st_1	Baseflows	0.58	-0.44	0.01	0.00	0.01
Cold_seeps_1	Baseflows	-0.17	0.17	0.01	0.00	0.00
BB7_Str_1	Baseflows	0.18	-0.19	0.02	0.00	0.01
BB6_Str_1	Baseflows	0.08	0.34	0.13	0.00	0.00
BB5_Seeps_1	Baseflows	-0.73	0.07	0.21	0.00	0.00
BB4_Seeps_1	Baseflows	-0.43	0.26	0.00	0.00	0.00
BB4_Str_1	Baseflows	1.57	-0.16	0.01	0.00	0.00
BB3_Seeps_1	Baseflows	-2.27	0.16	0.09	0.00	0.00
BB2_Seeps_1	Baseflows	-1.19	0.09	0.06	0.00	0.00
BB2_Str_1	Baseflows	0.49	-0.15	0.01	0.00	0.00
BB1_Seeps_1	Baseflows	-1.05	0.04	0.04	0.33	0.00
BB8_Str_1	Baseflows	0.02	-0.03	0.01	0.03	0.00
Day_Seeps_1	Baseflows	-0.15	0.17	0.00	0.00	0.00
Day_Str_1	Baseflows	0.85	-0.22	0.01	0.00	0.00
Merri2_Riv_1	Baseflows	0.00	0.05	0.00	0.01	-0.02
Merri1_Riv_1	Baseflows	0.01	0.06	0.01	0.08	0.00
BB5_Riv_1	Baseflows	0.77	0.10	-0.41	0.00	0.00
BB3_Riv_1	Baseflows	1.97	0.07	-0.35	0.00	0.00
BB2_Riv_1	Baseflows	0.21	0.02	-0.03	-0.01	0.00
BB1_Riv_1	Baseflows	0.39	0.06	0.14	-0.72	0.00

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