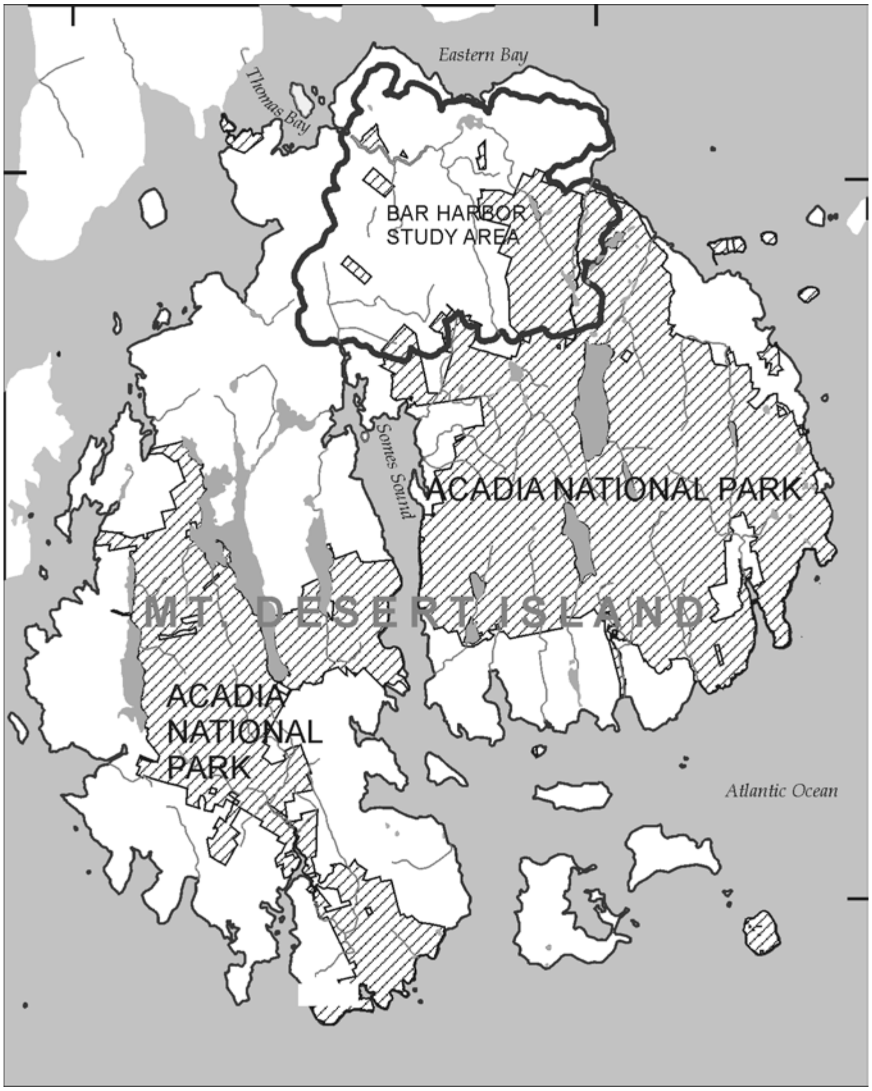
In cooperation with the Town of Bar Harbor and the National Park Service

Estimated quantity of water in fractured bedrock units on Mt. Desert Island, and estimated ground-water use, recharge, and dilution of nitrogen in septic waste in the Bar Harbor area, Maine

Open-File Report 02-435



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

Cover: Map of Mt. Desert Island, Maine, with National Park Service and Bar Harbor study area.

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Open-File Report 02-435

By Martha G. Nielsen

Augusta, Maine
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallons per acre (gal/acre)	.009354	cubic meters per hectare
acre-inch (acre-in)	102.8	cubic meter
	Flow rate	
gallon per minute (gal/min)	3.785	liters per minute
gallon per day (gal/d)	0.003785	cubic meter per day

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Estimated quantity of water in fractured bedrock units on Mt. Desert Island, and estimated ground-water use, recharge, and dilution of nitrogen in septic waste in the Bar Harbor area, Maine

by Martha G. Nielsen

ABSTRACT

In 2002, the U.S. Geological Survey, in cooperation with the town of Bar Harbor, Maine, and the National Park Service, conducted a study to assess the quantity of water in the bedrock units underlying Mt. Desert Island, and to estimate water use, recharge, and dilution of nutrients from domestic septic systems overlying the bedrock units in several watersheds in rural Bar Harbor.

Water quantity was calculated as the static volume of water in the top 600 feet of saturated thickness of the bedrock units. Volumes of water were estimated on the basis of effective fracture porosities for the five different rock types found on Mt. Desert Island. Values of porosities for the various bedrock units from the literature range more than five orders of magnitude, although the possible range in porosities for most individual rock types is on the order of three orders of magnitude. The static volume of water in the various units may range from a low of 4,000 gallons per acre for intrusive igneous rocks (primarily granites) to 20 million gallons per acre for the Cranberry Island Volcanics, but given the range in porosity estimates, these numbers can vary by orders of magnitude.

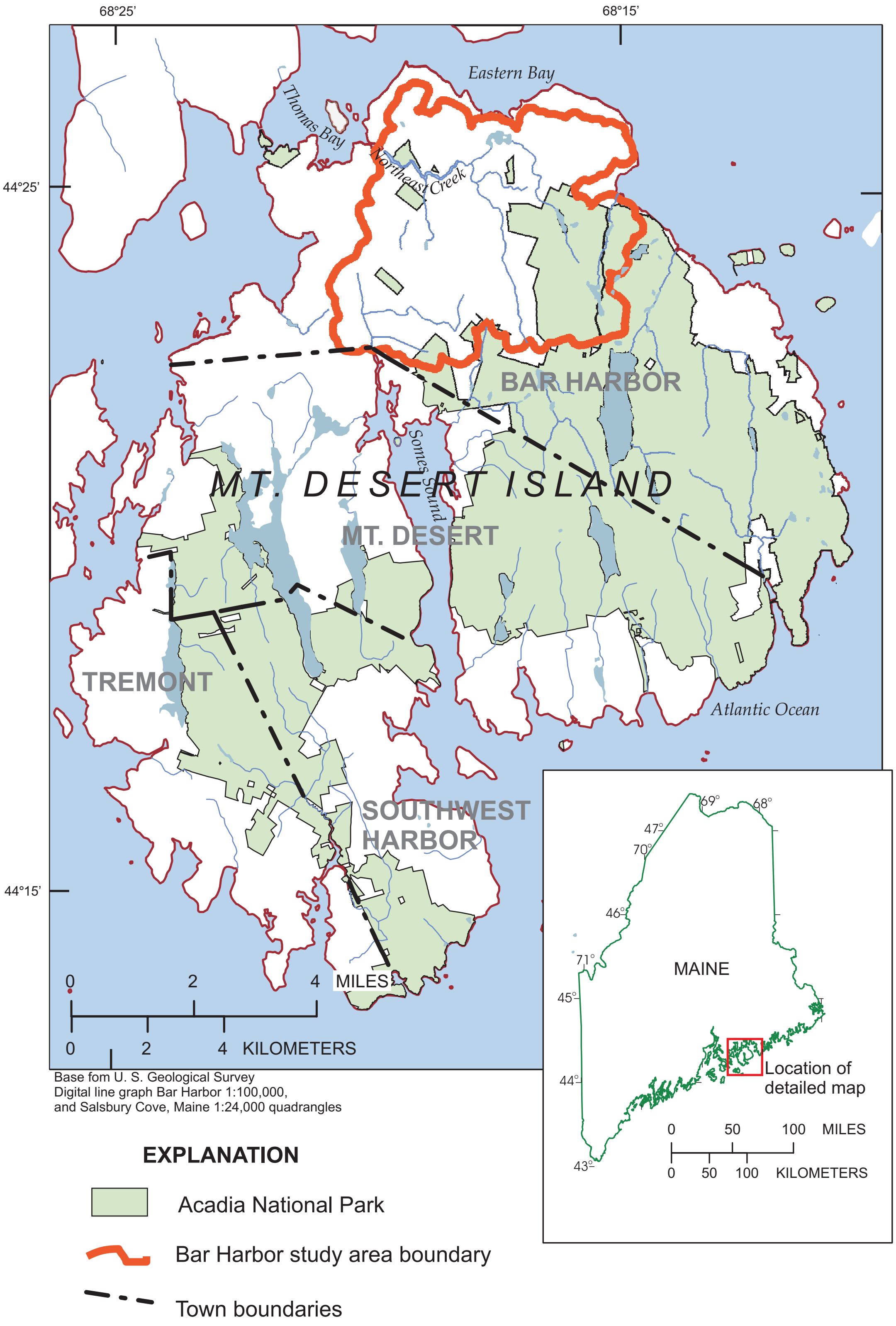
Water-use data for the municipal water supply in the Town of Bar Harbor (1998-2000) indicate that residential usage averages 225 gallons per household per day. Recharge to the bedrock units in rural Bar Harbor was bracketed using low, medium, and high estimates, which were 3, 9, and 14 inches per year, respectively. Water use in 2001 was about 2.5 percent of the total estimated medium recharge (9 inches per year) in the study area.

Dilution of nitrogen in septic effluent discharging to the bedrock aquifer was evaluated for the development density in 2001. On the basis of an assumed concentration of 47 mg/L of nitrogen in septic system discharge, dilution factors in populated rural Bar Harbor watersheds ranged from 4 to 151, for the housing density in 2001. Understanding that ground water in this fractured bedrock system mixes slowly, the fully mixed average nitrate-nitrogen concentrations in ground water estimated for the watersheds ranged from 0.1 to 11 mg/L.

INTRODUCTION

Water resources in many island communities are affected by rapidly increasing development. Mt. Desert Island, on the Maine coast (fig. 1), has few abundant ground-water resources. Although freshwater lakes and ponds supply abundant water to the developed town centers with public water-supply systems, rural residents rely on water from wells completed in the fractured bedrock units for their water supply. Acadia National Park, which occupies half of the island area, interfingers with rural residential developments in several areas, and concerns have arisen in recent years about maintaining pristine conditions in wetlands and streams downgradient of these developments. In an effort to ensure future residents have abundant, clean drinking water, towns also have begun to consider the effect of rural development on the bedrock units used for domestic water supplies.

In 1998, the U. S. Geological Survey (USGS), in cooperation with the National Park Service, began work on several regional, interdisciplinary studies of water resources and nutrient enrichment effects on ecosystems on Mt. Desert Island, Maine. As part of these studies, water-quality conditions in several watersheds across the island have been examined, with particular emphasis on the watersheds of the Northeast Creek estuary and adjacent watersheds within the town of Bar Harbor (Nielsen, 2002; Nielsen and others, 2002). Water and nitrogen budgets for these watersheds have been developed, and ongoing work is focusing on



Base fom U. S. Geological Survey
Digital line graph Bar Harbor 1:100,000,
and Salsbury Cove, Maine 1:24,000 quadrangles

Figure 1. Location of Mt. Desert Island study area, and a smaller area of more detailed study in Bar Harbor, Maine.

understanding how elevated concentrations of nitrogen in surface water and ground water from upland areas may impact seagrass habitat in the estuary (Hilary Neckles, USGS, written commun., 2000). Because of the interconnectedness of surface-water and ground-water resources, and because of a general lack of data on ground-water resources on the Island, more information is needed to define the island-wide ground-water system. The need for more ground-water data also has been targeted by the National Park Service's Water Resources Management Plan (Kahl and others, 2000). As a first step towards understanding the ground-water system on the Island, a preliminary assessment of the water-bearing and storage capacity of the bedrock units is needed. Understanding of how island-wide residential development may affect ground water also is needed. Because of the availability of information from previous work in the Northeast Creek watershed and adjacent watersheds, and because of rapidly increasing development there, this area in the northern part of the Island was selected for studying the impact of rural residential development on ground water resources.

In 2002, the U.S. Geological Survey (USGS), in cooperation with the town of Bar Harbor, Maine, and the National Park Service, conducted a study to assess the quantity of water in the bedrock units on Mt. Desert Island, and a pilot study to estimate water use, recharge, and septic nutrient dilution in the watersheds around the Northeast Creek estuary in the town of Bar Harbor. The study had three main objectives: (1) to define, as closely as possible using existing information, the static quantity of water in the bedrock aquifer on Mt. Desert Island; (2) to evaluate water use and ground-water recharge rates in rural parts of Bar Harbor; and (3) to estimate how nitrogen loads from septic systems in residential developments in rural Bar Harbor (and possibly other similar areas) may affect ground-water resources.

Purpose and Scope

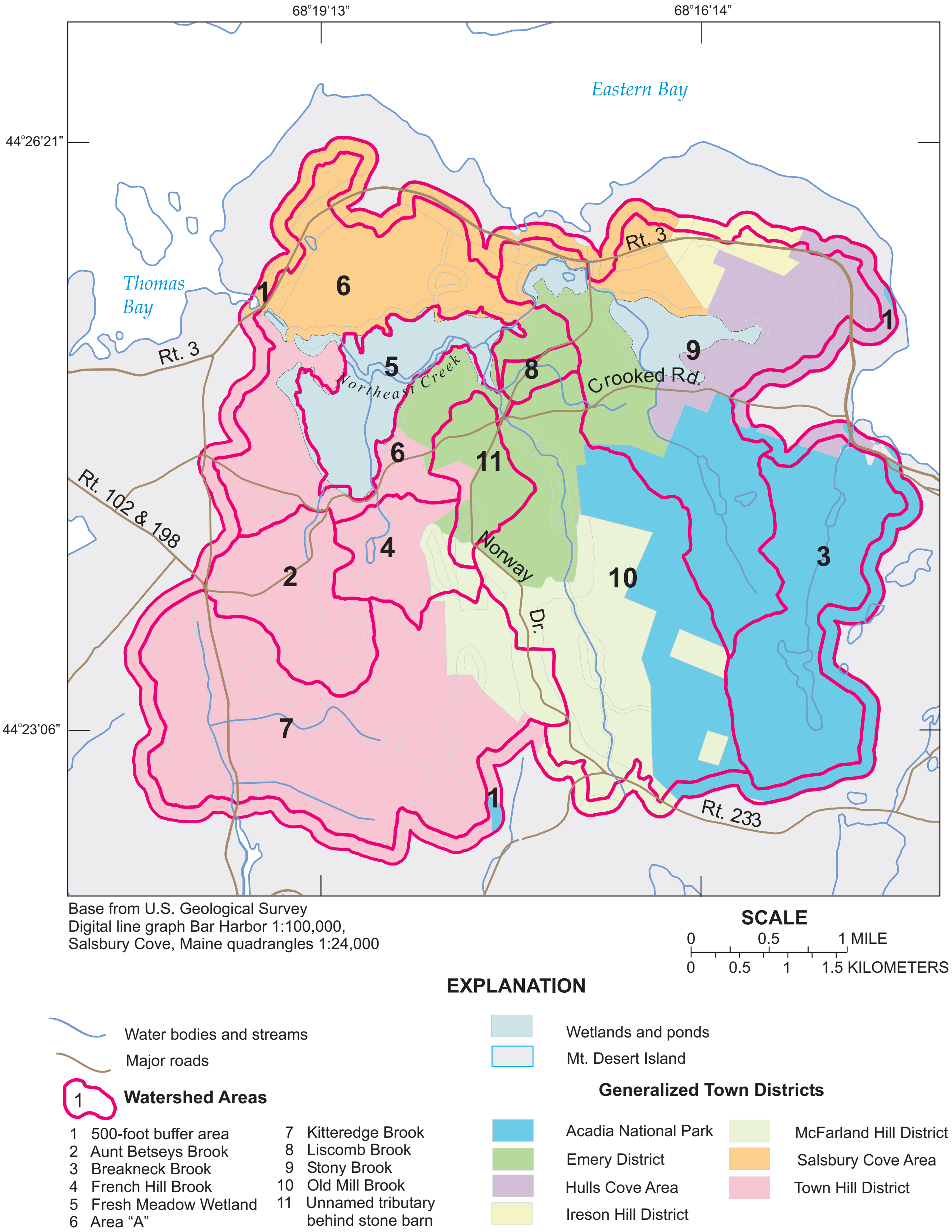
This report provides a general description of the geohydrology of the bedrock units on the Island and provides estimates of the quantity of ground water in these units. The report also contains an analysis of water use, recharge, and nutrient dilution for the pilot study in the Northeast Creek and surrounding watersheds in the town of Bar Harbor. Additional data needs are identified to help improve the estimates. A range of possible values for estimates of water storage, recharge, and nutrient dilution are provided on the basis of available data. The results for water use, recharge, and nutrient dilution are presented in terms of recent (2001) development patterns in the Bar Harbor pilot study area. Although results are presented for conditions in this pilot study area, they would be applicable to other areas on the Island with similar development patterns and geology.

Description of Study Area

Mt. Desert Island (fig. 1) is a 110-mi^2 island on the coast of Maine and is the largest island on the U.S. Atlantic coast north of Cape Cod, Massachusetts. The island is divided into four towns: Bar Harbor, Mt. Desert, Southwest Harbor, and Tremont. The combined year-round population of the four towns is 8,770 (U. S. Bureau of the Census, 2001). Acadia National Park, which occupies almost 50 percent of the island, receives 2.5 million visitors a year, primarily in the summertime (David Manski, Acadia National Park, Natural Resources Manager, oral commun., 2001).

For the pilot investigation into potential effects of island-wide rural residential development on ground-water resources, a smaller study area was selected in the town of Bar Harbor (fig. 1). Information on geology, land use, and housing density was available for the Northeast Creek watershed and two adjacent watersheds (Breakneck Brook and Kitteredge Brook). This area has been undergoing rapid subdivision in recent years (Dana Reed, Bar Harbor Town Manager, oral commun., 2002), making it an area where managers in the Town and the Park are interested in understanding potential impacts of development. These watersheds, plus a 500-ft buffer area around them, defined the rural Bar Harbor study area (fig. 1).

Results for the more-detailed study area in Bar Harbor were analyzed by dividing the study area two different ways, resulting in two sets of geographic domains. One set, which defined the extent of the study area, was the individual watersheds, plus the 500-ft buffer around the watersheds (fig. 2). The second set consisted of town zoning districts within the defined study area. However, it was necessary to aggregate the 20 to 30 individual town zoning/management districts and subdistricts into a manageable number of districts to be shown on a map. Thus, the subdistricts on the current town zoning map, including all resource conservation areas and the land in Acadia National



Base from U.S. Geological Survey
Digital line graph Bar Harbor 1:100,000,
Salsbury Cove, Maine quadrangles 1:24,000

Figure 2. Watershed areas and generalized town districts, Bar Harbor Study Area, Maine.

Park, were consolidated into seven generalized town districts within the study area.

Water resources on the island include several large lakes that serve as public drinking-water supplies for the municipalities and National Park Service facilities, a fractured-bedrock aquifer, and many small streams with drainage areas that range from 1 to 15 mi^2. No significant surficial aquifers are present on the island (as defined by the Maine Geological Survey's Significant Sand and Gravel Aquifers mapping program (Maine Geological Survey, 2001)), although some residents use water from dug wells completed in glacial till and some thin sandy deposits. Annual precipitation recorded from 1981 to 2000 at the National Park Service weather station averaged 55 in/yr (Nielsen and others, 2002).

The bedrock units consist mostly of igneous intrusive rocks, primarily granites (Gilman and others, 1988). These rocks are used for domestic water supply in rural areas on the island, and are described in more detail below.

Geohydrologic Setting

The distribution of bedrock and surficial materials has been mapped by Gilman and others (1988). The bedrock aquifer on Mt. Desert Island is composed of granites and other intrusive igneous rocks; a schist (the Ellsworth Schist); a weakly deformed sedimentary rock (the Bar Harbor Formation); a series of volcanic tuffs and other felsic volcanic rocks (the Cranberry Island volcanics); and a "shatter zone" of contact metamorphism and shattering of the rocks surrounding the Cadillac Mountain Granite (Gilman and others, 1988). The bedrock geologic map was generalized for the purpose of this study into these five general categories, which are further described below (fig. 3).

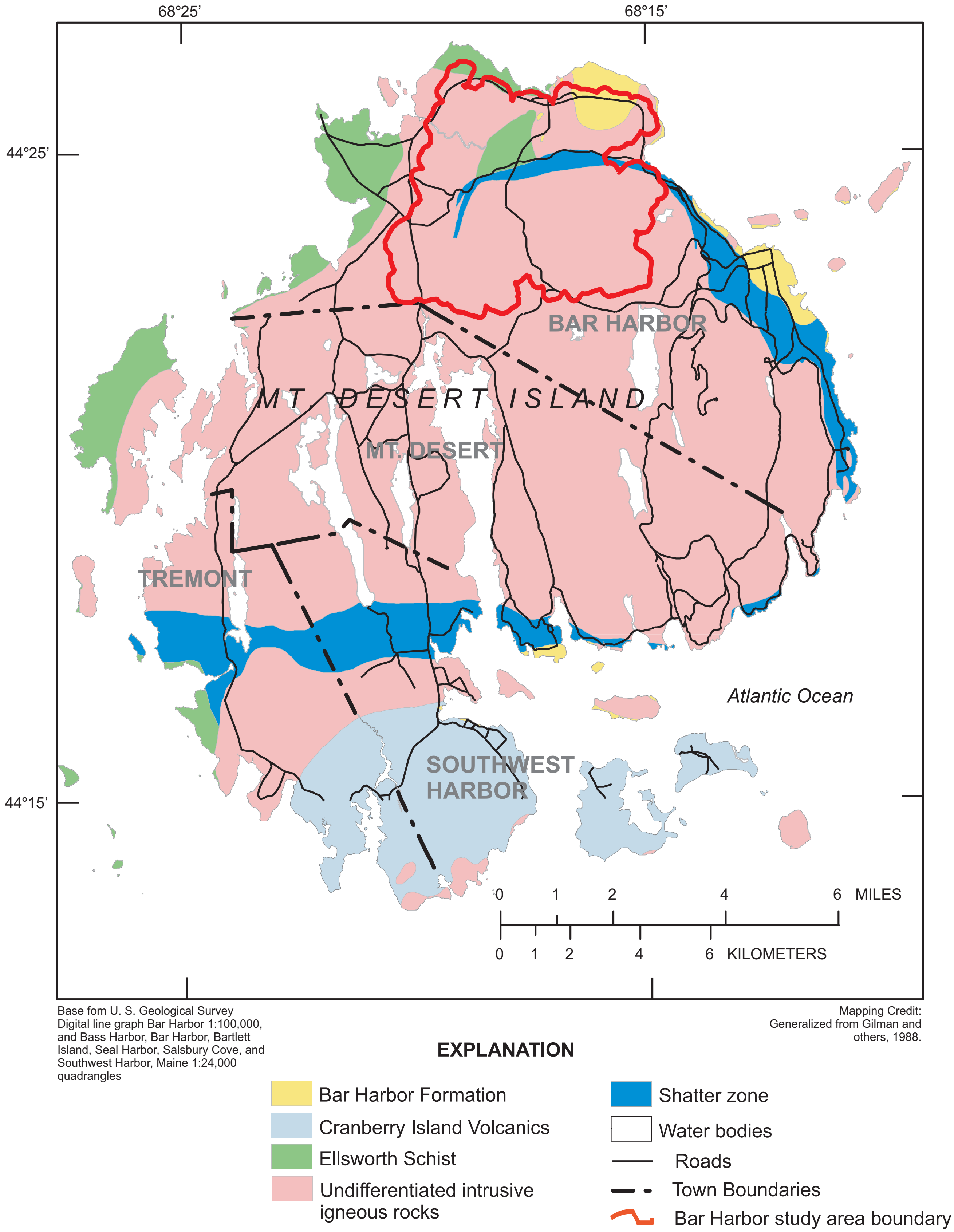
The granites, which are the most common rocks on the island, are characterized by large, massive rock bodies with few to many fractures. They are light gray, tan, or pinkish rocks with small flecks of different mineral grains. No spaces are present between the grains, and all water in this type of rock is held within the small fractures that run throughout the rock. Gabbro and diorite, which are darker igneous rocks, also are present, primarily on the north and west sides of the island.

The Ellsworth Schist is a metamorphic rock characterized by bands of light and dark rock. The dark bands may be greenish or dark gray in color. The bands often are complexly folded.

The Bar Harbor Formation is a sedimentary rock (siltstone), that was deposited on the ocean bottom after the deformation of the Ellsworth Schist (Gilman and others, 1988). The rock is layered, but the layers are slightly dipping, regular in thickness, and are not highly deformed.

The Cranberry Island Volcanics are felsic (rich in light-colored, silica-rich minerals) volcanic rocks and sediments at the southern end of Mt. Desert Island, and were formed during and after the Bar Harbor Formation (Gilman and others, 1988). The most distinctive of these rocks is a volcanic tuff, which is a rock formed as small pieces of rock debris settled after a volcanic eruption. It is light gray in color, and small pieces of angular rock fragments can be seen in outcrops. Further descriptions and photographs of all these rock types can be found in Gilman and others (1988).

The surficial sediments (all the unconsolidated materials above the bedrock surface that were deposited during and after the end of the last glaciation) are not thick enough to form any significant aquifers in the study area. Some rural residents, however, use dug wells that get water from some surficial sediments, such as till. One surficial unit, called the Presumpscot Formation, is a silt and clay layer of variable thickness and extent that was deposited in seawater during and after glacial retreat when sea level was probably between 350 and 400 ft higher than it is today (Smith, 1985; Lowell, 1989). This unit, which is not continuous in the Bar Harbor study area, acts as a barrier to water flow because of its clayey composition. This is an important consideration in this study, because this unit inhibits recharge to the bedrock units and inhibits the movement of septic discharge. The surficial geologic map (Gilman and others, 1988) is not very detailed in the Bar Harbor area, and additional information from a more recent county soil survey (Jordan, 1998) was used with the surficial geologic map to produce a map of the inferred extent of the Presumpscot Formation in the Bar Harbor study area (fig. 4). Soil units with clay-rich compositions and thicknesses greater than 60 in. were used to help infer the extent of the Presumpscot Formation.



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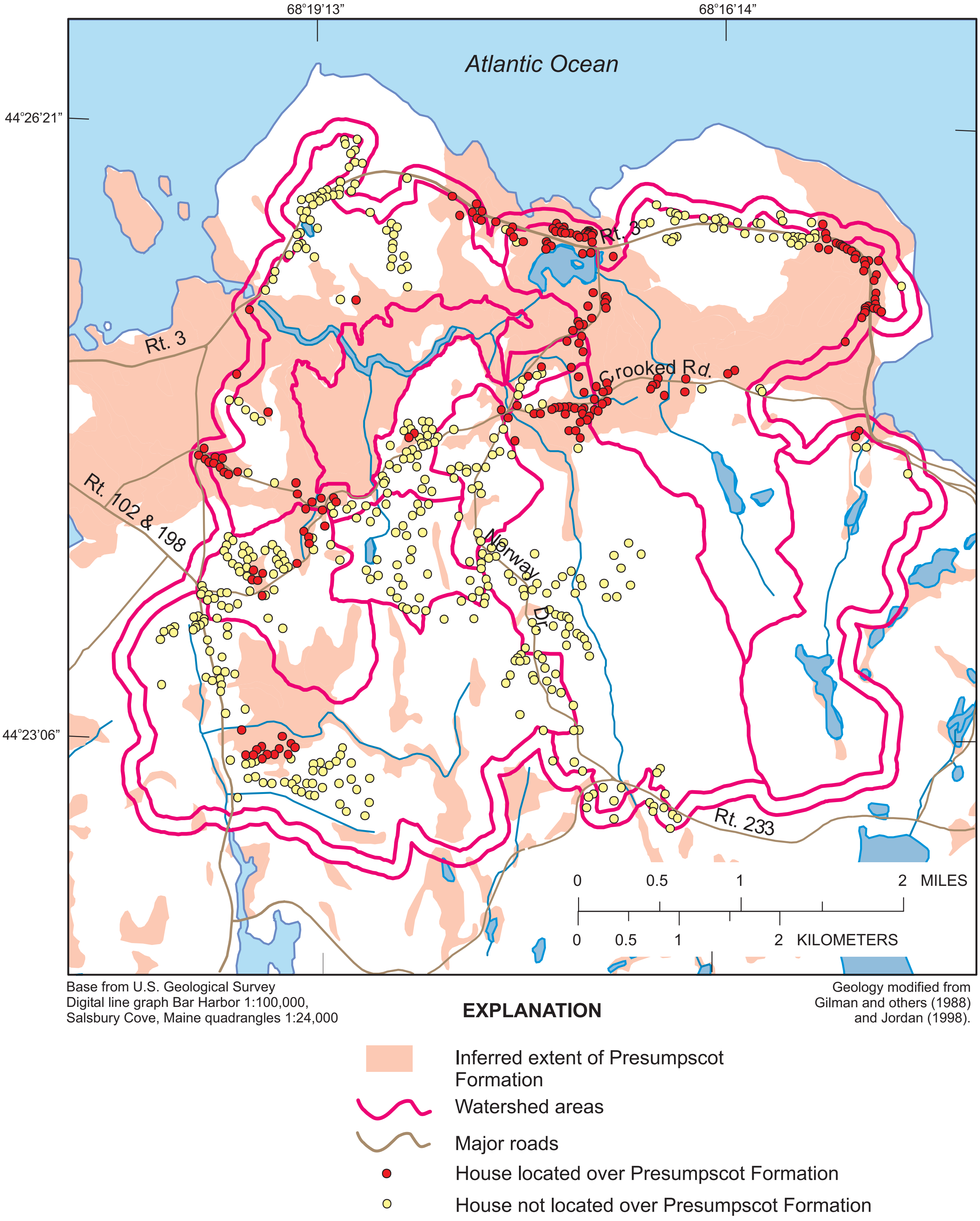
and Bass Harbor, Bar Harbor, Bartlett
Island, Seal Harbor, Salsbury Cove, and
Southwest Harbor, Maine 1:24,000
quadrangles

Mapping Credit:
Generalized from Gilman and
others, 1988.

Figure 3. Generalized fractured bedrock units, Mt. Desert Island, Maine.



Base from U.S. Geological Survey
Digital line graph Bar Harbor 1:100,000,
Salsbury Cove, Maine quadrangles 1:24,000

Geology modified from
Gilman and others (1988)
and Jordan (1998).

Figure 4. Inferred extent of Presumpscot Formation and locations of houses, Bar Harbor

Previous Studies

A small study of the ground-water resources of Mt. Desert Island was conducted for the National Park Service in the late 1970s (Hansen, 1980). This study reported water yields of 160 wells completed in bedrock units; yields ranged from 0.5 to 100 gal/min, with a median of 10 gal/min. Hansen (1980) discussed the fractured nature of the bedrock units and the various rock types, but did not elaborate specifically on hydraulic properties of the rocks. Additional well data, including well depths and some location information, were compiled by Caswell and Lanctot (1975).

The USGS has been conducting studies since 1998 on water and nutrient cycling in the watersheds surrounding Northeast Creek (Old Mill Brook, Aunt Betsey's Brook, French Hill Brook, and Stony Brook), plus the surrounding watersheds of Kitteredge Brook, and Breakneck Brook in the Bar Harbor area (fig. 2). These studies provided important information on surface-water resources, but did not investigate the ground-water resource in detail (Nielsen, 2002). Hydrologic data collected as part of these previous studies include continuous streamflow at a streamflow-gaging station on Old Mill Brook from 1999 to 2000 (Nielsen and others, 2002), concentrations of nutrients in streams (Nielsen and others, 2002), and estimates of nutrient yields from the watersheds (Nielsen, 2002).

Acknowledgments

Many people assisted in the completion of this study. The author would like to thank the town of Bar Harbor for their gracious access to town plat maps. David Manski and others at Acadia National Park provided encouragement, guidance, and the funding to collect significant amounts of the previous data. The author would like to express appreciation to the local land owners who allowed access to conduct the geophysical survey. The author also greatly appreciates the assistance provided by the USGS Office of Ground Water and the Branch of Geophysics, particularly the hard work of James R. Degnan and Michael Lambert. Pamela J. Lombard of the USGS is greatly appreciated for her assisted in the compilation and analysis of water-use data.

DATA COMPILATION AND ANALYSIS

This study is based almost exclusively on available data and information. This included descriptions of the geology of Mt. Desert Island, hydraulic properties of the rock types found on the island, recharge rates for the bedrock units, and nitrogen loading rates from domestic septic systems. For the compilation of hydraulic properties of the rocks, including porosity and specific yield, no reliable data were found in the literature for the shatter zone and the Ellsworth Schist. A geophysical investigation was undertaken to collect data from these specific rock units. Although much of the best available information on recharge rates came from the literature, continuous streamflow data for Old Mill Brook (Nielsen and others, 2002) were used to estimate recharge in the Old Mill Brook watershed using methods described by Rutledge (1998).

Geographic Information

Almost all of the calculations and estimates made during this study required the use of a geographic information system (GIS). The Arc/Info (version 8.0.2) system was used to store and process the GIS data. Calculations and estimates were based on the areal distribution of geologic units, soils, housing, watersheds, and town zoning districts.

The geology of Mt. Desert Island (bedrock and surficial) was mapped by Gilman and others (1988) at a scale of 1:50,000. The mapped extent of the geologic units was made available as GIS coverages from the National Park Service. The geologic units were grouped according to their lithology, textures, and hydraulic properties for the purposes of this study (fig. 3). In addition to the surficial geologic map of Gilman and others (1988), soils data mapped at a scale of 1:12,500 were published in 1998 by the Natural Resources Conservation Service (NRCS) (Jordan, 1998) and were made available in digital form by the NRCS. In consultation with the Maine Geological Survey, soil units were aggregated based on thickness, texture, slope, and description into groups. These aggregated soil units were used with the surficial geologic map to evaluate recharge through the surficial units to the bedrock aquifer and to evaluate the susceptibility of the bedrock aquifer to nutrient enrichment from septic-system discharge.

Hydraulic Properties

A detailed literature review was conducted of porosity and specific yield data for each of the generalized rock types on Mt. Desert Island (see appendix 1). The literature review itself was not sufficient to determine the porosity or specific yield for two of the rock units in the study area. Therefore, a geophysical study was conducted during the summer of 2002 in the Bar Harbor area to attempt to refine the range of possible porosity values of these two units, the Ellsworth Schist and the shatter zone.

The geophysical study used a square-array direct-current resistivity technique (Habberjam and Watkins, 1967; Lane and others, 1995). In this technique, a square is laid out on the land surface with electrodes at the corners (the square is many meters on a side). The electrodes are inserted into the ground above the bedrock area of interest. A high-voltage current is applied to from electrodes to the unconsolidated sediments and underlying bedrock, and the electrical resistance along each axis of the square is measured. The square is rotated around a central point, repeating the whole procedure every 15 degrees around the arc. Because water-filled fractures in the bedrock conduct electricity better than the rock itself, the square-array resistivity method can detect the orientation of the fractures, and under ideal conditions, the total volume of water-filled fractures (the porosity) (Lane and others, 1995). When this study was conducted in June 2002, conditions in the unconsolidated materials above the bedrock enabled the estimation of the porosity of these two units. Details of the surveys performed, the data collected, and analysis of the results are presented in appendix 2 .

Water-Use and Recharge

Water-use data for the Bar Harbor area were obtained from the Bar Harbor Water Company, which is municipally owned. Data on water use for residential connections were compiled for the period 1998 to 2000. Because these data represent users in the town center of Bar Harbor and not the rural areas, an assumption was made that water use by households in the rural areas was equivalent to that in the area served by the public water utility.

Recharge values used in the study were determined from the available literature on recharge to bedrock aquifers in northern New England and other analogous aquifers. Many of these studies used ground-water-flow models to determine recharge.

Another method used to estimate recharge based on site-specific data which is described by Rutledge (1998), involves a computerized method of estimating recharge on the basis of streamflow data. Because streamflow is derived from ground-water discharge during low-flow periods and between precipitation events, it can be separated into components that represent stormflow runoff and ground-water discharge. In this method, the ground-water-discharge portion of a streamflow hydrograph is summed over a period of time (often a year). Assuming that the amount of recharge to and discharge from an aquifer are roughly equal, the amount of recharge to the aquifer can then be determined. In the Bar Harbor study area, continuous data from the Old Mill Brook streamflow-gaging station for April 1999 to September 2000 (Nielsen and others, 2002) were analyzed in this way. See Rutledge (1998) and Rutledge (2000) for additional details about the methodology used.

Actual recharge to bedrock aquifers depends on site-specific conditions, which have not been rigorously determined in this study area. Therefore, from the range of values in the literature and the value determined using the method described above, three values were selected that represent the upper, middle, and lower portions of the total range.

Analysis of Dilution of Septic-Nitrogen Discharge

In evaluating the current water-use patterns and effects of septic-system discharge on the bedrock aquifer in the Bar Harbor area, the locations of houses that were built by the beginning of the study period were needed. A GIS coverage of house locations in the watersheds in rural Bar Harbor was constructed for an ongoing study (Glenn Guntenspergen, U. S. Geological Survey, written commun., 2001), by using 1998 digital orthophotographs at a scale of 1:6,000, and intensive field mapping in 2001 to identify additional house locations and verify the house locations identified on the orthophotographs. This coverage was further modified by overlaying a coverage of all property boundaries in the study area to ensure the locations of the houses corresponded to individual lot locations. No other data were included in this coverage.

To estimate the potential dilution of nitrogen in septic-system effluent and average concentrations of nitrate-nitrogen in the bedrock units, some information was needed on the total nitrogen concentration in the discharged effluent from domestic septic systems. A literature review was conducted, and values for the total nitrogen concentration in septic-system effluent were tabulated (see appendix 1). Overall, nitrogen concentrations reported in the literature range from 20 to 100 mg/L; however, the concentration of effluent is related to the discharge volume, and a lower concentration does not necessarily imply a lower total amount of nitrogen entering the system (the nitrogen load). In general, households that use less water would have higher effluent concentrations than households of the same size that use a greater amount of water for in-home uses. If Bar Harbor residents use relatively more or less water than average, then nutrient effluent concentrations might be slightly lower or higher, respectively, than average.

Septic-system technology also influences the concentration of nitrogen in effluent discharged from the septic system. New rural housing in Bar Harbor has been using native soil-bed leaching systems since the 1980s (Kimberly Keene, Town of Bar Harbor Code Enforcement Division, oral commun., 2002). In a recent study of three residential sites with coarse-grained soils (Harrison and others, 2000), similar soil-only systems removed between 18 and 55 percent of the nitrogen leaving the septic tank.

The average concentration of nitrogen (as nitrate) in recharge to the bedrock units (from precipitation plus septic discharge) was estimated using an equation by Hantzsche and Finnemore (1992). Of the many methods available to estimate water-quality concentrations below unsewered residential areas, this method was chosen because of the availability of input data required by the equation, and its use of specific recharge and septic nitrogen-concentration information. The equation (equation 1) is presented in terms of the nitrate-nitrogen concentration in the net recharge over a particular area, which contains the nitrogen contribution from ambient recharge (natural recharge in areas unaffected by houses) plus the nitrogen contribution from septic systems. The method assumes complete transformation of total nitrogen in septic waste to nitrate-nitrogen (Hantzsche and Finnemore, 1992). The equation has been slightly modified from the original to reflect that septic systems in the Bar Harbor area do not contribute additional volumes of water to the amount of recharge. (In many other places, houses have public-supplied water, and their septic discharge volumes must be added to the natural recharge volumes.) Over time, all the water in the aquifer will have the same average water-quality characteristics as the net recharge. (The time it takes for the whole aquifer to reach the net recharge nitrate-nitrogen concentration depends on the residence time of water in the aquifer.) The equation is:

$$n_r = \frac{(1-d)In_w + (R-I)n_b}{R}, \qquad (1)$$

where n_r is the averaged nitrate-nitrogen concentration in the net recharge, in mg/L,

d is the fraction of nitrate loss because of denitrification in the soils,

I is the volume rate of wastewater from septic tanks entering the aquifer, averaged over the development area, in in./yr

n_w is the total nitrogen concentration of wastewater, in mg/L,

R is the recharge rate, in in., and

n_b is the background total nitrogen concentration in ambient recharge, in mg/L.

The calculations are presented for average recharge to each of the generalized town districts and each of the watersheds in the study area. In the calculation of I, the distribution of the Presumpscot Formation was taken into consideration because of its clay-rich nature. The Presumpscot Formation inhibits recharge to underlying bedrock units and, thus, probably also inhibits the downward movement of wastewater from individual septic systems. The calculation of I was accomplished in the following way. For each geographic area (town district or watershed),

$$I = \frac{N_{WU}H}{A}, \qquad (2)$$

where N_{WU} is the net wastewater-discharge rate per household, in acre-in per year (see below),

H is the number of houses in each geographic area that are not underlain by Presumpscot Formation, and

A is the number of acres in each geographic area that are not underlain by Presumpscot Formation.

The calculation of N_{WU} is based on an assumed household water-use rate of 225 gal/d, 10-percent consumptive use (water use that is not returned to the aquifer), and a conversion factor of 3.682 * 10^{-5} from gal/household/year to acre-in./household/year of net wastewater discharge. The geographic data used to calculate *I* for each generalized town district and watershed area in the Bar Harbor study area are presented in table 1. Large wetlands and ponds were excluded from the generalized town districts, because they are considered conservation areas and were not small enough to be generalized into any of the existing town districts (fig. 2).

ESTIMATED QUANTITY OF GROUND WATER IN THE FRACTURED BEDROCK UNITS ON MT. DESERT ISLAND

Managing water resources effectively requires an understanding of the boundaries and limitations of those resources. On Mt. Desert Island, the groundwater resource is limited by several factors: the depth to which wells are typically drilled; the depth of the water table; the physical character of the rocks that constitute the aquifer; the rate (and source) of recharge to the

Table 1. Area, number of houses, and percent of area underlain by Presumpscot Formation for generalized town districts and watersheds in the Bar Harbor study area

[Fm., Formation]

Geographic division	Area (acres)	Number of houses 2001	Number of houses not underlain by Presumpscot Fm.	Percent of area underlain by Presumpscot Fm.
Generalized Town Districts				
Acadia National Park	2,251	*2	*2	2
Emery District	1,168	96	39	51
Hulls Cove Area	662	46	8	70
Ireson Hill District	179	23	23	4
McFarland Hill District	1,179	84	86	3
Salsbury Cove Area	1,169	110	68	35
Town Hill District	3,267	228	182	26
Watershed Areas				
500-foot buffer	1,377	71	37	23
Aunt Betseys Brook	498	57	45	29
Breakneck Brook	917	4	3	4
French Hill Brook	320	35	35	3
Fresh Meadow Wetland	449	0	0	96
Area “A”	1,380	103	82	43
Kitteredge Brook	1,848	101	88	20
Liscomb Brook	69	11	4	78
Old Mill Brook	1,692	84	62	9
Stony Brook	1,831	103	33	48
Unnamed tributary behind Stone Barn	249	20	19	16

* The two “houses” in Acadia National Park are actually the Park’s Visitor Center. They are not included in the calculations of wastewater discharge and water use because they are on town water and sewer.

aquifer; and the interface with saltwater at the edges of the island.

In theory, freshwater should be present to depths of several thousand feet beneath Mt. Desert Island (Hansen, 1980). There are no known wells that approach those depths, however, and bedrock wells on Mt. Desert Island typically are 100 to 500 ft deep. Water levels, based on data from 167 wells across the island, are typically within 5 to 35 ft of land surface (unpublished data, Maine Geological Survey, 2001). Even on the top of Cadillac Mountain, the highest point on the island, recorded water levels were only 50 ft below land surface (unpublished data from 1967, U.S. Geological Survey, Augusta, Maine). For the current analysis, the ground-water resource is evaluated for the upper 300 and 600 ft of the total saturated thickness, because we consider those to be the typical (300 ft) and reasonable maximum (600 ft) amount of the bedrock aquifer that is utilized on the Island.

Hydraulic Properties of the Fractured Bedrock Units

A common feature of all the bedrock units described above is that the water in the bedrock aquifer flows almost exclusively in the small fractures that run throughout the rocks. Differences in water-bearing properties are related to differences in fracture size, frequency, length, and interconnectedness. For a few units, water also is held in pore spaces between mineral grains. Specific yield and porosity are properties used to determine the static volume of water in the the bedrock units. The specific yield refers to the amount of water that can be drained from the fractures and (or) pore spaces in the rock. It is often expressed as a dimensionless fraction of the aquifer volume. The porosity is the total volume of fracture/pore space in the rock, commonly expressed as a percentage. Porosity that represents interconnected fractures/pore spaces through which water can flow is sometimes called the "effective porosity" or "flow porosity." Not all the water contained in fractures and pore spaces can be drained, because of electrostatic and hygroscopic forces acting at the rock/water interface. Thus, the specific yield will always be lower than the total porosity. Porosity data, however, while not quite as useful as specific yield data, are much easier to find in the literature.

A detailed literature review was conducted of porosity and specific yield data for each of the generalized rock types on Mt. Desert Island (see appendix 1). Porosities of granites and other intrusive igneous rocks (restricting the compilation to fracture, "effective", or "flow" porosities) range over four orders of magnitude from 0.0005 to 5 percent. A great majority of porosity values published for these rocks are less than 1 percent. No specific yield values were found that specifically were for fractured granites or intrusive igneous rocks. Generalized nonporous fractured bedrock had specific yield values of 0.0002 (Daniel and others, 1989; Randall and others, 1988). References to schists in the literature were compiled in Wolff (1982). Specific yield ranged from 0.22 to 0.33 as reported by Morris and Johnson (1967). Another reference to specific yield in "layered fractured rocks" was 0.01, and porosity references ranged from 0.62 to 58.4 percent (Wolff, 1982). Schists can also be considered under the general heading of "fractured crystalline rocks", which had porosities from 0.0005 to 1 percent (see appendix 1).

Because the literature had such a wide range in possible values for the porosity of schists, a geophysical study (described earlier) was conducted in the Bar Harbor area in an effort to refine the range of possible porosity values for the Ellsworth Schist (John Lane, U. S. Geological Survey, Branch of Geophysics, written commun, 2002). The shatter zone surrounding the Cadillac Mountain Granite is a unique rock unit, and no other single rock type can be considered analogous, although it also can be considered within the generalized "fractured crystalline rock" category. The geophysical survey was also used to determine an approximate porosity for the shatter zone.

Because water-filled fractures in the bedrock conduct electricity better than the rock itself, the square-array direct-current resistivity method can detect the orientation of the fractures, and under ideal conditions, the total volume of water-filled fractures (the porosity) (Lane and others, 1995). When this study was performed in June 2002, conditions in the soil enabled the estimation of the porosity of these two units. Two surveys were conducted in each rock type, and the estimated range of porosities for the Ellsworth Schist were 0.08 to 1.4 percent and 0.1 to 0.7 percent for the shatter zone (John Lane, U.S. Geological Survey Branch of Geophysics, written commun., 2002). Details of the surveys performed, the data collected, locations of the sites, and analysis of the results are presented in appendix 2.

Table 2. Values for porosity of rocks used in water-quantity analysis

Rock type	Porosity (percent)		
	Low	Medium	High
Granites/other intrusive rocks	0.002	0.05	1
Ellsworth Schist/ other schists	.1	1.5	10
Shatter Zone	.1	.5	0.7
Siltstones (used for Bar Harbor Formation)	1	10	30
Volcanic tuffs (used for Cranberry Island Volcanics)	3	10	35

Use of Porosity Values to Estimate Quantity of Ground Water

The porosity data were consolidated and summarized and are shown in table 2. Each rock type was assigned a low, medium, and high porosity value, based on values from the literature and the geophysical survey. Because specific yield values found in the literature were insufficient to evaluate the probable range for each rock type, the analysis was limited to the porosity values. Because the lower values in table 2 are more representative of studies that specifically determined the effective (or flow) porosities, it is assumed that the low to moderate values are the most realistic to use in estimating how much water might be in storage. It should be noted that the Bar Harbor Formation and the Cranberry Island Volcanics are rock types that may have significant primary porosity, in addition to porosity associated with fractures (secondary porosity)The low and medium porosities were applied to the saturated thicknesses to obtain gross estimates for the amount of water stored in the aquifer per acre of land covered by each rock type (table 3). Volumes in storage were not calculated using the high porosity values, because these numbers were not considered representative of interconnected fracture porosity in which water could flow. In the top 300 ft of saturated thickness, the potential amount of water in storage ranges over several orders of magnitude for the various rock types. The granites and other intrusive igneous rocks may have a static volume of water in storage as little as 2,000 gal/acre in the top 300 ft of saturated

Table 3. Estimated static volume of water contained in the bedrock aquifer of Mt. Desert Island, by rock type

[gal/acre; gallons per acre; ft, feet]

Rock Type	Water in upper 300 ft of saturated thickness, gal/acre		Water in upper 600 ft of saturated thickness, gal/acre	
	Low porosities	Medium porosities	Low porosities	Medium porosities
Undifferentiated granites/intrusive igneous rocks	2,000	49,000	4,000	98,000
Ellsworth Schist	100,000	1,500,000	200,000	2,900,000
Shatter zone	100,000	490,000	200,000	980,000
Bar Harbor Formation	980,000	9,800,000	2,000,000	20,000,000
Cranberry Island Volcanics	2,900,000	9,800,000	5,900,000	20,000,000

thickness (table 3), whereas the tuffs and other rocks in the Cranberry Island Volcanics may have a storage of almost 3 million gal/acre. Rocks in the Ellsworth Schist and shatter zone may not contain more than 100,000 gal/acre. The Bar Harbor Formation may have almost 1 Mgal/acre for the low estimate of porosity. At medium porosity values, the granites could contain almost 50,000 gal/acre; the schist, 1.5 Mgal/acre; the shatter zone, 500,000 gal/acre; and the Bar Harbor Formation and Cranberry Island Volcanics could both contain as much as 9.8 Mgal/acre. Estimates for the amount of water contained in the top 600 ft of saturated thickness are double those in th e top 300 ft, providing that fracture density (and porosity) are the same. Although many hydrologists consider fracture porosity to decrease with depth (for example, Hansen, 1980; Trainer, 1988), this is not a universally held belief, and to simplify the calculations here, it was assumed that porosity does not change with depth. The differences in estimated water-bearing capacity shown in table 3 may be due to differences between the primary porosity of the tuffs and silts compared to that of the granites, schists, and shatter zone, which lack primary porosity. It has not been determined whether wells in the Cranberry Island Volcanics or Bar Harbor Formation yield more water than the other rock types.

Factors Affecting Well Yield

Although the static amount of water in storage can be useful in evaluating the relative water-bearing capacity of different rock types, it should not be assumed that wells drilled in rocks with lower porosities will always yield less water than wells drilled in higher porosity rock types. The amount of water that a well yields is related to several factors, the most important of which is the amount of recharge the fractures intersecting the well receive, and the width of those fractures. Recharge to fractures can come from precipitation and infiltration of water into the aquifer, from nearby surficial sediments, and from water bodies, such as lakes and streams. If a well yield is high, the fractures the well intersects may be more numerous or wider than those wells with lower yield, and the fractures may be tapping into a water body or surficial sediments that contain large amounts of water, even though the porosity of the rock body may be low. For example, anecdotal reports (Gary Friedmann, Bar Harbor Conservation Commission, oral commun., 2002) may indicate that well yields in the shatter zone are lower than those in the granites. The fractures in the granites, although fewer in number, are typically longer and more interconnected than the contorted, short fractures of the shatter zone. The amount of water in the overlying till and other sediments also is important in determining how much water is available to a well. Wells in areas with thick, fully saturated sediments above the bedrock receive recharge from them, in contrast to wells in areas with thin soil and sediment cover.

ESTIMATED GROUND-WATER USE, RECHARGE, AND NITROGEN DILUTION IN RURAL BAR HARBOR

The analysis for the remainder of the study was conducted for the watersheds around the Fresh Meadow Wetland and Northeast Creek, and the Kitteredge Brook and Breakneck Brook watersheds in the Bar Harbor area (fig. 2). Estimates are provided by watershed area and by generalized town districts. Estimates for the town districts are only for the portion of each district within the study area as defined by the watershed boundaries (fig. 2).

Estimates of Ground-Water Use

Data from the Bar Harbor Water Company, which is municipally owned, were compiled for the period 1998 to 2000. Water for the public water supply comes from Eagle Lake, which is located in Acadia National Park. For the years analyzed, there were approximately 1,700 residential connections. Residential delivery of water accounted for between 25 to 30 percent of all water delivered. Water use increased dramatically during the summer because of the additional influx of summer residents and tourists.

Water-use data for the municipal water supply in the town of Bar Harbor (1998-2000) indicate that residential connections to the Town water system used an average of 227 gal/household/d. By using 2000 census data (U. S. Bureau of the Census, 2001), which indicated 2.25 persons/household in Bar Harbor, the average water-use rate was 100 gal/person/d, which was rounded to 225 gal/household/d. Several basic assumptions about water-use patterns were made in an effort to apply water-use estimates derived from municipal water-supply data to the rural households of Bar Harbor. These assumptions are that each residential connection represents an individual household, and that households in rural Bar Harbor use water at the same rate as users connected to the public water supply. A constraint in this assumption may be that residential houses in the public supply area are more often vacant during the winter than residential houses in the rural areas, which would imply that rural usage may be greater than usage in the public-supply area. Another constraint may be that rural users are more conservative with their water use and users supplied with public water, which would imply that water use in the rural area may be less than in the public-supply area. The national average water-use rate in 1995 was 270 gal/household/d, but the per person national average water-use rate of 101 gal/person/d (Solley and others, 1998) is virtually the same as the rate in Bar Harbor.

Estimates of Recharge to the Fractured Bedrock Units

The review of literature on recharge to bedrock aquifers in northern New England and other analogous aquifers showed a range of recharge rates that might be expected in the Bar Harbor area (table 4). Most of the relevant recharge estimates in the literature came from calibrated ground-water-flow models. Many of these represent areas that are hydrologically similar to the Bar Harbor study area; that is, thin overburden, hilly terrain, and a low-porosity fractured bedrock aquifer, although precipitation in Bar Harbor generally is higher than in most of the other areas. The lowest estimates of recharge to bedrock aquifers were made by Gerber and Hebson (1996), who compiled results from a number of calibrated models conducted by consulting companies in the early 1990s. They presented recharge rates to the bedrock aquifer as typically being 2 to 8 in/year. A number of hypothetical aquifer scenarios modeled by Harte (Harte and Winter, 1995), with sloping hillsides covered by till, indicated less than 1 to 4 in/yr through the till to the bedrock for most of the various scenarios. Other recent studies (Starn and others, 2000; Lyford and others, 1999; Tiedeman and others, 1997; Melvin and others, 1995) of bedrock aquifers in New England found recharge to bedrock aquifers to be on the order of 8 to 11 in/yr, although, again, these values are in areas with slightly less precipitation than Bar Harbor.Based on the analysis of records from 1999 to 2000 for the Old Mill Brook streamflow-gaging station, recharge to the bedrock aquifer upstream of the station is estimated to have been approximately 25 percent of the incoming precipitation, or 14 to 15 in./yr. Although this value is higher than other estimates of recharge for bedrock aquifers, the study area does get almost 20 percent more precipitation per year than other areas in New England, according to climate summaries (National Oceanic and Atmospheric Administration, 1979-2000). This streamflow analysis was conducted using data from a very short time interval, however, and may not be representative of long-term conditions.

Table 4. Published rates of recharge to fractured bedrock aquifers in New England

[in/yr, inches per year; <, less than]

Source	Recharge Rate
Tiedeman, and others	10.2 -11 in/yr
Lyford, and others	10 in/yr
Starn,and others	8.8 in/yr
Melvin, and others	9.6 in/yr
Gerber and others	2 - 8 in/yr
Harte and others	< 1 - 4 in/yr to bedrock through till

Because of the wide variation in recharge estimates for bedrock ground-water studies in New England (from 1 to 11 in./yr), and the higher value of possible recharge obtained using the streamflow-analysis method (14 to 15 in./yr), recharge to the bedrock units in the Bar Harbor area was bracketed with a low, medium, and high estimate. The values selected were 3, 9, and 14 in./yr, respectively, which were chosen to represent the low, medium, and high portions of the total possible range. Because of the relatively high amount of precipitation on Mt. Desert Island, the highest of these values (14 in./yr) is probably more realistic than the lowest (3 in./yr).

As described earlier, the typically fine-grained composition of the Presumpscot Formation inhibits recharge to the underlying bedrock units; however, few studies have been conducted that directly address to what degree the Presumpscot Formation inhibits recharge. Factors that affect this include the degree of saturation; thickness of the unit; the relative percentage of clay and silt; and whether it is fractured, and if so, how deep the fractures extend. One published value of recharge through the Presumpscot Formation was 0.5 in./year (Lyford and others, 1999). Gerber and Hebson (1996) reported recharge rates of 1.9 and 0.5 in./yr based on ground-water-flow modeling, and 0.24 in./yr using an age-dating technique. If the medium recharge rate of 9 in./yr is assumed, a recharge rate of 0.5 in./yr through the Presumpscot Formation would indicate a reduction of recharge by approximately 95 percent. Recharge could be inhibited by the Presumpscot Formation by between 80 to 99 percent, if the total range of 0.24 to 1.9 inches of recharge per year through the Presumpscot Formation is compared to the rate of 9 in./yr. The actual recharge rate through the Presumpscot Formation in Bar Harbor depends on the factors listed above. For this study, a value of 90 percent reduction was used in the calculations.

Estimates of recharge to each generalized town district and watershed area were calculated, adjusting for the amount of area covered by the Presumpscot Formation (see table 1). Areas within each geographic area that are not covered by the Presumpscot Formation (table 1) were applied the given recharge rate (low, medium, or high). Areas within each geographic area that were covered by the Presumpscot Formation were applied 10 percent of the given recharge rate, and the total amount of recharge was divided by the total number of acres in that area.

Recharge is shown in gal/acre/year in figure 5 and can be compared to the estimated total amount of ground water in storage at any one time, which is in gal/acre (table 3). Based on data from the literature and the recharge estimate derived from streamflow records, the medium to high values may be assumed to represent the estimated average recharge condition for the Bar Harbor area; the low estimates may represent recharge during drought years. In most of the town districts and watersheds, the medium to high estimates of recharge fall in the range of 100,000 to 400,000 gal/acre/yr. The low estimates of recharge for these areas fall in the range of 20,000 to 80,000 gal/acre/yr. Although in this analysis, recharge is varied only on the basis of the distribution of the Presumpscot Formation, recharge rates also vary depending on the local relief and the thickness and texture of other overlying sediments. High-relief areas with thin soil and sediment cover are more likely to have less recharge than areas of low relief and coarse-grained, thick soils.

A sensitivity analysis of the effect of varying the percentage reduction in recharge for the Presumpscot Formation is presented in appendix 3. A sensitivity analysis shows how changing the value of one variable in a calculation affects the outcome of that calculation, and is usually used to determine how sensitive the outcome is to changes in that one variable. Overall, bracketing the reduction in recharge by the Presumpscot Formation to values between 80 percent and 95 percent yielded a median of 5 percent change in the total recharge volumes, although areas where the Presumpscot Formation was extensive were much more sensitive to changes in this variable (in some areas with almost complete coverage by the formation, recharge changed by as much as 200 percent).

Comparison of Estimated Water Use and Estimated Recharge

The comparison of estimated water use to estimated recharge can help determine whether ground water is used faster than it is recharged to the system. One should not assume, however, that if water use is less than recharge, no change in the system will result (Bredehoeft, 2002). Whenever water is withdrawn from a ground-water system, the natural discharge of that system is reduced somewhere. Water does not flow to wells directly from recharge; water withdrawn from wells is derived from storage in the aquifer, a reduction in discharge, and from storage in other geologic units and/or water bodies. Understanding the actual effects of water pumpage on the aquifer requires modeling of the system (Bredehoeft, 2002).

Amounts of ground-water use in each geographic area (generalized town districts and watershed areas) shown in table 5 were estimated on the basis of the number of houses in the area in 2001 (see table 1). Each house in the given geographic area was assumed to use the average rate of 225 ga/household/yr. Commercial and industrial uses were not included in the analysis. A comparison of the estimated water use and estimated recharge (table 5) indicates that ground-water use in 2001 was less than the total estimated amount of water recharged to the bedrock aquifer in rural Bar Harbor, even for the low recharge estimates. Overall, the total estimated ground-water use was 2.5 percent of the total amount of estimated recharge (using the medium rate) for the Bar Harbor study area. Ground-water use in individual watersheds and generalized town districts ranged from 0 to 18 percent of the

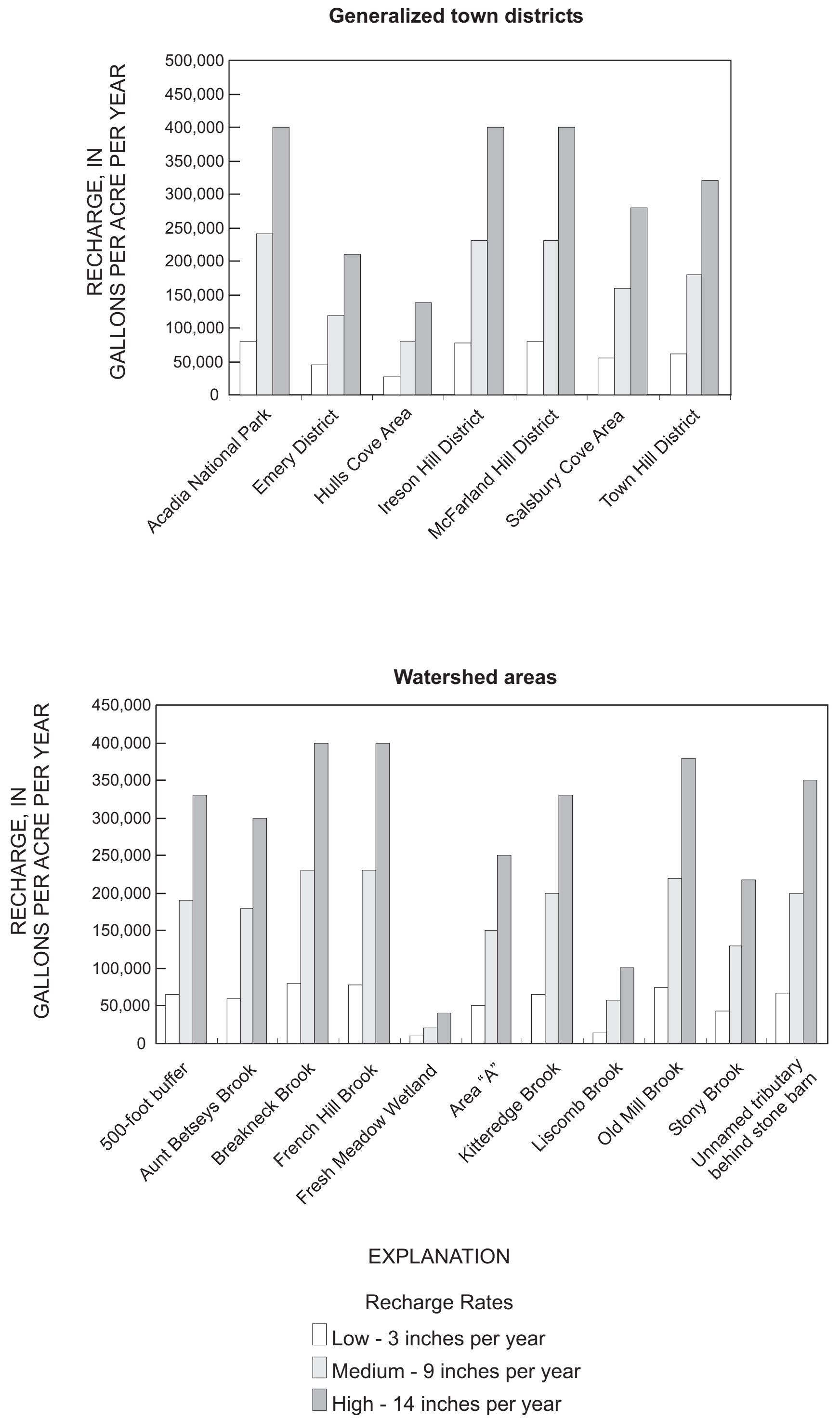


Figure 5. Recharge estimates for generalized town districts and watershed areas in the Bar Harbor study area.

medium amount of estimated recharge; only one exceeded 7 percent (table 5). Although the groundwater-use values are estimates, small changes in the numbers of houses per area or water-use rates would not affect the ground-water-use estimates enough to change them substantially with respect to the recharge.

Nitrogen Dilution in Ground Water

Mt. Desert Island communitites, including Bar Harbor, depend on having an adequate amount of high-quality water, which is needed for several uses. The most apparent is its use as a drinking-water supply for rural residents, as discussed above. Ground water on the Island also recharges lakes, reservoirs, wetlands, and streams with water from springs and diffuse seepage from the aquifer to those water bodies. This supports wildlife and other aspects of the natural ecosystem.

Because Island communities depend on water in the bedrock aquifer to dilute wastewater from individual household septic tanks, estimates were made in the Bar Harbor study area of how much dilution may be achieved in the aquifer. The concentration of a contaminant after dilution (presented here as the average concentration in recharge to the aquifer from rainfall

Table 5. Estimates of total recharge and ground-water use in 2001 for the generalized town districts and watershed areas
[in, inches; yr, year; gal, gallons]

Geographic Areas	Estimated total amount of recharge, in gal/year, for three recharge rates			Estimated ground water use, in gal/yr	Water use as a percentage of the medium recharge amount
	Low (3 in/yr)	Medium (9 in/yr)	High (14 in/yr)		
Generalized Town Districts					
Acadia National Park	180,000,000	532,000,000	909,000,000	0	0.0
Emery District	51,000,000	152,000,000	260,000,000	8,000,000	5.3
Hulls Cove Area	20,000,000	59,000,000	101,000,000	4,000,000	6.8
Ireson Hill District	14,000,000	41,000,000	71,000,000	2,000,000	4.9
McFarland Hill District	93,000,000	276,000,000	472,000,000	7,000,000	2.5
Salisbury Cove Area	65,000,000	192,000,000	329,000,000	9,000,000	4.7
Town Hill District	204,000,000	603,000,000	1,031,000,000	19,000,000	3.2
Wetlands/Ponds	10,000,000	30,000,000	50,000,000	0	0
Watershed Areas					
500-ft buffer	89,000,000	263,000,000	449,000,000	5,800,000	2.2
Aunt Betseys Brook	30,000,000	89,000,000	151,000,000	4,700,000	5.3
Breakneck Brook	72,000,000	212,000,000	363,000,000	411,000	0.2
French Hill Brook	25,000,000	75,000,000	127,000,000	2,900,000	3.9
Fresh Meadow Wetland	5,000,000	14,000,000	24,000,000	0	0.0
Area “A”	69,000,000	204,000,000	348,000,000	8,000,000	3.9
Kitteredge Brook	122,000,000	362,000,000	618,000,000	8,000,000	2.2
Liscomb Brook	2,000,000	5,000,000	8,000,000	900,000	18
Old Mill Brook	126,000,000	372,000,000	636,000,000	6,900,000	1.8
Stony Brook	84,000,000	248,000,000	424,000,000	8,000,000	3.2
Unnamed tributary behind stone barn	17,000,000	51,000,000	88,000,000	1,600,000	3.1

and from return flow to the aquifer from septic systems) can be compared to the concentrations that would cause degradation of either the ecosystem or human health. Dilution is defined as the concentration of the incoming septic effluent divided by the estimated average concentration in ground water. While the estimates presented here apply to the study area in Bar Harbor, the results are expected to approximate conditions in similar areas across the Island. Using other locale-specific information, the methodology could be applied to other areas in the region.

Nitrogen concentration guidelines for human and aquatic health

The U.S. Environmental Protection Agency (USEPA) has published water-quality criteria for nitrogen for the protection of aquatic life and human health. The total nitrogen criteria for the protection of aquatic life in USEPA Ecoregion VIII (which includes Maine) is 0.38 mg/L of total nitrogen for rivers and streams and 0.24 mg/L total nitrogen for lakes and reservoirs (U. S. Environmental Protection Agency, 2001). Increases in nitrogen are generally accompanied by an increase in nuisance aquatic growth and a decline in the original organisms inhabiting the area. The threshold value for the conversion of rivers and streams from oligotrophic to mesotrophic status is 0.7 mg/L (U.S. Environmental Protection Agency, 2001). Thresholds and criteria for wetlands have not yet been published for Ecoregion VIII. The human-health limit for nitrate-nitrogen (there is no established limit for total nitrogen) in drinking water is 10 mg/L (U.S. Environmental Protection Agency, 1999).

Calculation of average nitrogen concentrations and dilution

The equation of Hantzsche and Finnemore (1992), as described above, was used to estimate average nitrogen (as nitrate) concentrations in the bedrock aquifer in the Bar Harbor study area. The equation is used to calculate the nitrate-nitrogen concentration in net recharge, which, as newly recharged ground water replaces ground water previously in the aquifer, then becomes the average concentration in the aquifer. A major point in interpreting the following results is that the nitrate-nitrogen values represent average concentrations for the entire aquifer, and assume that the water in the aquifer is thoroughly mixed. In a fractured bedrock aquifer, however, water is not expected to mix quickly between fractures, and concentrations would be expected to vary widely around the "average." Most of the fractures would be expected to have low concentrations, and the remainder would have much higher concentrations. The "average" concentration would fall somewhere in the middle.

On the basis of a study by Harrison and others (2000), who analyzed septic discharge from systems using the same construction and similar soil types as have been used in Bar Harbor since 1980, a value of 47 mg/L of total nitrogen in septic-system discharge (n_w) was chosen to use in the analysis; they calculated the mean concentration of total nitrogen from 369 samples to be 47 mg/L. Unlike most other studies, which measured the total nitrogen concentration of septic waste in the septic tank, Harrison and others (2000) investigated the concentration below the infiltration beds, which is the concentration needed for the analysis. The fraction of nitrate-nitrogen in the septic effluent lost to denitrification in the aquifer (d) was set at 5 percent on the basis of conversations with soil scientists working on Mt. Desert Island; this is a reasonable estimate to use because the soils below a septic system contain little organic carbon (I. Fernandez, University of Maine, oral commun., 2002). Changing the denitrification rate in a sensitivity analysis of the calculations did not affect the estimated concentration of nitrate-nitrogen in ground water very much (see appendix 3). However, given that a septic plume would provide additional organic carbon, the actual denitrification rate may vary considerably. The values of ambient nitrate-nitrogen concentrations in recharge (n_b) are based on an earlier study (Nielsen, 2002, and unpublished data, U.S. Geological Survey, Augusta, Maine), which measured the concentrations of nitrate in streams that drained undeveloped watersheds across Mt. Desert Island. The concentrations from five streams during low-flow conditions, which represent ground-water discharge, averaged 0.03 mg/L of nitrate-nitrogen, which is the value used here for ambient ground water recharge.

The estimated nitrate-nitrogen concentrations in net recharge, and thus the average estimated concentrations in ground water, for watershed areas and generalized town districts are higher for low recharge rates compared to those based on the high recharge rates (table 6). Higher concentrations result in lower dilution factors. As described earlier, dilution is calculated as the total nitrogen concentration of the input septic effluent divided by the estimated nitrate-nitrogen concentration in net recharge (and the average concentration in ground water). A dilution factor of 10 would represent a ground-water nitrate-N concentration one-tenth the total-nitrogen concentration of the input septic-waste. Because no houses are located in the Fresh Meadow Wetland area or in Acadia National Park, the nitrogen concentrations in ground water are assumed to be the same as the ambient concentrations in ground water (0.03 mg/L); thus no dilution factors were calculated. (These calculations do not consider the movement of ground water beyond the unit area of the analysis, and the quality of ground-water in discharge zones for the bedrock units, such as wetlands and streams, may be expected to have water-quality properties that reflect the land uses where the ground water was recharged.)

In populated watersheds (excluding Breakneck Brook, over 95 percent of which is in Acadia National Park, and the Fresh Meadow Wetland, which cannot be built on) the estimated average nitrogen concentration in ground water ranged from 0.3 mg/L (Stony Brook watershed and the 500-ft buffer area, high recharge estimate) to 11 mg/L (in Liscomb Brook watershed, low recharge estimate). Dilution factors ranged from 4 to 151. In the generalized town districts, estimated average nitrogen concentrations ranged from 0.4 mg/L in the Hulls Cove area (high recharge estimate) to 5.4 mg/L in the Ireson Hill District (low recharge estimate). These results are quite sensitive to the estimated amount of recharge. Development of a better understanding of recharge dynamics would be helpful in reducing the range in estimated values.

The estimated average nitrate-nitrogen concentrations in ground water for the 2001 housing density generally do not exceed the 10 mg/L human health limit for nitrate-nitrogen. The estimated concentration in the Liscomb Brook watershed does exceed this limit for the low recharge estimate, because of its relatively high number of houses per unit area and in areas not covered by the Presumpscot Formation.

The aquatic limits established by the USEPA for the protection of streams and lakes, however, would be exceeded in most of the recharge scenarios when the

Table 6. Estimated average nitrate-nitrogen concentrations in the bedrock aquifer and dilution factors for 2001 housing density, Bar Harbor study area

[in/yr, inches per year; mg/L, milligrams per liter; intermit., intermittent; ft, foot]

Geographic area	High recharge (14 in/yr)		Medium recharge (9 in/yr)		Low recharge (3 in/yr)	
	Average concentration (mg/L)	Dilution factor	Average concentration (mg/L)	Dilution factor	Average concentration (mg/L)	Dilution factor
WATERSHED AREAS						
500-ft buffer	0.3	151	0.5	94	1.4	33
Aunt Betseys Brook	1.1	44	1.7	27	5.2	9
Breakneck Brook	.1	816	.1	619	0.2	280
French Hill Brook	.9	50	1.6	30	4.6	10
Fresh Meadow Wetland	.03	--	.03	--	.03	--
Area "A"	.9	54	1.4	33	4.2	11
Kitteredge Brook	.5	91	.8	56	2.5	19
Liscomb Brook	2.1	22	3.5	13	11	4
Old Mill Brook	.4	132	.6	82	1.7	28
Stony Brook	.3	150	.5	94	1.4	33
Unnamed tributary behind stone barn	.8	62	1.3	38	3.7	13
GENERALIZED TOWN DISTRICTS						
Acadia National Park	.03	--	.03	--	.03	--
Emery District	.6	81	.9	50	2.8	17
Hulls Cove Area	.4	133	.6	83	1.6	29
Ireson Hill District	1.1	42	1.8	26	5.4	9
McFarland Hill District	.6	74	1.0	45	3.1	15

ground water in the bedrock units discharged to surface-water bodies. Existing data on the concentration of total nitrogen in Stony Brook, Old Mill Brook, Aunt Betsey's Brook, and French Hill Brook (Nielsen, 2002) show that the total nitrogen concentration aquatic limit currently is exceeded in these streams for at least part of the year. Although the source of total nitrogen in streams is not only from discharging ground water, ground water containing elevated concentrations of nitrogen certainly contributes to the concentrations in streams. Eastern Bay, Thomas Bay, and Somes Sound (figs. 1 and 2) also are likely discharge points for ground water from the Bar Harbor study area, and water-quality effects of elevated nitrogen in the ground water could occur in those coastal discharge zones.

To understand the sensitivity of these results to some of the other variables, sensitivity analyses were conducted for two watersheds in the study area--Aunt Betsey's Brook and Old Mill Brook. These were chosen to represent areas with higher and lower than average 2001 development densities (table 1). The changes in estimated concentrations for a range in septic-waste nitrogen concentrations (25, 47, and 70 mg/L) are shown in table 7. The 25 mg/L and 70 mg/L values were chosen to represent the high and low range of values for septic-waste nitrogen concentrations found in the literature (appendix 1). (Table 6 presents results using the 47-mg/L concentration only). Overall, the results are more sensitive to the estimated ground-water recharge values than they are to the septic-waste nitrogen concentrations. Additional sensitivity analyses are presented in appendix 3.

STUDY LIMITATIONS AND SUGGESTIONS FOR IMPROVING ESTIMATES

Because this preliminary study of ground-water resources on Mt. Desert Island and the pilot area in Bar Harbor relied primarily on existing data, many simplifying assumptions were made regarding the calculations. To reduce the uncertainty inherent in those assumptions, additional data could be collected as described below.

The water-use estimates for the Bar Harbor study area involved several assumptions. The data from the Bar Harbor Water Company on which the estimates are based do not differentiate between year-round residential connections and seasonal connections. Better estimates of residential use for year-round residents could be obtained if the seasonal connections were differentiated from the permanent resident connections. The

Table 7. Sensitivity of average nitrate-nitrogen concentrations in net recharge and dilution factors for three recharge scenarios using three septic-waste concentrations for Aunt Betsey's Brook and Old Mill Brook, Bar Harbor study area

[in/yr, inches per year; mg/L, milligrams per liter; N, nitrogen; values in bold are the numbers discussed in the text]

unit areas and septic waste concentrations	High recharge (14 in/yr)		Medium recharge (9 in/yr)		Low recharge (3 in/yr)	
	Average nitrate-N concentration in recharge, mg/L	Dilution factor	Average nitrate-N concentration in recharge, mg/L	Dilution factor	Average nitrate-N concentration in recharge, mg/L	Dilution factor
Waste N concentration = 25 mg/L						
Aunt Betsey's Brook	0.6	43	0.9	27	2.8	9
Old Mill Brook	.2	123	.3	78	0.9	28
Waste N concentration = 47 mg/L (numbers discussed in text, and in table 6)						
Aunt Betsey's Brook	**1.1**	**44**	**1.7**	**27**	**5.2**	**9**
Old Mill Brook	**.4**	**132**	**.6**	**82**	**1.7**	**28**
Waste N concentration = 70 mg/L						
Aunt Betsey's Brook	1.6	45	2.6	27	7.7	9
Old Mill Brook	.5	135	.8	83	2.5	28

number of persons per household also is assumed to be the same in the population served by the public water supply as in the rural study area. Data on the actual number of persons per household in the water-supply database and in the rural areas could be used to improve the estimates. Additionally, it was assumed that rural households use water at the same rate, in general, as the households served by the water utility. A study of yearly water use by rural households could verify that assumption.

Because the estimates of water contained in the bedrock units across the island have a large range of uncertainty, the results are presented as ranges of values. The range of values in porosities, which covers five orders of magnitude, could be reduced substantially by collecting data on porosities for all the rock types across the island. This type of site-specific study could enable the calculation of realistic estimates of water in storage, and show the actual variation in porosity between the various bedrock types. Such a study could involve collection of data at a large number of sites to accurately characterize the natural variability of porosity in each rock type on the island. The storage estimates involved calculating the volumes of water for the top 300 and 600 ft of the saturated zone. A more detailed survey of well depths on the island could result in a more realistic estimate of the depth of water actually available for domestic use.

In this study, each town district or watershed area was assigned a percentage of coverage by the Presumpscot Formation. Detailed surficial geologic mapping of the Presumpscot Formation in the Bar Harbor study area could assist in more accurate delineation of areas where recharge and septic-system discharge might not penetrate to the bedrock aquifer.

Estimates of nutrient concentration in septic-system effluent were derived from studies found in the literature. Nitrogen concentration data for local effluent could improve the reliability of the septic-nitrogen dilution study, because actual nitrogen contributions to the ground-water system would be known for this area. Such a study could involve instrumenting several new septic systems, using the same construction techniques that have been used historically in Bar Harbor, so that the effluent leaving the leach beds could be collected and analyzed.

The variation in recharge values used in the analysis was 11 inches, and the estimate of nitrate-nitrogen in the bedrock ground water was most sensitive to this variable. Recharge varies considerably from year-to-year, and developing an understanding of the actual recharge and variation in recharge for the study area could decrease the uncertainty in the septic-nitrogen dilution calculations. There are a number of techniques available to study recharge. Natural variation in water levels in wells has been proposed as a method to evaluate recharge (Richard Healey, U. S. Geological Survey, written commun., 2002), but the specific yield of the aquifer must be known or estimated for this to be applied accurately. To capture the variability in recharge, wells could be instrumented for several years with continuous water-level recorders and precipitation gages. A second technique involves the analysis of streamflow hydrographs, as described briefly in the section on recharge. To understand the spatial variation in recharge, several streams could be instrumented with continuous-record streamflow-gaging stations that could be run for several years so that the temporal variability in recharge could be characterized. Ground-water-flow models could also be used to estimate recharge.

Finally, this study estimated an aquifer-averaged concentration of nitrate-nitrogen in the bedrock aquifer in rural Bar Harbor for recent (2001) housing density. A more scientific study of current water-quality conditions could involve concurrent sampling of a number of randomly chosen wells in the study area. To determine sources of nitrogen in the water, the samples could be analyzed for “septic markers,” which are chemicals that are not naturally occurring, and that would indicate a septic source. Examples of these include boron, caffeine, and pharmaceutical compounds.

SUMMARY

Water resources in many island communities are affected by rapidly increasing development in those communities. In 1998, the U.S. Geological Survey (USGS) in cooperation with the National Park Service, began work on a regional, interdisciplinary study of water resources and nutrient enrichment effects on ecosystems on Mt. Desert Island, Maine. As part of this effort, in 2002, the USGS, in cooperation with the Town of Bar Harbor, Maine and the National Park Service, conducted a study to assess the quantity of water in the fractured bedrock units on Mt. Desert Island and estimate water use, recharge, and septic-nitrogen dilution in the fractured bedrock units in several watersheds in rural Bar Harbor. The study had three main objectives: (1) to estimate by using existing information, the static volume of water available in the bedrock aquifer on Mt. Desert Island; (2) to estimate water use and ground-water recharge rates in rural parts of Bar Harbor, and (3) to estimate how wastewater nitrogen loads from septic systems in residential developments in the Bar Harbor study area (and possibly other similar areas) may affect ground-water resources that are used for residential drinking water and that recharge wetlands on the island.

Water resources on the island include several large lakes that serve as public drinking-water supplies for the municipalities and various National Park Service facilities; a fractured bedrock aquifer; many small streams with drainage areas of 1 to 15 mi^2; and surficial sediments that are thick enough in places to provide water to dug domestic wells. The bedrock aquifer on the island is composed of granite and other intrusive igneous rocks; a schist (the Ellsworth Schist); a weakly deformed sedimentary rock (the Bar Harbor Formation); a series of volcanic tuffs and other felsic volcanic rocks (the Cranberry Island Volcanics); and a “shatter zone” of contact metamorphism and shattered country rocks surrounding the Cadillac Mountain Granite. The Presumpscot Formation, an unconsolidated, discontinuous silt and clay unit of variable thickness overlying the bedrock, acts as a barrier to water flow, inhibiting recharge to the bedrock units and the movement of septic-system discharge.

Ranges of porosity values from the literature were applied to the area covered by each rock type on the island to estimate the amount of water in storage. The estimated volume of water contained in fractures in the various rock types in the bedrock aquifer on Mt. Desert Island ranges over several orders of magnitude. In the upper 300 ft of saturated thickness in the bedrock, and using a low estimate of porosity, the estimated amount of water in storage ranges from 2,000 gal/acre for granites and other intrusive igneous rocks to almost 3 Mgal/acre for the tuffs and other rocks in the Cranberry Island Volcanics. Rocks in the Ellsworth Schist and shatter zone might contain 100,000 gal/acre and 200,000 gal/acre, respectively. The Bar Harbor Formation may have almost 1 million gal/acre in storage. By using a medium porosity range for the rock units, the granites might contain almost 50,000 gal/acre; the shatter zone, 500,000 gal/acre; the schist, 1.5 million gal/acre; and the Bar Harbor Formation and Cranberry Island Volcanics might contain as much as 9.8 million gal/acre. Because they were not considered representative of Mt. Desert Island, high porosity estimates were not used to calculate water in storage.

Although the estimated static amount of water in storage can be used to evaluate the water-bearing capacity of different rock types, it should not be assumed that wells drilled in rocks with lower porosities will always yield less water than wells drilled in higher-porosity rock types. The amount of water that a well yields is related to several factors, the most important of which is the amount of recharge the fractures intersecting the well receive, and the width of those fractures. Recharge to fractures can come from infiltration of precipitation into the aquifer, from nearby saturated surficial sediments, and from water bodies such as lakes and streams. If a well yield is high, the fractures it intersects may be wider than wells with lower yield, and the fractures may be tapping into a water body or surficial sediments containing large amounts of water, even though the porosity of the rock body may be relatively low. The amount of water in the overlying till and other sediments is also very important in determining how much water is available to a well. Wells in areas with thick, fully saturated sediments above the bedrock can receive recharge from them, in contrast to wells in areas with thin soil and sedment cover.

In addition to the estimation of the quantity of water in the bedrock aquifer, further analysis was conducted of watersheds around the Fresh Meadow Wetland and Northeast Creek, and the adjacent Kitteredge Brook and Breakneck Brook watersheds in the Town of Bar Harbor. Recharge to the bedrock units in these areas of rural Bar Harbor was bracketed with low, medium, and high estimates of 3, 9, and 14 in/year, respectively. Based on a literature review, it was assumed that the Presumpscot Formation reduced recharge by 90 percent. Estimated recharge to the watershed areas and generalized town districts ranged from 100,000 to 400,000 gal/acre/yr assuming the medium to high recharge rates. The low recharge rates yielded estimates of recharge from 20,000 to 80,000 gal/acre/yr.

Water-use data from 1998-2000 for the municipal water supply in the town of Bar Harbor indicate that residential connections to the Town water system used an average of 227 gal/connection/day, which was rounded to 225 gal/household/day. Estimated water use in 2001 was less than the total amount of estimated recharge to the bedrock aquifer in rural Bar Harbor, even for the low recharge estimates. However, one should not assume that even if water use is less than recharge, no change in the system will result. Whenever water is withdrawn from a ground water system, the natural discharge of that system will be somewhere reduced.

By using a previously published method, average nitrogen (as nitrate) concentrations in the bedrock aquifer in the Bar Harbor study area were estimated. An important point in interpreting the results is that the values represent concentrations averaged over the entire aquifer, and it is assumed that the water in the aquifer is thoroughly mixed. In a fractured bedrock aquifer, however, water does not mix quickly between fractures, and concentrations would be expected to vary widely around the "average". In populated watersheds (excluding Breakneck Brook's watershed, which is more than 95 percent in Acadia National Park, and the Fresh Meadow Wetland, which cannot be built on), the estimated average nitrate-nitrogen concentrations in ground water ranged from 0.3 mg/L to 11 mg/L. Dilution factors ranged from 4 to 151. In the generalized town districts, estimated average nitrate-nitrogen concentrations ranged from 0.4 mg/L in the Hulls Cove area (high recharge estimate) to 5.4 mg/L in the Ireson Hill District (low recharge estimate). The estimated average nitrate-nitrogen concentrations in ground water for the 2001 housing density do not generally exceed the 10 mg/L limit human health limit, although some areas might have concentrations exceeding this limit because of limited mixing in this aquifer. These results are quite sensitive to the assumed amount of recharge. Development of a better understanding of recharge dynamics would be helpful in reducing the range in estimated values.

Based on the estimates, the aquatic limits for total nitrogen established by the USEPA (2001) for the protection of high-quality streams and lakes, which is 0.38 mg/L, would be exceeded in most of the recharge scenarios when the ground water in the bedrock aquifer discharged to surface-water bodies. The total nitrogen aquatic limit was exceeded in Stony Brook, Old Mill Brook, Aunt Betsey's Brook, and French Hill Brook at least part of the year during 1999 to 2000 (Nielsen, 2002).

Because this study relied primarily on existing data, many simplifying assumptions were made regarding the estimates. Additional data and studies could be conducted in the following areas to increase the certainty of the estimates presented here: water use in rural Bar Harbor; porosities in the bedrock formations; more detailed mapping of surficial geology; concentrations of nitrogen in local septic effluent; and better data to calculate recharge. In addition, water-quality samples from bedrock wells in Bar Harbor could be used to evaluate the accuracy of the estimates of septic nutrient dilution.

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APPENDIX 1:

LITERATURE REVIEW

Table 1-A. Literature survey of porosity and specific yield of various types of fractured bedrock

[--, no data; <, less than; %, percent]

Source	Rock type	Porosity (percent)	Specific yield (dimensionless)	Notes
FRACTURED CRYSTALLINE BEDROCK				
Lane and others (1995)	crystalline bedrock at Mirror Lake, N.H.	1-10	--	Determined by square resistivity array; secondary porosity due to fractures. They estimate it might be high because it ignores foliation.
Lane and others (1995)	crystalline bedrock at Mirror Lake. N.H.	0.1	--	Fracture porosity determined by mapping fractures (one well)
Daniel and others (1989)	schist/gneiss/granite	--	.0002	Calculated from specific capacity tests
Trainer (1988)	crystalline rocks	.05 to .0005	--	Includes fractures; lower values at greater depths
Randall and others (1988)	nonporous fractured bedrock	--	.0002	Compiled from many sources.
Snow (1968)	many: all hard fractured rocks	.05 - .0005	--	Analysis based on dam grouting sites
Davis and others (1959)	plutonic and other “hard rocks”	--	0	Many rock types listed as “0”, except volcanic, which had 3 percent specific yield
INTRUSIVE IGNEOUS ROCKS				
Drozhko and others (1996)	“highly fractured porphyrite”; igneous rock with phenocrysts	1.0 - 0.2	--	Using water-balance and nitrate-ion methods
Taylor and Flemming (1988)	gabbro	0.2-0.8	--	Using resistivity surveys and field mapping
Reynolds and others (1988)	diabase	.01 - .04	--	
Wolff (1982)	quartz diorite and granites	.2-.003, .002, 5-.004	--	Compilation of many sources. Numbers in this table represent what is called “effective flow porosity” (appears to include fractures)
Gustafsson and Klockar (1981)	gneissic granite and granodiorite (Sweden)	.08-.09	--	“bulk kinematic porosity.” Dye-tracer methods. Dilution and dispertion data also
Norton and Knapp (1977)	granites	.2 - .005	--	“flow porosities”

Table 1-A. Literature survey of porosity and specific yield of various types of fractured bedrock—Continued

[--, no data; <, less than; %, percent]

Source	Rock type	Porosity (percent)	Specific yield (dimensionless)	Notes
Davis and others (1966).	plutonic igneous	1-3	--	Values for unweathered bulk rock (not interconnected). Text states that fractures add only a small increase in the overall porosity
De Marsily (1986)	unaltered granite	0.02 - 1.8	--	Total porosity; kinematic porosity less
SCHISTS				
Gburek and Folmar (1999)	"layered fractured rock"	--	0.01	Recharge study in east-central Pennsylvania
Wolff (1982)	schists, weathered	4.4-58.4, 38-46 means[1]	--	All well-weathered schists
Wolff (1982)	schists	0.62 - 3.12	--	For unweathered schists; not including fractures (many references)
Morris and Johnson, 1967	schist	--	0.22 - 0.33	Cited in Anderson and Woessner (1992)
De Marsily, 1986	shales, slates, mica schists	0.5- 7.8	--	Total porisity; kinematic porosity less
SEDIMENTARY ROCK TYPES				
Melvin and others, 1994	fractured sandstone in Conn.	1.1 - 2.7	--	Porosities for fracture porosity only; does not include bulk porosity
Wolff (1982)	siltstones	16.7 -35 (means)	--	Total range of 1.1 to 41
Domenico and Schwartz (1990)	siltstone	--	0.12	
TUFFS				
LeCain and others (1998)	welded tuffs	3 - 5	--	In-situ measurements at several points; Yucca Mountain, Nevada
Domenico and Schwartz (1990)	tuff	--	0.21	
Istok and others (1992)	tuffs, mostly nonwelded	< 10 to 40	--	Hundreds of core samples at Yucca Mountain, Nevada
Keller (1960)	tuff, welded	14.1	--	
De Marsily (1986)	tuff	30-40	--	Total porosity
Wolff (1982)	tuff	33 (mean)	--	From 14 separate references

Table 1-A. Literature survey of porosity and specific yield of various types of fractured bedrock—Continued

[--, no data; <, less than; %, percent]

Source	Rock type	Porosity (percent)	Specific yield (dimensionless)	Notes
OTHER				
Wolff (1982)	shale	1 - 27.2	--	Many references, mean appears to be around 10; not including fractures
Ait-ssi and others (1989)	Archean gneiss	.06	--	Overall value from stochastic modelling; article in French.
Reynolds and others (1988)	fractured pelite	.06	--	Range of 0.018 - 0.099%

[1] "Means" here refers to the range of mean values cited in several separate studies.

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Table 1B. Literature survey of total nitrogen concentrations in septic-system discharge

[mg/L, milligrams per liter; N, nitrogen]

Source	Total N	Notes
Whelan and Titamnis (1982)	100 mg/L	From Australia. 5 households sampled for 15 days.
Nizeyimana and others (1996)	73 mg/L	Their average concentration from the literature
Bunnell and others (1999)	53-63 mg/L	Compared different septic designs, 19 systems sampled
Townshend (1997)	48 mg/L Ammonia-N	12 samples from 1 house
Sham and others (1995)	29 mg/L	Assumption of concentration entering water table; basis for assumption not well described
Harrison and others (2000)	47 mg/L ***below infiltration beds, average.***	Tested soil-only systems, 369 samples at three sites.
Tchobanoglous and Burton (1991)	20 mg/L weak 40 mg/L medium 85 mg/L strong	First edition was in 1972, these may be old numbers
Fetter (1999)	52 mg/L	Mean from 6 septic tanks

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Harrison, R.B., Turner, N.S., Hoyle, J.A., Krejsl, J., Tone, D.D., Henry, C.L, Isaksen, P.J., and Xue, D., 2000, Treatment of septic effluent for fecal coliform and nitrogen in coarse-textured soils--Use of soil-only and sand filter systems: Water, Air, and Soil Pollution, v. 124, p. 205-215.

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Townshend, A.R., 1997, Nitrogen removal in septic tank effluent using separate nitrification-denitrification biotextile filters: The American Society for Testing Materials, ASTM Special Technical Publication 1324, p. 113-128.

Whelan, B.R., and Titamnis, Z.V., 1982, Daily chemical variability of domestic septic tank effluent: Water, Air, and Soil Pollution, v. 17, no. 2, p. 131-139.

APPENDIX 2:

SUPPORTING DOCUMENTATION FOR GEOPHYSICAL SURVEY

Letter from John Lane

United States Department of the Interior

U. S. GEOLOGICAL SURVEY

WRD Office of Ground Water
Branch of Geophysics
11 Sherman Place Unit 5015
Storrs Mansfield, CT 06269
phone 860-487-7402/fax 860-487-8802

June 24, 2002

Martha Nielsen
USGS-Maine District
26 Ganneston Drive
Augusta, ME 04330

Dear Martha,

This letter presents the results of surface two-dimensional resistivity surveys conducted by the OGW Branch of Geophysics from June 4-6, 2002, on Mt. Desert Island, Maine.

The purpose of the geophysical surveys was to determine secondary porosity of bedrock in the region, specifically that of the Ellsworth Schist and Shatter Zone units. The survey method was square-array direct-current resistivity, azimuthally rotated about a common center point. Theoretical investigations have shown that similarly-oriented, steeply-dipping fractures within a homogeneous rock mass and overburden lead to a predictable pattern of resistivity values (Habberjam, 1975). The maximum resistivity values are oriented perpendicular to the strike of the fracture sets, allowing for the determination of fracture strike from simple graphical analyses.

Determination of secondary porosity is possible by treating fracture sets as resistors in a circuit with their resistance proportional to the volume of water in the fracture, an indicator of the secondary porosity, and the specific conductance of that water. A detailed description may be found in Taylor and Fleming (1988) and Lane and others (1995).

Surveys were made at two different sites at each of the Shatter Zone and Ellsworth Schist areas. Results from both surveys in the Shatter Zone area each show a fracture set that strikes at 60 degrees. Results from the two surveys in the Ellsworth Schist area are very different – one shows up to three separate fracture sets with a primary fracture strike of 30 degrees while the other shows one fracture set with a strike of 105 degrees. The two surveys in the Ellsworth Schist area were conducted about 1 mile apart from each other. Possible causes for the differences may be changes in structural features between the two field sites, or overburden effects.

Resistivity measurements from the three largest squares for each of the four surveys estimated secondary porosity values ranging from 0.0001 to 0.01. The three largest squares were used to ensure that values are representative of the bedrock and to minimize the effects of the overburden. The range of two orders of magnitude in the secondary porosity is reasonable given the large range of specific conductance values used in the calculations and the fact that two different rock types were considered.

For a more complete review of the results of the surveys, please refer to the attached graphs and tables. If there are any questions, please contact Mike Lambert at 860-487-7402 x21 or myself at x13.

Thank you for the opportunity to assist you on this project. We look forward to working with you in the future.

Sincerely yours,

John W. Lane, Jr.
Chief, OGW Branch of Geophysics

Habberjam, G.M., 1975, Apparent resistivity, anisotropy and strike measurements: Geophysical Prospecting, v. 23, p. 211-247.

Lane, J.W., Jr., Haeni, F.P., and Watson, W.M., 1995, Use of a square-array direct-current resistivity method to detect fractures in crystalline bedrock in New Hampshire: Ground Water, v. 33, no. 3, p. 476-485.

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METHODS USED IN AZIMUTHAL SQUARE-ARRAY DIRECT-CURRENT RESISTIVITY SURVEYS IN BAR HARBOR, MAINE

Geophysical surveys take advantage of physical changes in rock properties, such as variations in electrical resistivity caused by fluid-filled fractures to help identify fractures in bedrock (Zohdy and others, 1974) . Surface-resistivity surveys were used in this study to characterize fractured bedrock. In crystalline bedrock of New England, variations in electrical resistivity are likely related to changes in lithology, water chemistry, and increases density and size of the fluid-filled fracture zones. Resistivity surveys measure the bulk electrical resistivity of the subsurface. Direct current is induced into the ground between two current electrodes and the voltage is measured across two potential electrodes. A resistance value is obtained by dividing the measured voltage by the induced current. Various survey electrode-array configurations and data-processing techniques can be used interpret geologic characteristics.

In the Bar Harbor area, surveys were conducted at four sites (figure 2-a) for the primary purpose of determining secondary porosity in bedrock. On the basis of geologic mapping (Gilman and others, 1988), two of the sites were located in the "shatter zone", and two sites were located in the Ellsworth Schist. The surveys were conducted in June, 2002.

Azimuthal square-array dc-resistivity surveys measure the subsurface resistivity in various orientations and allow for the determination of the strike of a conductive anomaly with depth (Habberjam and Watkins, 1967). To determine the strike of near-vertical conductive anomalies in the bedrock, a horizontal-layered overburden must be assumed. This technique cannot correct for bedrock or surface topography; therefore, the surveys (arrays) were collected where the topography was flat. The topography of the bedrock surface was not determined at any of the survey sites.

Electrodes were set in square arrays, and direct current was produced in the ground by two current electrodes on one side of the square. A potential difference was measured at two electrodes on the other side. The length of the side of the square is termed the A-spacing. From these four electrodes, apparent resistivity is calculated from electrode spacing and a geometric factor. Reciprocal measurements 180 degrees from each other should have a very similar result and were used as an error check in these surveys.

During the survey, a resistance value is obtained by dividing the measured voltage by the induced current. The apparent resistivity is calculated from the resistance value and geometric factors that are different for each array type (arrangement of current and potential electrodes in relation to each other) and takes into account the electrode spacing. The apparent resistivity measured is an average resistivity of all materials surveyed to the depth of the investigation.

Resistivity represents an average resistance of subsurface materials between the electrodes. The mid-point of resistivity can be projected to a specified depth and compass direction on the basis of the side length of the square, defined by A-spacing and the array orientation. The effective survey depth is roughly equal to the A-spacing. For each survey, apparent resistivity data were collected with a series of array "squares" rotated around the center at 15° intervals, and with a number of different A-spacings (table 2-a). Fracture strike was determined graphically (Lane and others, 1995) by plotting the apparent resistivity with radial orientation on a rose diagram (figure 2-b). Strike directions of conductive fracture zones and secondary porosity were determined as described by Lane and others (1995), and are presented in this appendix.. The estimation of secondary porosity requires knowledge of the specific conductance of the ground water. A range of specific conductance values characteristic of the region were used in the secondary porosity calculations to test its sensitivity to local variations. Primary conductive strikes are orthogonal to the resistivity maximum. Secondary conductive strikes are orthogonal to the second largest resistivity measurements.

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Gilman, R.A., Chapman, C.A., Lowell, T.V., and Borns, H.W., Jr., 1988, The geology of Mount Desert Island, a visitor's guide to the geology of Acadia National Park: Maine Department of Conservation, Geological Survey Bulletin 38, 50 p., 2 pl.

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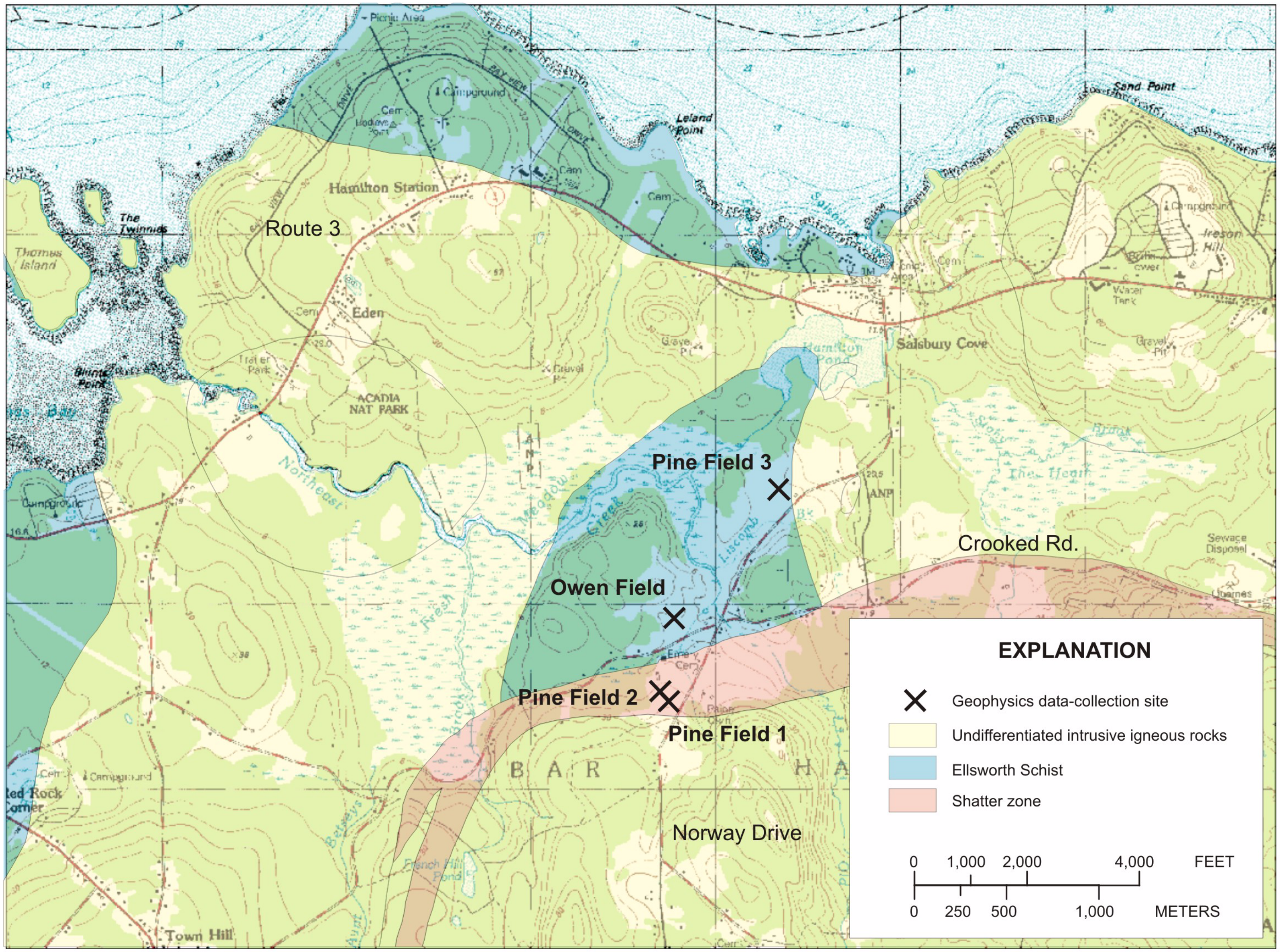
Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geological Survey Water-Resources Investigations, book 2, chap. D1, 86 p.



Base from U.S. Geological Survey
Digital line graph Bar Harbor 1:100,000,
Salsbury Cove, Maine quadrangles 1:24,000

Geologic mapping from Gilman and Others, 1988,
scale 1:50,000

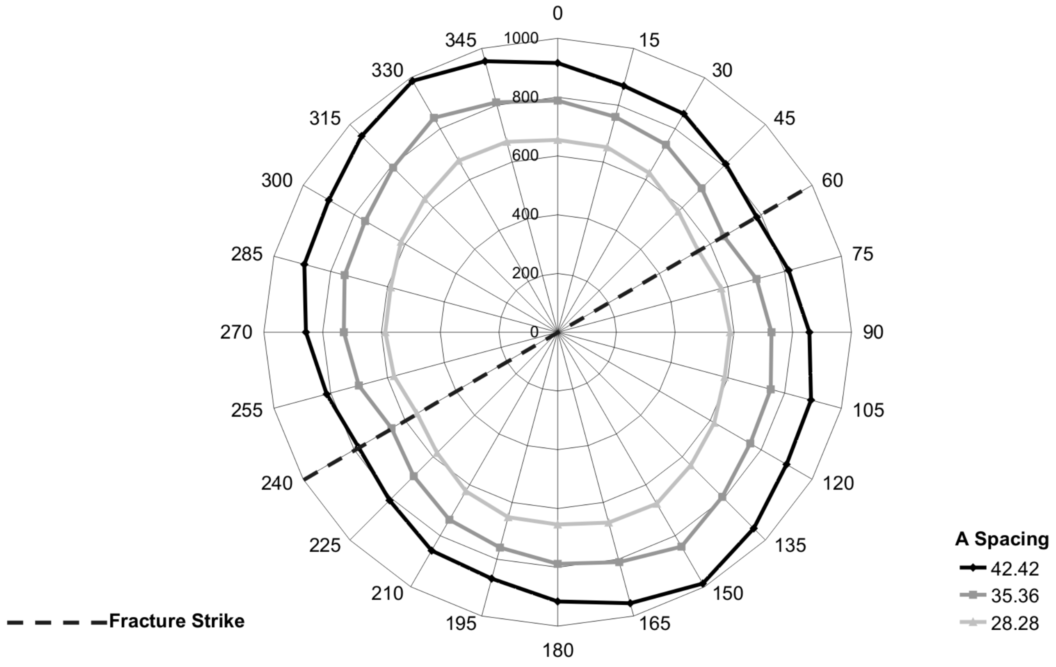
Figure 2-a. Locations of square-array dc-resistivity geophysical surveys in Bar Harbor, Maine. Pine Field #1 and #2 are in the shatter zone. Pine Field #3 and the Owen Field site are located in the Ellsworth Schist.

Table 2A. Apparent Resistivity Data for sites in Bar Harbor, Maine

	Pine Field #1			Pine Field #2		
	Apparent resistivity (Ohm-m) for the following A-spacings:			Apparent resistivity (Ohm-m) for the following A-spacings:		
Azimuth	42.42 m	35.36 m	28.28 m	42.42 m	35.36 m	28.28 m
0	916.24	788.32	654.39	1430	1214.1	998.44
15	867.77	758.06	651.39	1300.7	1095.5	905.97
30	858.08	736.60	625.11	1142.8	1019	864.74
45	809.34	693.18	581.03	1022.6	965.38	815.22
60	782.86	653.36	552.91	1041.5	949.82	844.88
75	813.98	700.65	576.24	1149.8	1053.1	910.95
90	856.71	727.84	586.83	1219.7	1108.4	955.74
105	892.98	750.44	588.31	1332.7	1207.9	1020.4
120	899.31	756.66	615.62	1498.9	1293.1	1056.1
135	944.18	792.30	640.95	1739.8	1413.5	1155.9
150	987.50	842.10	674.08	1739.1	1459.3	1155.4
165	954.83	810.01	670.92	1578.7	1349.2	1075.1
180	916.24	788.32	654.39	1430	1214.1	998.44
195	867.77	758.06	651.39	1300.7	1095.5	905.97
210	858.08	736.60	625.11	1142.8	1019	864.74
225	809.34	693.18	581.03	1022.6	965.38	815.22
240	782.86	653.36	552.91	1041.5	949.82	844.88
255	813.98	700.65	576.24	1149.8	1053.1	910.95
270	856.71	727.84	586.83	1219.7	1108.4	955.74
285	892.98	750.44	588.31	1332.7	1207.9	1020.4
300	899.31	756.66	615.62	1498.9	1293.1	1056.1
315	944.18	792.30	640.95	1739.8	1413.5	1155.9
330	987.50	842.10	674.08	1739.1	1459.3	1155.4
345	954.83	810.01	670.92	1578.7	1349.2	1075.1

Table 2A. Apparent Resistivity Data for sites in Bar Harbor, Maine--continued.

	Owen Field			Pine Field #3		
	Apparent resistivity (Ohm-m) for the following A-spacings:			Apparent resistivity (Ohm-m) for the following A-spacings:		
Azimuth	42.42 m	35.36 m	28.28 m	42.42 m	35.36 m	28.28 m
0	2300	2250	2000	811.25	677.10	524.03
15	1925	1875	1725	863.90	687.03	535.10
30	1800	1700	1525	770.02	638.08	505.70
45	1850	1790	1600	710.09	587.07	474.82
60	2225	2090	1790	633.41	556.73	464.29
75	2390	2210	1820	580.81	525.52	460.83
90	2375	2200	1950	526.70	472.81	418.63
105	2585	2475	2225	504.54	468.72	411.53
120	2975	2850	2550	590.77	517.14	443.33
135	2825	2750	2300	666.22	583.05	493.42
150	2425	2300	2075	748.36	623.10	509.31
165	2300	2240	2050	814.58	652.03	502.85
180	2300	2250	2000	811.25	677.10	524.03
195	1925	1875	1725	863.90	687.03	535.10
210	1800	1700	1525	770.02	638.08	505.70
225	1850	1790	1600	710.09	587.07	474.82
240	2225	2090	1790	633.41	556.73	464.29
255	2390	2210	1820	580.81	525.52	460.83
270	2375	2200	1950	526.70	472.81	418.63
285	2585	2475	2225	504.54	468.72	411.53
300	2975	2850	2550	590.77	517.14	443.33
315	2825	2750	2300	666.22	583.05	493.42
330	2425	2300	2075	748.36	623.10	509.31
345	2300	2240	2050	814.58	652.03	502.85


Pine Field 1 (Shatter Zone) Square Array Resistivity (Ohm-m)

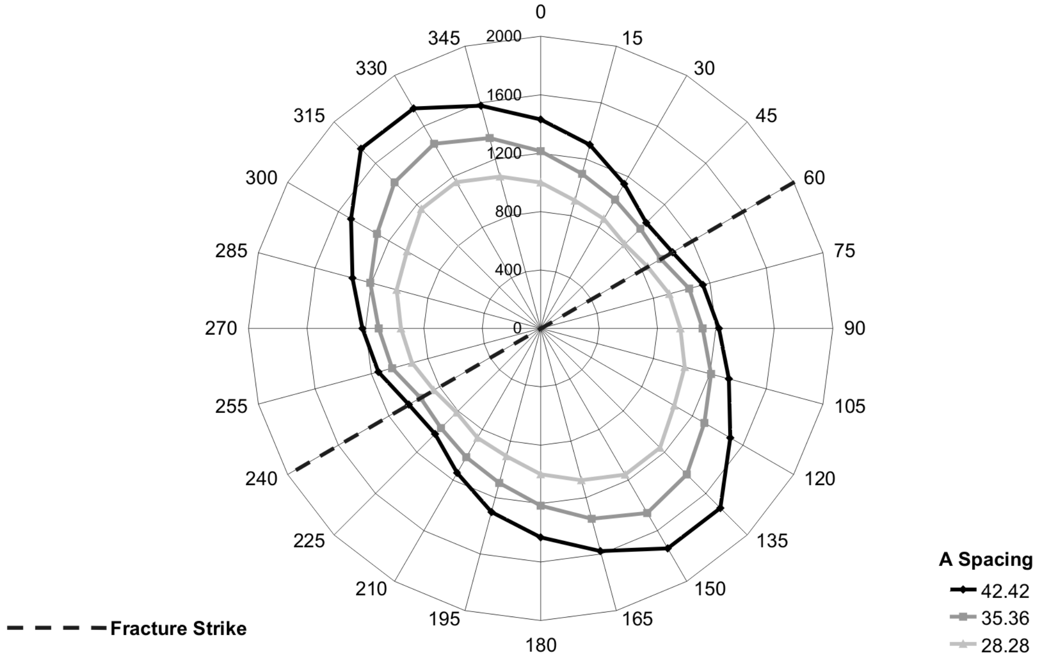
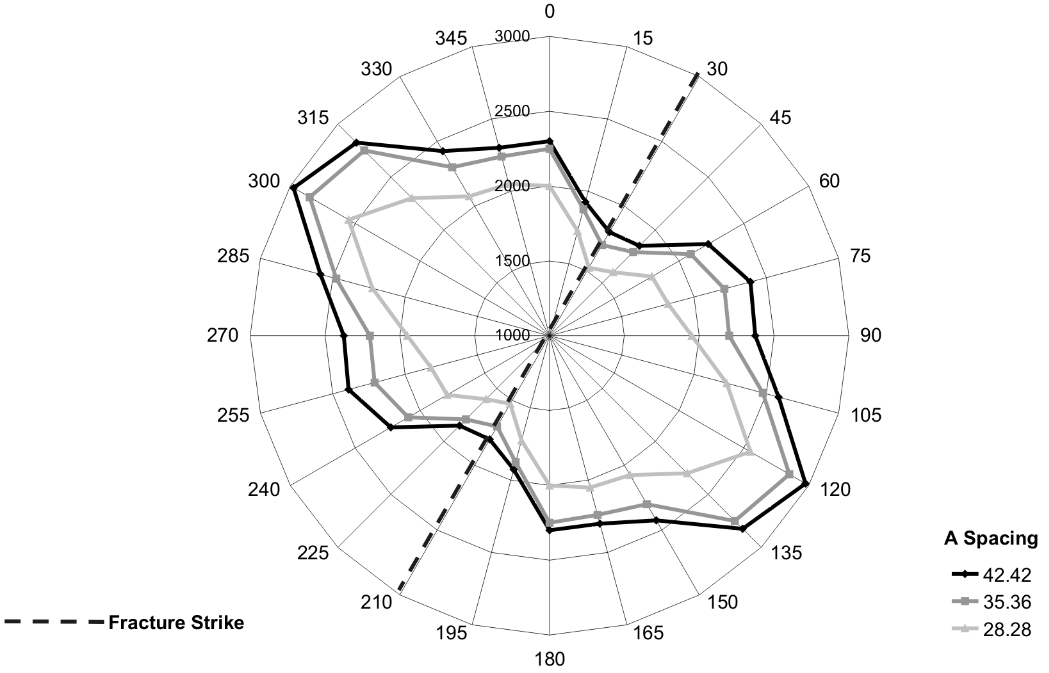

Pine Field 2 (Shatter Zone) Square Array Apparent Resistivity (Ohm-m)

Figure 2-b (1). Rose diagram of apparent resistivity data for sites in Bar Harbor, Maine.

Owen Field (Ellsworth Schist) Square Array Apparent Resistivity (Ohm-m)



Pine Field 3 (Ellsworth Schist) Square Array Resistivity (Ohm-m)

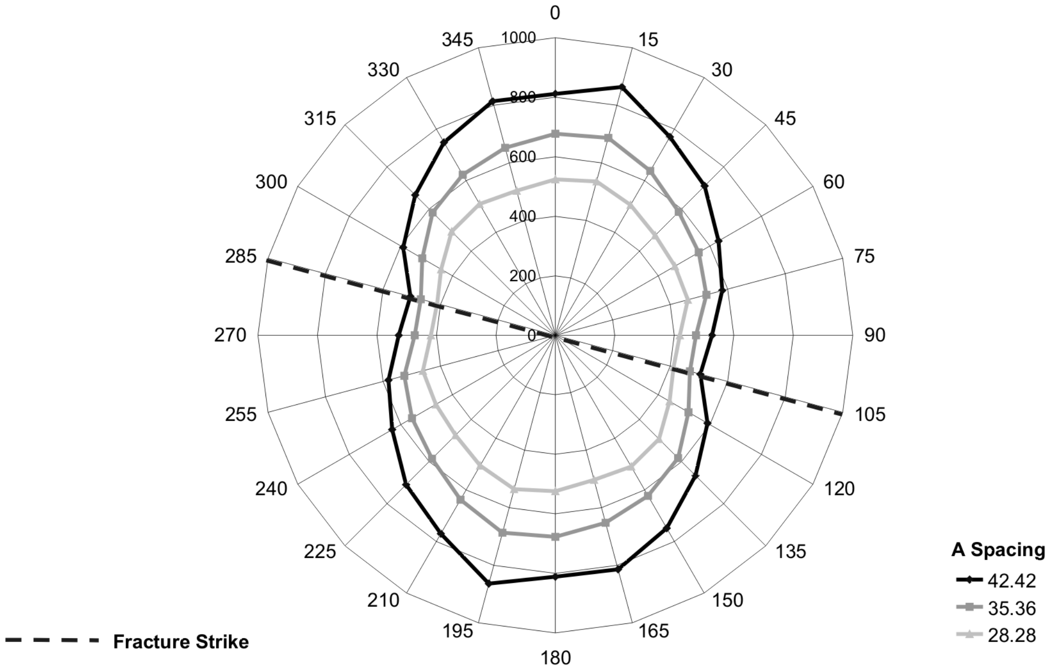


Figure 2-b (2). Rose diagram of apparent resistivity data for sites in Bar Harbor, Maine.

Secondary Porosity Estimates

Shatter Zone

Pine Field 1	Secondary Porosity for 3 A-spacings		
	A-Spacings (meters):		
Specific Conductance	42.42	35.36	28.28
100	0.0050	0.0058	0.0058
200	0.0025	0.0029	0.0029
300	0.0017	0.0019	0.0019
400	0.0013	0.0014	0.0015
500	0.0010	0.0012	0.0012
600	0.0008	0.0010	0.0010

Pine Field 2	Secondary Porosity for 3 A-spacings		
	A-Spacings (meters):		
Specific Conductance	42.42	35.36	28.28
100	0.0078	0.0075	0.0074
200	0.0039	0.0038	0.0037
300	0.0026	0.0025	0.0025
400	0.0020	0.0019	0.0019
500	0.0016	0.0015	0.0015
600	0.0013	0.0013	0.0012

Ellsworth Schist

Owen Field	Secondary Porosity for 3 A-spacing		
	A-Spacings (meters):		
Specific Conductance	42.42	35.36	28.28
100	0.0039	0.0041	0.0044
200	0.0019	0.0020	0.0022
300	0.0013	0.0014	0.0015
400	0.0010	0.0010	0.0011
500	0.0008	0.0008	0.0009
600	0.0006	0.0007	0.0007

Pine Field 3	Secondary Porosity for 3 A-spacing		
	A-Spacings (meters):		
Specific Conductance	42.42	35.36	28.28
100	0.0145	0.0130	0.0099
200	0.0072	0.0065	0.0049
300	0.0048	0.0043	0.0033
400	0.0036	0.0032	0.0025
500	0.0029	0.0026	0.0020
600	0.0024	0.0022	0.0016

APPENDIX 3:

ADDITIONAL SENSITIVITY ANALYSES

Sensitivity analyses of recharge amounts to variations in the recharge through the presumpscot formation:

Sensitivity to consumptive use:

		Concentration of nitrate-nitrogen in net recharge (mg/L)		I	
	Consumptive use:	Aunt Betsey's Brook	Old Mill Brook	Aunt Betsey's Brook	Old Mill Brook
	15%	1.6	0.5	0.33	0.10
value used in report	**10%**	**1.8**	**0.6**	**0.35**	**0.11**
	7%	1.8	0.6	0.36	0.11
	5%	1.8	0.6	0.36	0.12
	3%	1.9	0.6	0.37	0.12
	1%	1.9	0.6	0.38	0.12

Parameters held constant:

n(waste) = 47 mg/L
rech = 9 in/yr
denitrification = 0.05
n(natural rech) = 0.03
water use = 225 gal/house/day

Sensitivity to water-use rate*:

		Concentration of nitrate-nitrogen in net recharge (mg/L)		I	
	Per-household water-use rate, gal/day	Aunt Betsey's Brook	Old Mill Brook	Aunt Betsey's Brook	Old Mill Brook
	300	2.3	0.8	0.46	0.15
National Average	270	2.1	0.7	0.41	0.13
	250	1.9	0.6	0.38	0.12
value used in report	**225**	**1.8**	**0.6**	**0.35**	**0.11**
	200	1.6	0.5	0.31	0.10
	180	1.4	0.5	0.28	0.09

Parameters held constant:

n(waste) = 47 mg/L
rech = 9 in/yr
denitrification = 0.05
n(natural rech) = 0.03
consumptive use = 10%

*** This does not take into account the probability that if water use decreases, then waste concentration would likely increase.**

Sensitivity to denitrification rate:

		Concentration of nitrate-nitrogen in net recharge (mg/L)	
	Denitrification rate	Aunt Betsey's Brook	Old Mill Brook
	0.5	0.9	0.3
	0.4	1.1	0.4
	0.3	1.3	0.4
	0.2	1.5	0.5
	0.1	1.7	0.5
value used in report	**0.05**	**1.7**	**0.6**
	0.02	1.8	0.6
	0.01	1.8	0.6

Parameters held constant:

n(waste) = 47 mg/L
rech = 9 in/yr
n(natural rech) = 0.03
consumptive use = 10%
water use = 225 gal/house/day

Variables:

rech is the recharge rate applied to watershed, in in.;
I is the volume rate of waste water entering soil over development area, in acre-in./yr
n(waste) is the concentration of total nitrogen in septic discharge;
n(natural rech) is the nitrate nitrogen concentration in ambient recharge

Sensitivity analysis of recharge amounts to variations in the recharge through the Presumpscot Formation:

Unit Areas	Recharge rates, in gal/acre, for medium recharge scenario (9 in/yr), with varying percentage reduction in recharge for Presumpscot Formation				Percent difference in total recharge between 80 and 95% reduction
	70%	80%	90%*	95%	
WATERSHED AREAS					
500-foot buffer	200,000	200,000	190,000	190,000	5.3%
Aunt Betseys Brook	190,000	180,000	180,000	170,000	5.9%
Breakneck Brook	230,000	230,000	230,000	230,000	0.0%
French Hill Brook	230,000	230,000	230,000	230,000	0.0%
Fresh Meadow wetland	80,000	60,000	30,000	20,000	200.0%
Ground water seepage	170,000	160,000	150,000	140,000	14.3%
Kitteredge Brook	210,000	200,000	200,000	190,000	5.3%
Liscomb Brook	116,000	87,000	73,000	58,000	50.0%
Old Mill Brook	220,000	220,000	220,000	220,000	0.0%
Stony Brook	160,000	150,000	140,000	130,000	15.4%
Unnamed tributary behind stone barn	210,000	210,000	200,000	200,000	5.0%
TOWN DISTRICTS					
Acadia National Park	240,000	240,000	240,000	240,000	0.0%
Bar Harbor Town area	220,000	220,000	220,000	220,000	0.0%
Emery District	150,000	140,000	130,000	120,000	16.7%
Hulls Cove Area	120,000	110,000	90,000	80,000	37.5%
Ireson Hill District	230,000	230,000	230,000	230,000	0.0%
McFarland Hill District	240,000	240,000	230,000	230,000	4.3%
Salisbury Cove Area	180,000	170,000	160,000	160,000	6.3%
Town Hill District	200,000	190,000	180,000	180,000	5.6%
Wetlands/Ponds	90,000	60,000	40,000	30,000	100.0%

* Values used in body of report.

Nielsen, M.G., 2002—ESTIMATED QUANTITY OF WATER IN FRACTURED BEDROCK UNITS ON MT. DESERT ISLAND, AND ESTIMATED GROUND-WATER USE, RECHARGE, AND DILUTION OF NITROGEN IN SEPTIC WASTE IN THE BAR HARBOR AREA, MAINE — USGS OFR 02-435