Hydrogeology and Quality of Ground Water on Guemes Island, Skagit County, Washington

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4236

Prepared in cooperation with
GUEMES ISLAND ENVIRONMENTAL TRUST and
SKAGIT COUNTY CONSERVATION DISTRICT

U.S. DEPARTMENT OF THE INTERIOR
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By S.C. Kahle and T.D. Olsen

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Tacoma, Washington
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U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

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FIGURES--Continued

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square mile (mi^2)	259.0	hectare
gallon (gal)	3.785	liter
acre-foot (acre-ft)	1,233	cubic meter
inch per day (in/d)	25.4	millimeter per day
foot per day (ft/d)	0.3048	meter per day
square foot per day (ft^2/d)	0.09290	square meter per day
cubic foot per day (ft^3/d)	0.028317	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
degree Celsius (°C)	°F = 1.8 x (°C + 32)	degree Fahrenheit (°F)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Guemes Island is an 8.2-square-mile island in the northern part of Puget Sound in western Washington State. The population of the island is increasing, as is the demand for ground water, which is the island's sole source of freshwater.

concentration was 236 mg/L (milligrams per liter). The secondary maximum contaminant level (SMCL) for dissolved solids, 500 mg/L, was exceeded in four samples. Twelve water samples were classified as moderately hard, the remainder as hard or very hard. Although calcium-magnesium/bicarbonate water types were most common, samples with relatively high amounts of sodium and chloride also were found. The median chloride concentration

The island consists of unconsolidated Pleistocene deposits and bedrock. A net of five hydrogeologic sections and a map of surficial geology were constructed and used to delineate six hydrogeologic units. The Double Bluff, Vashon, and beach aquifers are the most productive hydrogeologic units on the island. The thickness of the unconsolidated deposits under most of the island is unknown.

Discharge to pumping wells was estimated to be 64.6 acre-feet during 1992, and virtually all the water was used for public supply and domestic purposes. An approximate water budget indicates that of the 21-29 inches of precipitation that falls on the island in a typical year, 0-4 inches runs off as surface water, 12-22 inches evaporates or transpires, and 2-10 inches recharges the ground-water system. Only 0.1-0.3 inch of the recharge is withdrawn by wells; the remainder recharges deeper aquifers or discharges from the ground-water system fairly rapidly to drainage ditches or the sea.

Water samples were collected from 24 wells to determine the chemical quality of ground water on the island. All samples were analyzed for concentrations of common ions, iron, manganese, arsenic, and fecal-streptococci and fecal-coliform bacteria. The median dissolved-solids ... The median chloride concentration was 21 mg/L; two samples had chloride concentrations above the chloride SMCL of 250 mg/L. The median nitrate concentration of 0.08 mg/L indicates that there is no widespread contamination from septic systems or from livestock. More samples did not meet the SMCL for manganese than for any other constituent; 11 samples exceeded the 50 µg/L (micrograms per liter) limit. Similarly, nine samples did not meet the SMCL of 300 µg/L for iron. Arsenic was detected in 5 of 24 samples and concentrations ranged from 1 to 14 µg/L. Fecal-streptococci bacteria were detected in one sample; fecal-coliform bacteria were not detected at all.

Water from five wells was analyzed for concentrations of volatile organic compounds, and trace concentrations of a single but different compound were detected in three samples; trichloromethane, 1,1,1-trichloroethane, and benzene were each present in one sample. All samples containing a volatile organic compound were collected from wells less than 70 feet deep. Of the five water samples analyzed for radon, one sample exceeded the proposed radon maximum contaminant level of 300 picocuries per liter.

Several coastal wells in West Beach, North Beach, and Indian Village yielded water with chloride concentrations exceeding 100 mg/L, possibly indicating early stages of seawater intrusion. Chloride concentrations appeared to vary seasonally in wells that had chloride concentrations greater than 100 mg/L; the higher values occurred from April through September and lower values occurred from October through March.

INTRODUCTION

Ground water is the sole source of freshwater for Guemes Island in the northern part of Puget Sound in Washington State, and there is no potential for local surface-water development. Because the population of the island is increasing rapidly, there is concern that the fresh ground-water resource is not adequate to support continued growth and that increased pumpage will adversely affect its availability and quality. The potential for seawater intrusion on Guemes Island is great because parts of the island's two major aquifers are below sea level, the rates of recharge to the aquifers are low, and most wells are in near-shore areas. Seawater intrusion along some of the more densely populated coastal areas of the island has been documented in previous studies (Walters, 1971; Dion and Sumioka, 1984). Arsenic in ground water also is a

(4) prepare a generalized water budget of the island; and

(5) discuss options for monitoring ground-water quantity and quality based on the results of this study.

Purpose and Scope

This report summarizes the findings of the objectives listed in the Introduction. The topics covered in this report include regional and local geologic history; areal distribution and physical properties of significant hydrogeologic units; basic principles of the hydrologic cycle and ground-water occurrence; precipitation; recharge and discharge of ground water on the island; water-level fluctuations and trends; water budget of the island; seawater intrusion; general chemistry of ground water; and the need for monitoring and additional studies.

Description of the Study Area

Guemes Island is one of numerous islands located in the coastal waters of Washington State. The island covers 8.2 mi^2 in western Skagit County, just north of the city of Anacortes (fig. 1). Other islands in the immediate vicinity include Lummi Island to the north and Cypress Island to concern because it has been found at high concentrations in ground water on nearby Lummi Island.

Although some water-quality information was available, a comprehensive assessment of the island's hydrogeology and water chemistry had not been made. Realizing the importance and need for this type of information to properly manage, protect, and (or) develop the local ground-water resource, a group of island residents coordinated efforts to initiate such a study. Consequently, in 1991 the U.S. Geological Survey (USGS) began a ground-water investigation on Guemes Island in cooperation with the Guemes Island Environmental Trust and the Skagit County Conservation District. The results of that study are presented in this report.

The objectives of the study are to:

(1) describe and quantify the ground-water system using existing or readily collectable data;

(2) determine the general chemical characteristics of waters in the major hydrogeologic units;

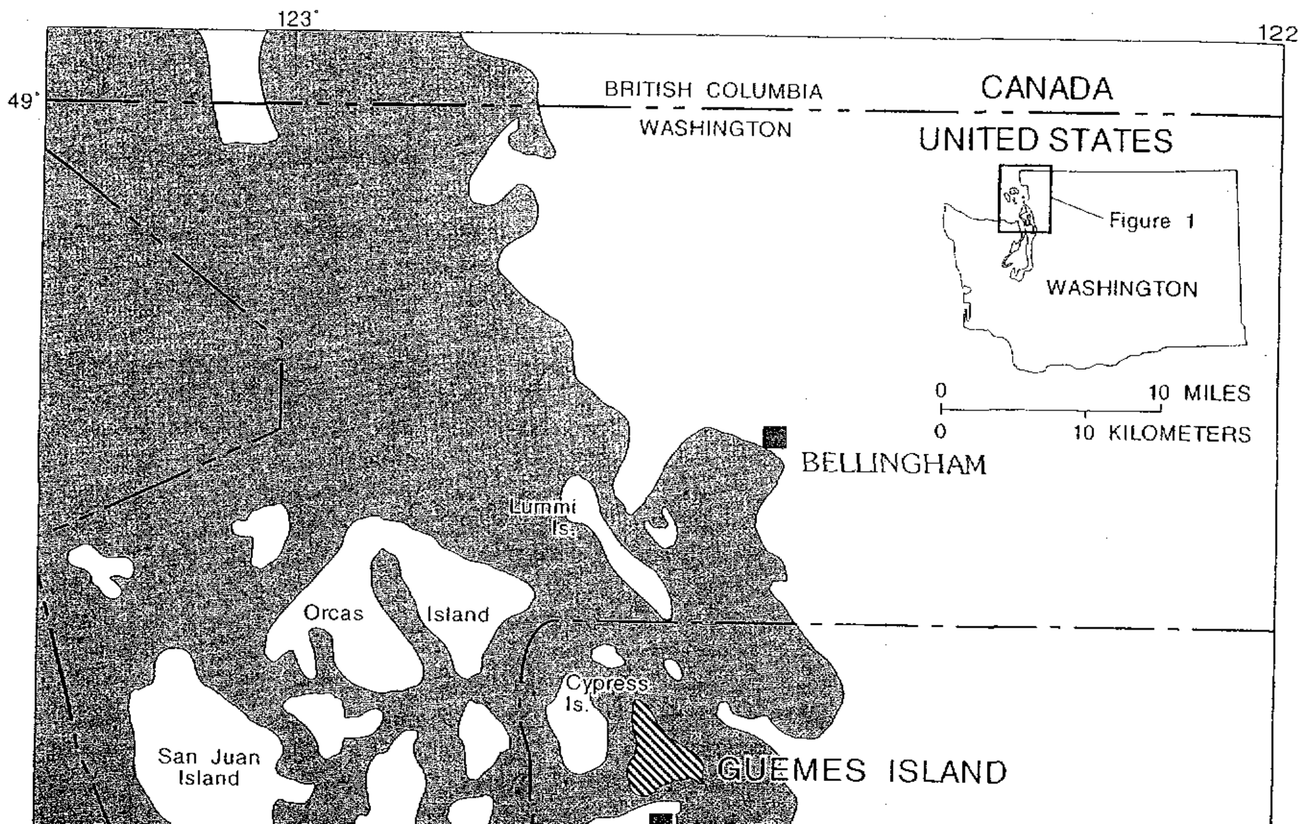
(3) describe any apparent widespread ground-water-quality problems, including seawater intrusion;

the west. The mainland is located to the east and south of Guemes Island. Public access to the island is limited to a county-operated ferry, which runs between Anacortes and Guemes Island.

The southeastern part of Guemes Island is hilly and composed of bedrock; the remainder is a gently rolling plain that is underlain by glacial drift (plate 1). The highest point on Guemes Island, located at the southeastern end of the island, is a bedrock hill 690 feet above sea level. The highest point on the glacial drift plain is about 190 feet.

Precipitation on the island averages about 25 in/yr (U.S. Department of Agriculture, 1965). A small perennial stream flows down the island's steep eastern bedrock slope and discharges into Square Harbor. An intermittent stream, located in a north-south trending valley just west of the bedrock part of the island, flows southward during wet periods. Wetlands exist locally, in poorly drained depressions or in low-lying coastal areas.

The year-round population of the island is about 540, and the summer population nears 2,200. Much of the island has a rural setting with most of the population concentrated along the coast. The more densely populated


123°
122°
49°
BRITISH COLUMBIA
WASHINGTON
CANADA
UNITED STATES
Figure 1
WASHINGTON
0
10 MILES
0
10 KILOMETERS
BELLINGHAM
Lummi Is.
Orcas Island
Cypress Is.
San Juan Island
GUEMES ISLAND

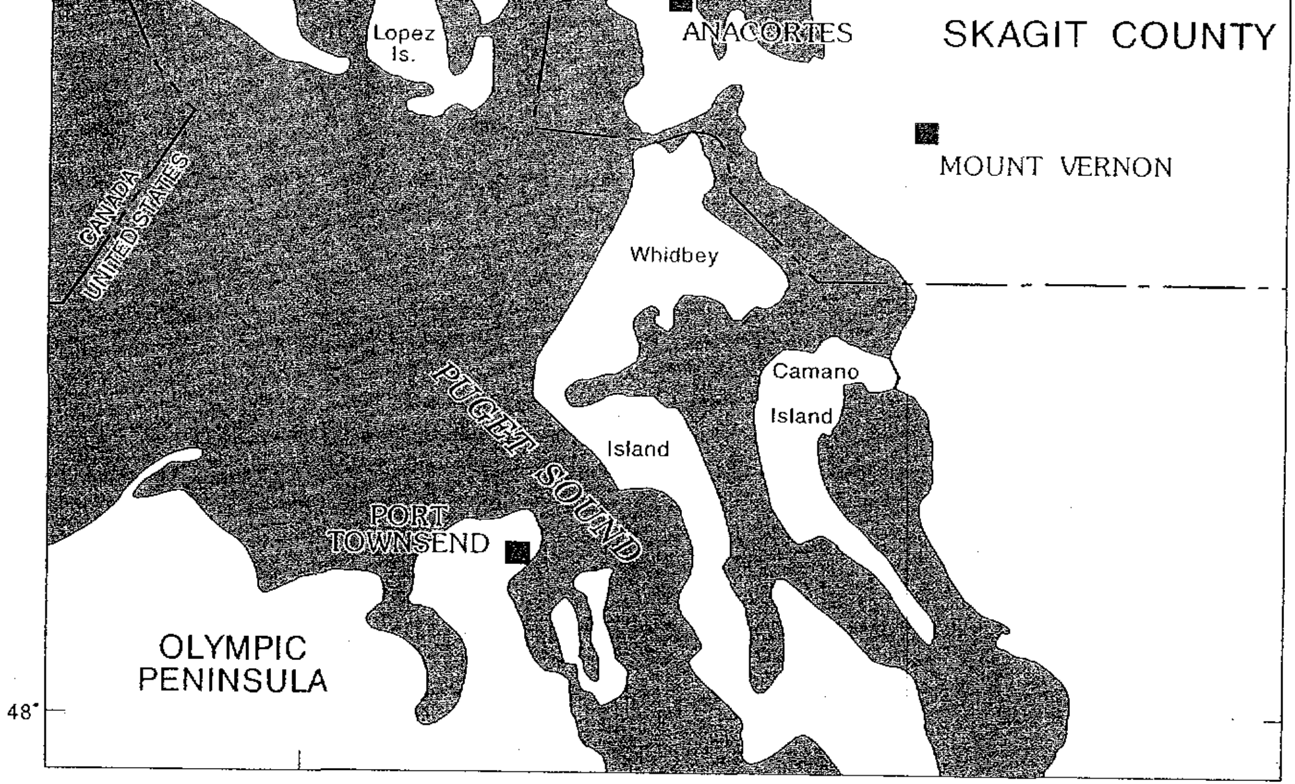


Figure 1.--Location of the study area.

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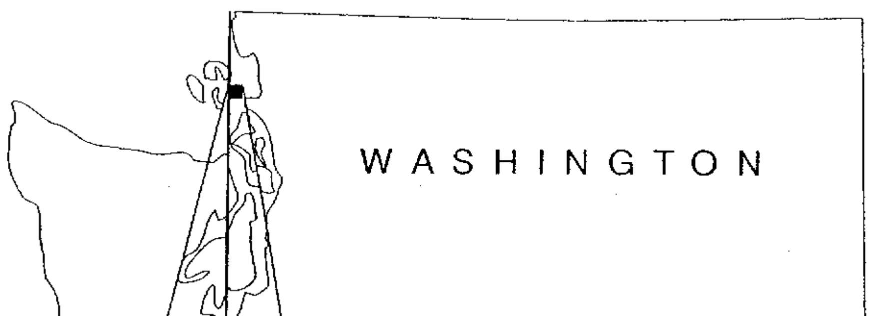
areas on the island, labeled on plate 1, are West Beach, Indian Village, North Beach, Seaway Hollow, Holiday Hideaway, South Shore, and Kelly's Point. Commerce and industry are mostly limited to a small resort at North Beach, a gravel pit, and several small businesses related to arts and crafts, construction trades, or livestock. Domestic water supplies are provided by privately owned wells and 14 small public-supply systems. There are no central sewer systems on the island; waste water is returned to the ground by way of septic tanks and drain fields.

Well- and Spring-Numbering System

In Washington, wells and springs are assigned numbers that identify their location within a township, range, section, and 40-acre tract. Number 35N/01E-12R02 (fig. 2) indicates that the well is in township 35 North (N) and range 1 East (E) of the Willamette base line and meridian. The numbers immediately following the hyphen indicate the section (12) within the township; the letter following the section gives the 40-acre tract of the section, as shown on figure 2. The two-digit sequence number (02) following the letter indicates that the well was the second one inventoried by USGS personnel in that 40-acre tract. An "S" following the sequence number indicates that the site is a spring. In some parts of this



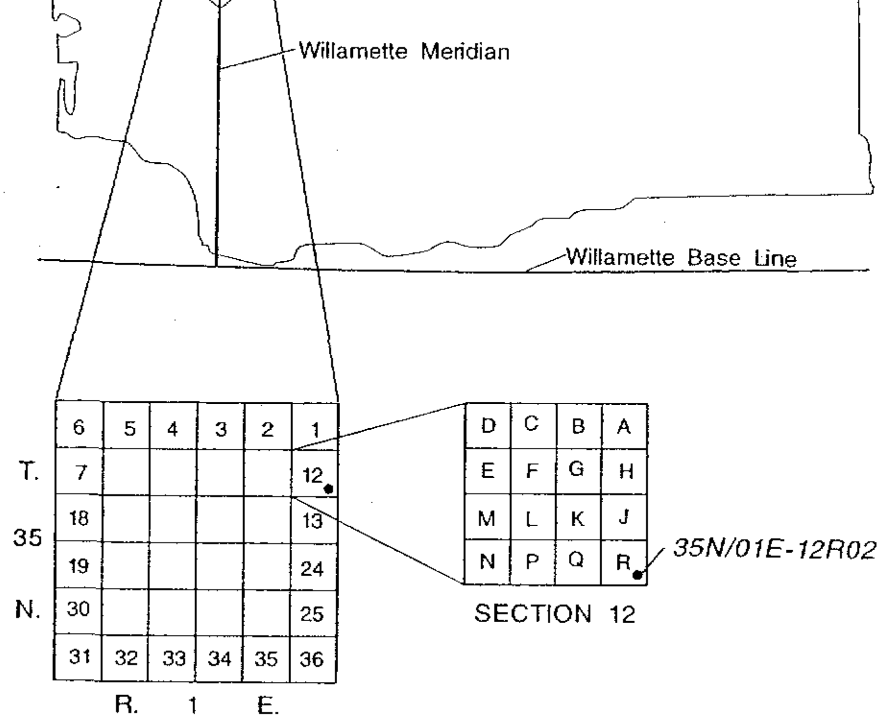


Figure 2.--Well- and spring-numbering system used in Washington.

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report, wells and springs are identified individually by only the section and 40-acre tract, such as 12R02, and township and range are shown as a grid.

Acknowledgments

The authors wish to acknowledge the cooperation of the many well owners and tenants who supplied information and allowed access to their wells and land during the field work, and the owners and (or) managers of various water systems who supplied well and water-use data. Geologic interpretations were aided by information provided by Patrick T. Pringle and Connie J. Manson of the Washington Department of Natural Resources Division of Geology and Earth Resources. Two drilling companies, Hayes Drilling, Inc., and Dahlman Pump and Drilling, Inc., were also of assistance in providing and clarifying well logs and records.

STUDY METHODS

The methods used to study and interpret the occurrence and quality of ground water on Guemes Island are discussed in this section. The general approach used to

(9) identify areas of widespread water-quality problems; and

(10) describe a possible long-term network to monitor ground-water quantity and quality.

Field Inventory

A comprehensive well and spring inventory was conducted in order to locate existing wells and springs with accuracy, to measure the depth to the water surface inside the well, and to make a preliminary assessment of the quality of the water. During October 1991, 111 wells and 1 spring were inventoried, the locations of which are shown on plate 1. Physical and hydrologic data for these sites are contained in Appendix 1. Criteria for site selection included availability of driller's report (obtained from Washington Department of Ecology) having lithologic information and vertical distribution of well openings, and permission from the owner or tenant to inventory the well. All sites were plotted on 1:24,000-scale topographic maps. Altitudes of the land surface at each well head, accurate to plus or minus 10 feet, were determined from those maps. Other information gathered at each site included the name of the landowner or tenant, primary use of the water, the achieve the study objectives included the following items:

(1) inventory wells and principal springs on the island;

(2) construct a net of hydrogeologic sections based on drillers' logs of inventoried wells and existing geologic maps;

(3) delineate vertical and areal extents of hydrogeologic units on the basis of the hydrogeologic sections and drillers' logs of inventoried wells;

(4) estimate hydraulic conductivity values for the hydrogeologic units;

(5) construct water-level contour maps for the principal aquifers and determine general ground-water flow directions;

(6) estimate the annual quantity of ground water withdrawn from the island and describe the uses of that water;

(7) determine an approximate water budget for the island;

(8) describe the general chemical characteristics of the ground water;

owner's comments about water quality and well yield, surrounding land use, and construction details of the well. The depth to water was measured using a graduated steel tape and is accurate to plus or minus 0.02 foot. Buried well heads or otherwise difficult access precluded water-level measurement in some wells. Water-level altitudes (well-head altitude minus depth to water) presented in this report are accurate only to plus or minus 10 feet because of the uncertainty in the well-head altitudes. A water sample was collected from most sites at the time of inventory and analyzed in the field for chloride concentration and specific conductance. Chloride concentrations were determined using titrimetric tests using mercuric nitrate titrant in acid solution with diphenylcarbazone as the end-point indicator. Specific conductance values were determined with a field conductance meter that was calibrated daily. Out of the 111 wells and 1 spring inventoried, 83 water levels were measured and 83 water samples were analyzed.

Hydrogeology

The generalized map of surficial geology for Guemes Island, shown on plate 1, is based on geologic maps in the Coastal Zone Atlas of Washington, Vol. 2 Skagit County (Washington Department of Ecology, 1978), soil survey maps of Skagit County (U.S. Department of Agriculture Soil Conservation Service, 1989), and lithologic descriptions in drillers' logs from 85 inventoried wells. Descriptions follow of each source of information and evaluations regarding its usefulness and possible limitations.

Geologic mapping for the Coastal Zone Atlas was done in order to evaluate geologic materials along Washington's shorelines for engineering properties, structural relations, and resource potential. The intent of the mapping was to provide land-use planning information in order to avoid land uses incompatible with the area's geology. The mapping was done by geologists of the Washington State Department of Natural Resources (DNR) largely by inspection of shoreline bluffs by boat (G. Thorsen, retired, Washington Department of Natural Resources, oral commun., 1993). Regional geologic maps, aerial photographs, and well drillers' logs also were used. The resulting maps provide a good description of geologic units along and near the coast.

Soil Surveys are maps of surficial soil types that are classified by the steepness of slopes on which the soil occurs, general pattern of drainage, natural or introduced vegetation growing on the soil, and type of bedrock or deposit on which the soil occurs. Although geologic formation names are not part of the classification scheme, it is helpful to know the type of parent material from which the

extent of the principal hydrogeologic units were constructed. The lithologic logs of wells used in constructing the hydrogeologic sections are presented in Appendix 2.

Water Quality

Water samples were collected from 24 of the inventoried wells during June 1992. The sampled wells were selected to provide broad geographic coverage and an equal representation of the hydrogeologic units. All samples were analyzed for concentrations of the major constituents, iron, manganese, arsenic, and fecal-coliform and fecal-streptococci bacteria. In addition, field measurements of temperature, specific conductance, pH, alkalinity, and dissolved-oxygen concentration were made at all sites. The sampling and analytical methods used in the water-quality part of this study follow guidelines presented in U.S. Geological Survey Techniques of Water-Resources Investigations (Fishman and Friedman, 1985; Friedman and Erdmann, 1982; Greeson and others, 1977; Wershaw and others, 1987; and Wood, 1981). With the exception of the field parameters, the samples were analyzed at the U.S. Geological Survey's National Water Quality Laboratory (NWQL) in Arvada, Colo.

Of the 24 sampled wells, a subset of 5 samples was analyzed for the trace constituents barium, cadmium, chrosoil has weathered. If, for example, a soil has developed on a clay-rich parent material of glacial origin, the source may be a lacustrine or glaciomarine deposit. On the other hand, soil derived from sand and gravel could indicate glacial outwash as the parent material. It was in this manner that the soil survey of Skagit County was used as an aid in extending the geologic mapping of the Coastal Zone Atlas.

Lithologic logs for field-located drilling sites provided subsurface information on the geologic unit(s) encountered. In most cases the logs verified existing geologic mapping. However, where numerous logs indicated a different type of deposit than was previously mapped, the logs were used to modify the existing maps.

Five hydrogeologic sections (plate 1) were constructed on the basis of lithologic data from drillers' logs and the surficial geologic map. Geologic units were identified and correlated on the basis of grain size, sorting, stratigraphic position, outcrop pattern, and color. The hydrogeologic sections were used to delineate six hydrogeologic units. Using the sections and additional logs of inventoried wells, maps of top (altitude), thickness, and

mium, copper, lead, mercury, selenium, silver, and zinc. A second subset of five samples was analyzed to determine concentrations of selected volatile organic compounds. A third subset of 12 samples, collected mostly from wells situated in more populated areas, was analyzed for boron and methylene blue active substances (MBAS), which are constituents found in household waste water. Finally, a fourth subset of samples from five wells was analyzed for concentrations of radon. A sampling matrix, indicating which subset(s) were included for each well and the hydrogeologic unit designation for each well, is shown in table 1. Water-quality data for the June 1992 sampling are contained in Appendixes 6-8.

In addition, water samples from 12 coastal wells were collected monthly from December 1991 through December 1992 to determine seasonal differences or trends in chloride concentration. Samples from this monthly network were analyzed for dissolved chloride concentration and specific conductance at the U.S. Bureau of Reclamation Water Quality Laboratory in Boise, Idaho. Water-quality data for the monthly network are contained in Appendix 5.

Table 1.--Sampling matrix indicating analyses performed and hydrogeologic unit of each sample site on Guemes island

[Hydrogeologic unit: Qsc, Surficial confining unit; Qva, Vashon aquifer; Qw, Whidbey confining unit; Qdb, Double Bluff aquifer; and Br, Bedrock]

Local well number	Hydro-geo-logic unit	Common constituents, iron, manganese, arsenic, and fecal-coliform and fecal-streptococci bacteria	Selected trace consti-tuents	Selected volatile organic compounds	Boron and methylene blue active substances	Radon
35N/01E-01C02	Qva	X				
35N/01E-01D01	Qdb	X				
35N/01E-01M01	Qdb	X	X		X	
35N/01E-01R01	Qdb	X				X
35N/01E-02L01	Qva	X		X	X	
35N/01E-12F01	Qva	X		X	X	
35N/01E-12P03	Qdb	X				
35N/01E-12R02	Qdb	X				
35N/01E-14B02	Qdb	X	X	X	X	X
35N/02E-06E01	Qdb	X				
35N/02E-06G01	Br	X				X

35N/02E-06G01	Br	X				X
35N/02E-07A01	Qw	X				
35N/02E-07G01	Qsc	X				
35N/02E-07H04	Qw	X			X	
35N/02E-08E02	Br	X	X		X	X
36N/01E-26H01	Qdb	X			X	X
36N/01E-26J01	Qdb	X	X		X	
36N/01E-26P01	Qva	X		X	X	
36N/01E-35F01	Qdb	X				
36N/01E-36C01	Qva	X			X	
36N/01E-36C05	Qva	X		X	X	
36N/01E-36Q01	Qdb	X	X			
36N/02E-31M01	Qdb	X				
36N/02E-31P01	Qdb	X			X	

HYDROGEOLOGY

Geologic Setting

The interpretation of the geologic framework of Guemes Island was based largely on existing data contained in geologic or soil maps (Washington Department of Ecology, *1978*, and *U.S. Department of Agriculture Soil* Conservation Service, 1989), scientific publications (McLellan, 1927; Easterbrook and others, 1967; Easterbrook, 1969; Blunt and others, 1987; Brandon and others, 1988; Brandon, 1989; and M. A. Jones, U.S. Geological Survey, written commun., 1994), and drillers' lithologic descriptions. The geologic units recognized during this study are referred to by formal geologic names, and corresponding map symbols, or by informal names of most common usage (Easterbrook, 1968; Dion and others, 1994; and Turney and others, 1995). The reader is referred to Kruckeberg (1991) for a description of the regional geology and natural history of the Puget Sound region in general, and to Oldow and others (1989) for a thorough description of the geologic evolution of the western part of the North American continent.

The geology of Guemes Island is illustrated on plate 1 by hydrogeologic sections and a map of surficial geology. Eight geologic units were identified: consolidated

unconsolidated deposit that has been encountered by drilling on Guemes Island. The Double Bluff Drift was deposited during the Pleistocene, from about 250,000 to 100,000 years ago. It is exposed at or near sea level in sea cliffs on the northern tip of the island and at two locations along the southern shoreline.

The Whidbey Formation consists of floodplain clay, silt, peat, and lenses of sand that accumulated on top of the Double Bluff Drift during the last major interglacial period in the Puget Sound Lowland. This Pleistocene unit was deposited during a time characterized by a warm climate, from about 100,000 to 90,000 years ago. On Guemes Island the unit is exposed only in sea cliffs.

The next youngest deposits found on Guemes Island are considerably younger than the Whidbey Formation. About 18,000 years ago, the final and most recent glaciation, referred to as the Vashon Stade of the Fraser Glaciation, began when ice slowly advanced southward from Canada and blanketed the entire Puget Lowland. This glaciation resulted in three deposits on Guemes Island: Vashon advance outwash, Vashon till, and Everson drift. Vashon advance outwash consists of sand and gravel and is exposed along the western edge of Guemes Island and in a small gravel pit located near the north-central part of the island where overlying till has been removed. Vashon till is a compact mixture of clay, silt, sand, gravel, and boulogy. Eight geologic units were identified: consolidated bedrock (Br), Double Bluff Drift (Qdb), Whidbey Formation (Qw), Vashon advance outwash (Qva), Vashon till (Qvt), Everson drift (Qe), peat (Qp), and beach deposits (Qb). The hydrogeologic sections indicate that there is considerable variation in the thickness of individual units, and that not all units are necessarily present at any one location. In general, younger unconsolidated deposits are more easily recognized and correlated because of surface or near-surface exposures and the fact that they have not undergone as much erosion and (or) burial as older deposits.

Bedrock is exposed only on the southeastern end of the island and is composed of locally fractured igneous and fine-grained marine sedimentary rocks of Middle Jurassic to Early Cretaceous age. Depth to bedrock (thickness of unconsolidated deposits) is largely unknown, but ranges from 0 feet to greater than 300 feet according to a map of thickness of unconsolidated deposits in the Puget Sound Lowland (M. A. Jones, U.S. Geological Survey, written commun., 1994).

The Double Bluff Drift is composed of till, glaciomarine drift, glaciofluvial sand and gravel, and glaciolacustrine silt and is named for an exposure at Double Bluff on Whidbey Island. It is the oldest and deepest

ders that occurs at land surface over much of the island.

Everson drift consists of pebbly clay and silt referred to as glaciomarine drift. It was deposited about 13,000 years ago when the ice of the final glaciation had thinned sufficiently to allow marine water back into the Puget Lowland and float the remaining ice; the progressive melting of the ice resulted in the deposition of the unit. On Guemes Island, Everson drift occurs mostly in low-lying areas.

At the end of the Pleistocene Epoch, about 10,000 years ago, the melting glacier had retreated back to near the United States-Canada border. Geologic processes dominating the Puget Lowland since that time include erosion and (or) deposition by wind, waves, and flowing water.

Two units are still being deposited on Guemes Island: peat and beach deposits. Peat, composed of partially decomposed and disintegrated organic matter, occurs in poorly drained low-lying areas. Beach deposits consist of sand and gravel that are weathered from sea bluffs or that have accumulated above high tide as a result of longshore drift, the wave-generated movement of sand or gravel parallel to the shore. Considerable amounts of beach deposits have accumulated at North Beach and West Beach.

Conceptual Model of the Hydrogeologic System

Water circulates continuously between the ocean, the atmosphere, and the earth's surface in a process known as the hydrologic cycle (fig. 3). Water in the atmosphere condenses to form clouds and eventually falls to the earth's surface as rain or snow. Part of the rain and snowmelt runs off to roadside drainage ditches, streams, ponds or marshes, or directly back to the sea; part infiltrates the ground, and part is evaporated back to the atmosphere from the soil and from free-water surfaces such as ponds. Some of the water entering the soil is drawn up by plant roots and is returned to the atmosphere by transpiration from leaves. Some of the water that enters the ground continues to percolate downward to the water table. A part of the ground water may return to the land surface by seepage to ponds, marshes, streams, and springs located along coastal bluffs. A small quantity is also withdrawn by wells. The rest of the ground water discharges by sub-sea outflow.

Occurrence of Ground Water

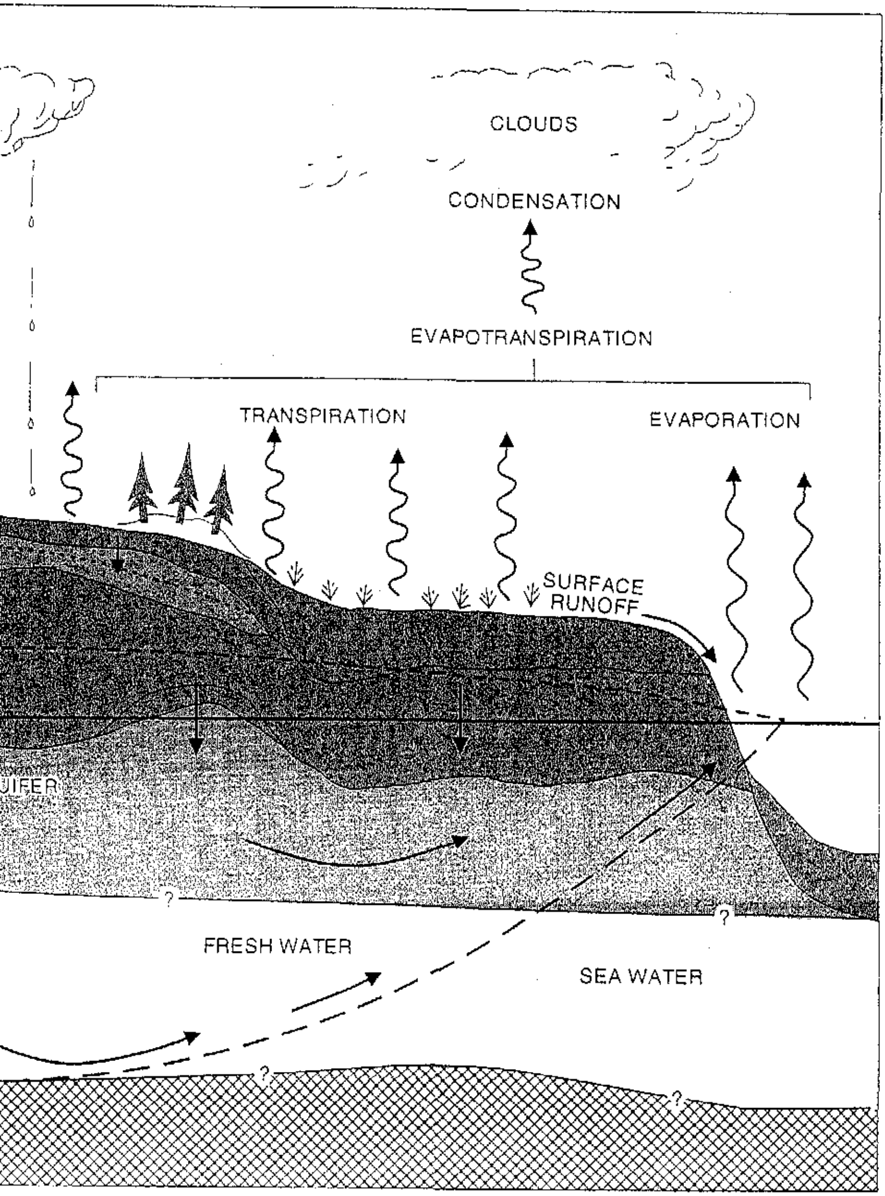
Saturated geologic materials can be considered either as water yielding or non-water yielding. An aquifer is defined as a saturated geologic material that is sufficiently permeable to yield water in significant quantities to a well or spring. Generally, well-sorted, coarse-grained deposits have higher permeabilities than do fine-grained or poorly sorted deposits. In the Puget Lowland, saturated glacial outwash and coarse-grained alluvium yield water to wells at high rates (10 to more than 1,000 gal/min), whereas glacial till, lacustrine deposits, glaciomarine drift, and bedrock generally yield water at much lower rates.

The manner of occurrence of ground water in consolidated bedrock differs greatly from that in unconsolidated deposits. In dense consolidated rock such as that found on Guemes Island, the principal movement of water is through interconnected fractures. In unconsolidated materials, such as sand or gravel, water moves through pore spaces separating the individual particles. Water moves more easily through the larger spaces within deposits of well-sorted sand or gravel than through the much smaller spaces between clay and silt particles or through poorly sorted materials such as till.

On islands, fresh ground water commonly occurs as a lens-shaped body that "floats" above the denser, more saline ground water (fig. 3). The thickness of this lens usually decreases from the center of an island toward its coast. Areally, ground water in an island environment generally moves radially from its area of recharge toward the coast; the approximate directions of ground-water flow are shown with arrows in figure 3. The bounding surface between the fresh and salty ground water, commonly referred to as the freshwater-seawater interface, actually is a zone of diffusion, or mixing.

The simplified conceptual model of the ground-water system of Guemes Island shown in figure 3 includes an assemblage of permeable units (sand and gravel) and less-permeable units (till, clay, silt, bedrock, and fine-grained bottom deposits of Puget Sound). Older unconsolidated material (undifferentiated deposits) may occur beneath these units and above bedrock. Bedrock is not considered a principal transmitter of water because it is poorly permeable compared with the sand or gravel deposits.

Ground water can occur under two general hydrologic conditions (fig. 4). Where water only partly fills an aquifer, the upper surface of the saturated zone (the water table) rises and falls with changes in recharge and discharge. In this situation, the ground water is said to occur under unconfined or water table conditions. The position of the water table is determined by measuring water levels in many wells open to the unconfined aquifer near the water table. Where water completely fills an aquifer that is overlain by a confining zone of less permeable materials, such as an extensive layer of clay, ground water is said to occur under confined or artesian conditions. Water levels in wells that tap a confined aquifer are above the top of the confined aquifer. The height to which water will rise in a well completed in a confined aquifer defines the water pressure or head at that location. The distribution of head defines the potentiometric surface. If the head is sufficient to raise the water level within the well above the top of the well, water will flow from the well and the well is called a flowing artesian well. Both the potentiometric surface and water table fluctuate in response to recharge and discharge of ground water. The direction of the slope (gradient) of the surfaces indicates the general direction of ground-water movement.



on Guemes Island.

NOT TO SCALE

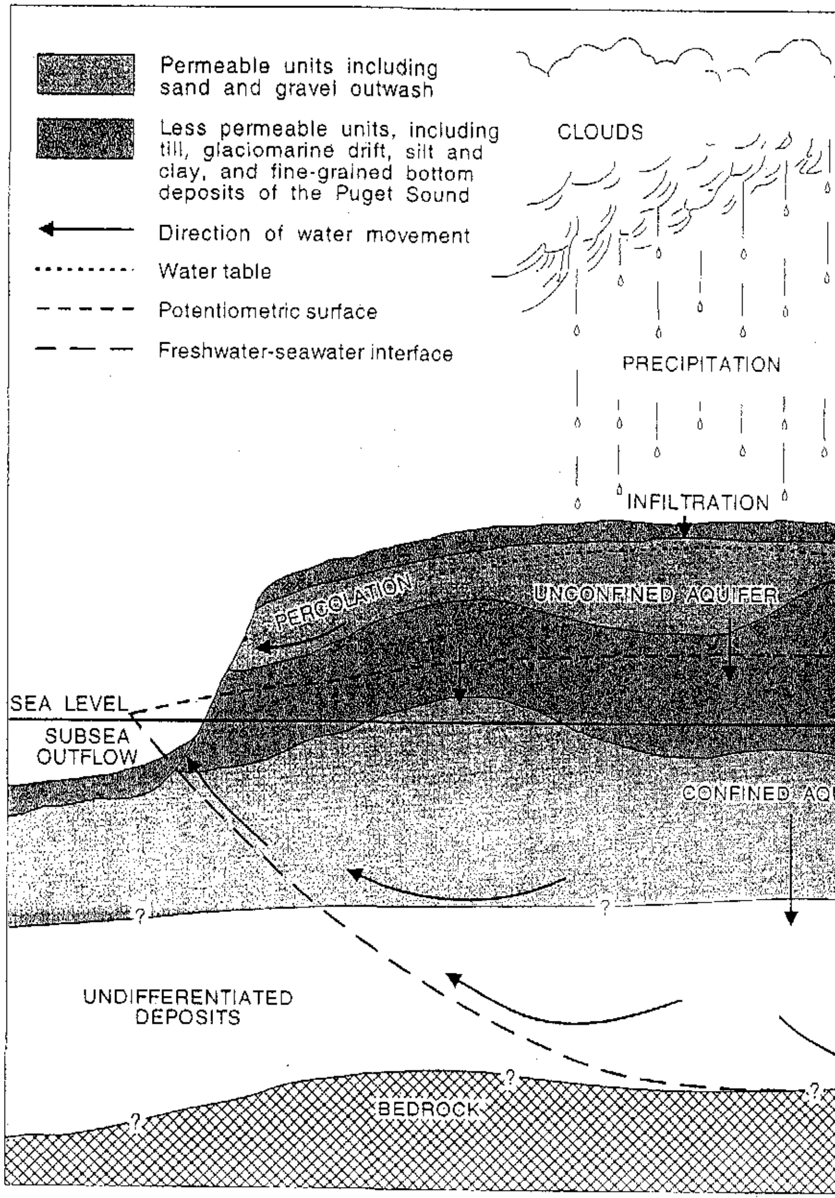


Figure 3.--Simplified conceptual model of hydrologic conditions c

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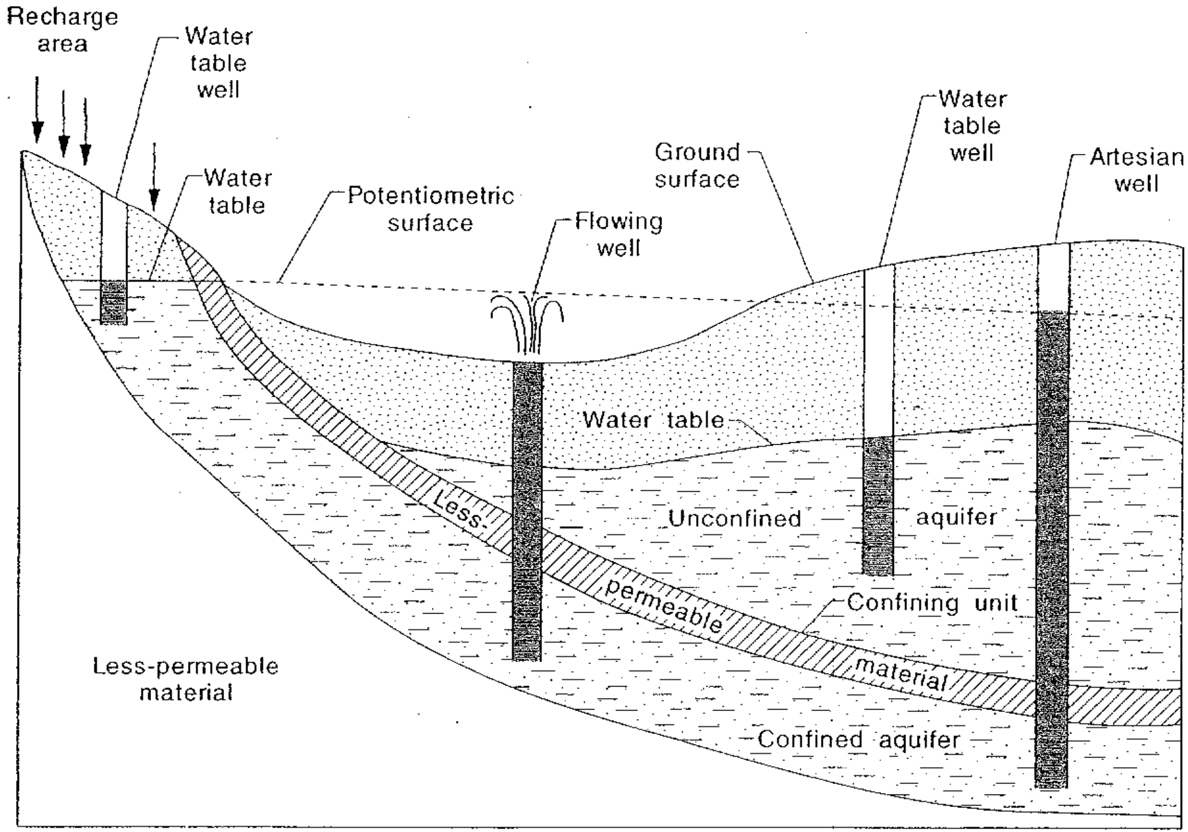
520-17



Recharge area
Water table well
Water table
Potentiometric surface
Flowing well
Ground surface
Water table well
Artesian well
Water table
Less-permeable material
Unconfined aquifer
Confining unit
Less-permeable material
Confined aquifer

Figure 4.--Unconfined and confined ground-water conditions. (Modified from Todd, 1980.)

Hydrogeologic Units

The geologic units described previously were differentiated into six hydrogeologic units, based on their areal extent and general water-yielding properties. The hydrogeologic units identified on Guemes Island, and described in figure 5 are, from youngest to oldest:

Beach aquifer (Qb),

Surficial confining unit (Qsc),

Vashon aquifer (Qva),

Whidbey confining unit (Qw),

Double Bluff aquifer (Qdb), and

Bedrock confining unit (Br).

With the exception of the surficial confining unit (Qsc), the hydrogeologic units listed above are nearly equivalent to the geologic units for which they are named.

The Beach aquifer consists of sand and gravel that has accumulated at the coast as a result of longshore drift. Only two inventoried wells are completed in this unit. The thickness of the unit is estimated to be 10 to 20 feet.

The surficial confining unit is composed of the Vashon till and the Everson drift. Five inventoried wells, tapping productive lenses, are completed in this unit. This poorly permeable unit occurs at the surface over most of the island at altitudes ranging from near sea level to more than 280 feet (fig. 6). Its thickness ranges from about 20 feet to more than 200 feet in the south-central part of the island (fig. 7).

The Vashon aquifer consists of partly saturated sands and gravels. The top of the unit ranges from approximately 40 to 120 feet above sea level (fig. 8). As illustrated in figure 9, the unit occurs in two separate areas,

ogic	Number of inventoried wells completed in unit	Geologic unit and unit label	Epoch and age (age in Ma--millon years before present)
vater is mostly unknown, nic matter in swampy confined aquifer.	2	Beach deposits (Qb)	Holocene (0.01 Ma to present)
ed sand, gravel, silt, and ine drift); overlain by ntains some	5	Peat (Qp) Everson Drift (Qe) Vashon till (Qvt)	Pleistocene (1.6 to 0.01 Ma)
nconfined) conditions. rings occur where unit is er is affected by	28	Vashon advance outwash (Qva)	
permeability and peat of at its base. Unit	17	Whidbey Formation (Qw)	
low sea level. Quality of me areas. Confined	54	Double Bluff Drift (Qdb)	
rocks. Locally yields are small.	5	Bedrock (Br)	Middle Jurassic to Early Cretaceous (187 to 98 Ma)

geologic units on Guemes Island, Washington.

Hydrogeologic unit and unit label	Typical thickness (feet)	Lithologic and hydrolo characteristics
Beach aquifer (Qb)	10-20	Discontinuous sand and gravel. Quality of w but may be affected by septic systems, orga areas, sea spray, or seawater intrusion. Unc
Surficial confining unit (Qsc)	20-200	Low-permeability unit consisting of compacte clay (till) and pebbly clay and silt (glaciomari peat in poorly drained depressions. Unit co water-bearing lenses.
Vashon aquifer (Qva)	40-100	Sand and gravel, mostly under water-table (u Unit is not fully saturated in most areas. Spr exposed along coastal bluffs. Quality of wat seawater intrusion in some areas.
Whidbey confining unit (Qw)	40-130	Generally clay, silt, fine-grained sand of low floodplain origin with local occurrences of till contains water-bearing lenses.
Double Bluff aquifer (Qdb)	Unknown	Sand and gravel. Commonly occurs at or be water is affected by seawater intrusion in so aquifer.
Bedrock (Br)	- -	Mostly igneous and fine-grained sedimentary water where rocks are fractured. Well yields

Figure 5.--Lithologic and hydrologic characteristics of the hydro

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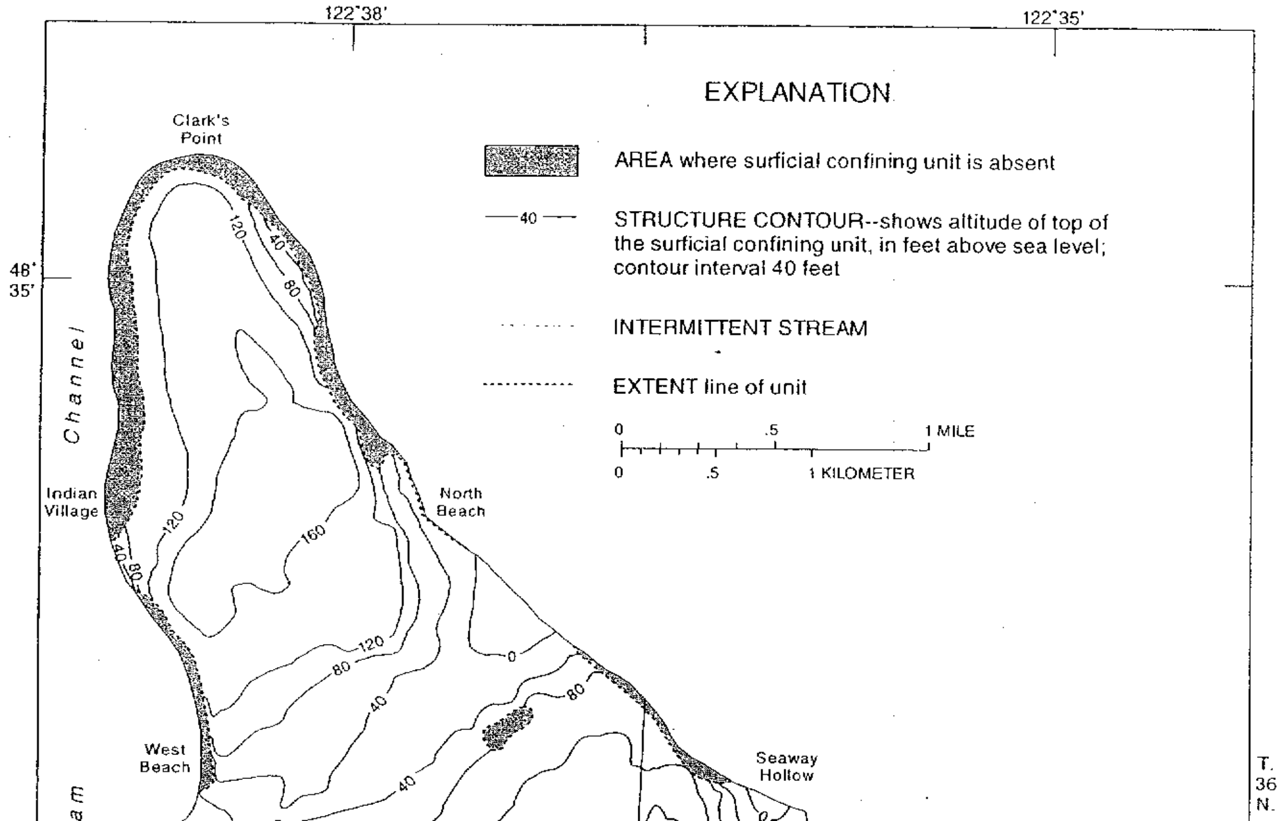
122°38'
122°35'
48°
35'
EXPLANATION
AREA where surficial confining unit is absent
STRUCTURE CONTOUR--shows altitude of top of the surficial confining unit, in feet above sea level; contour interval 40 feet
40
INTERMITTENT STREAM
EXTENT line of unit
0
.5
1 MILE
0
.5
1 KILOMETER
Clark's Point
Channel
Indian Village
North Beach
West Beach
Seaway Hollow
T. 36 N.
120
40
80
160
0

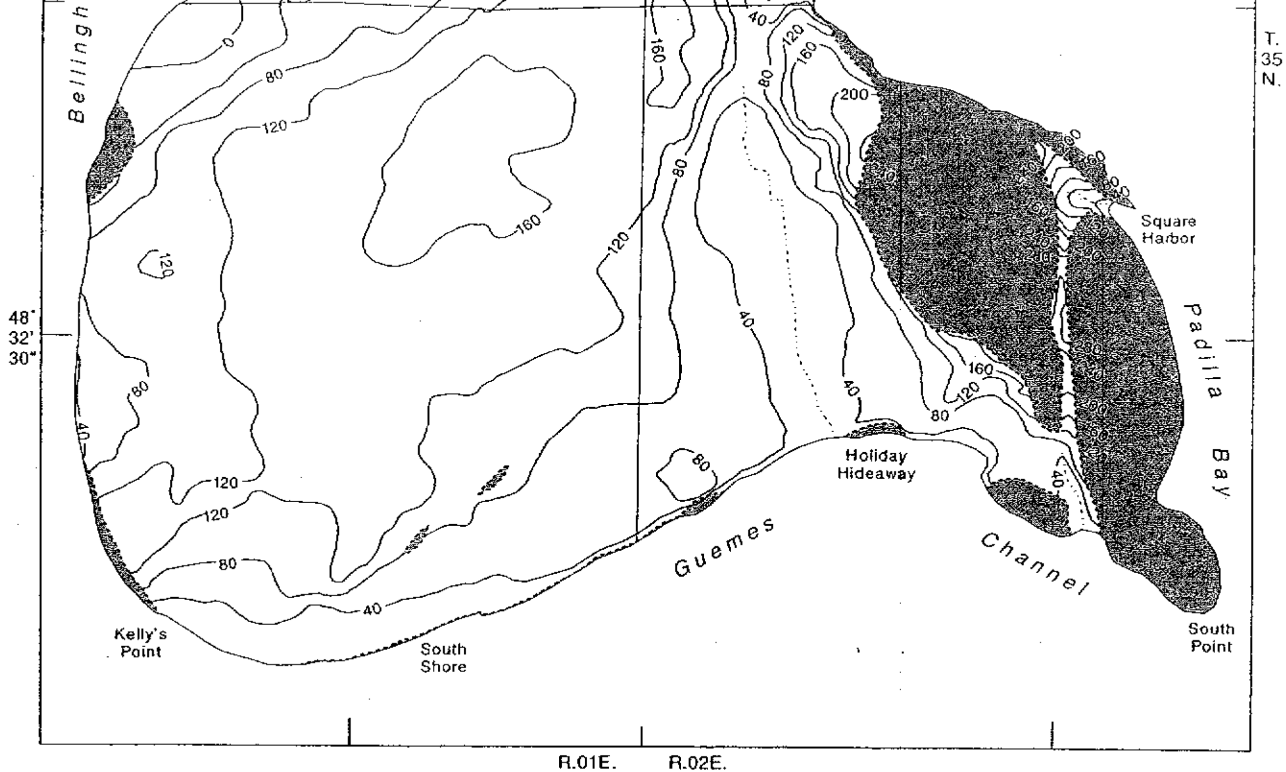

Figure 6.--Extent and altitude of the top of the surficial confining unit.

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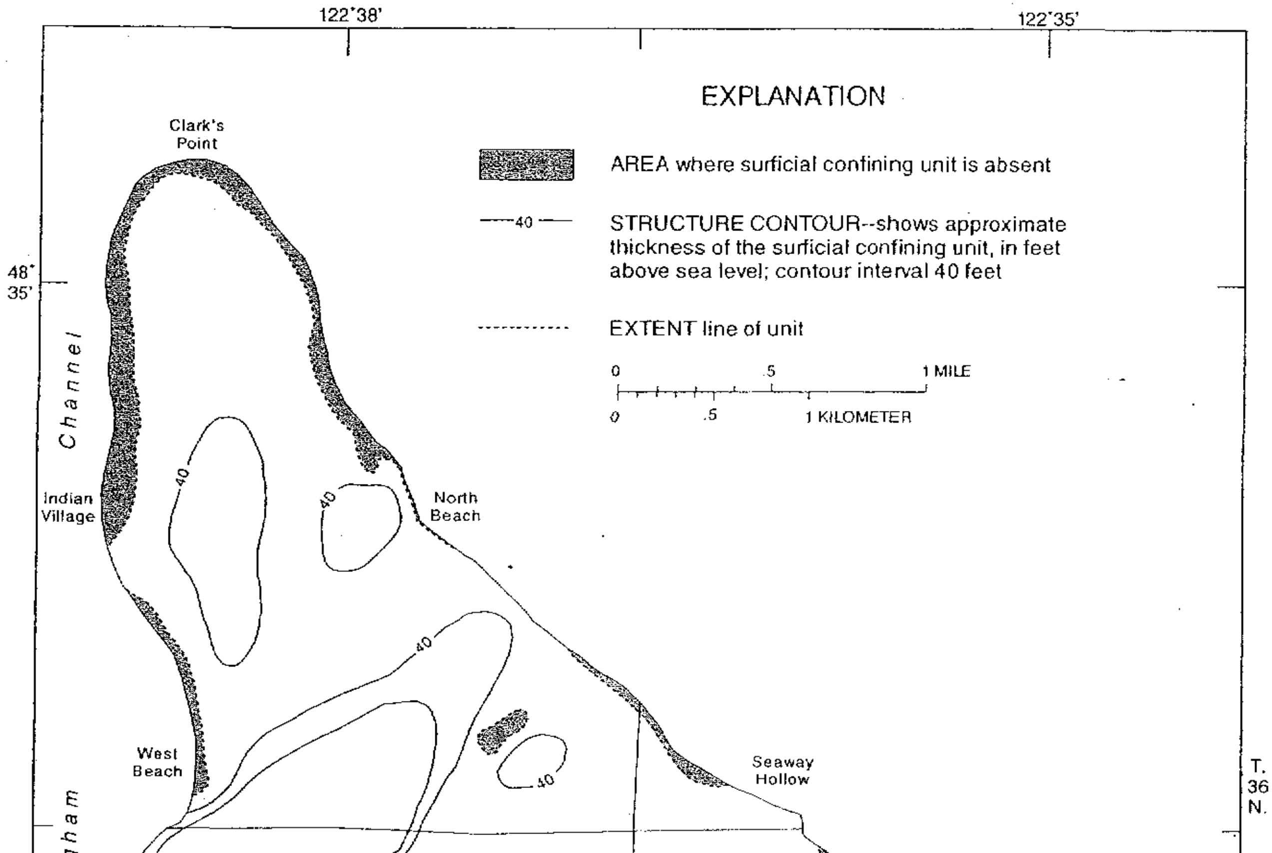

122°38'
122°35'
EXPLANATION
AREA where surficial confining unit is absent
40
STRUCTURE CONTOUR--shows approximate thickness of the surficial confining unit, in feet above sea level; contour interval 40 feet
EXTENT line of unit
0
.5
1 MILE
0
.5
1 KILOMETER
Clark's Point
48° 35'
Channel
Indian Village
North Beach
West Beach
Seaway Hollow
40
40
40
40
T. 36 N.

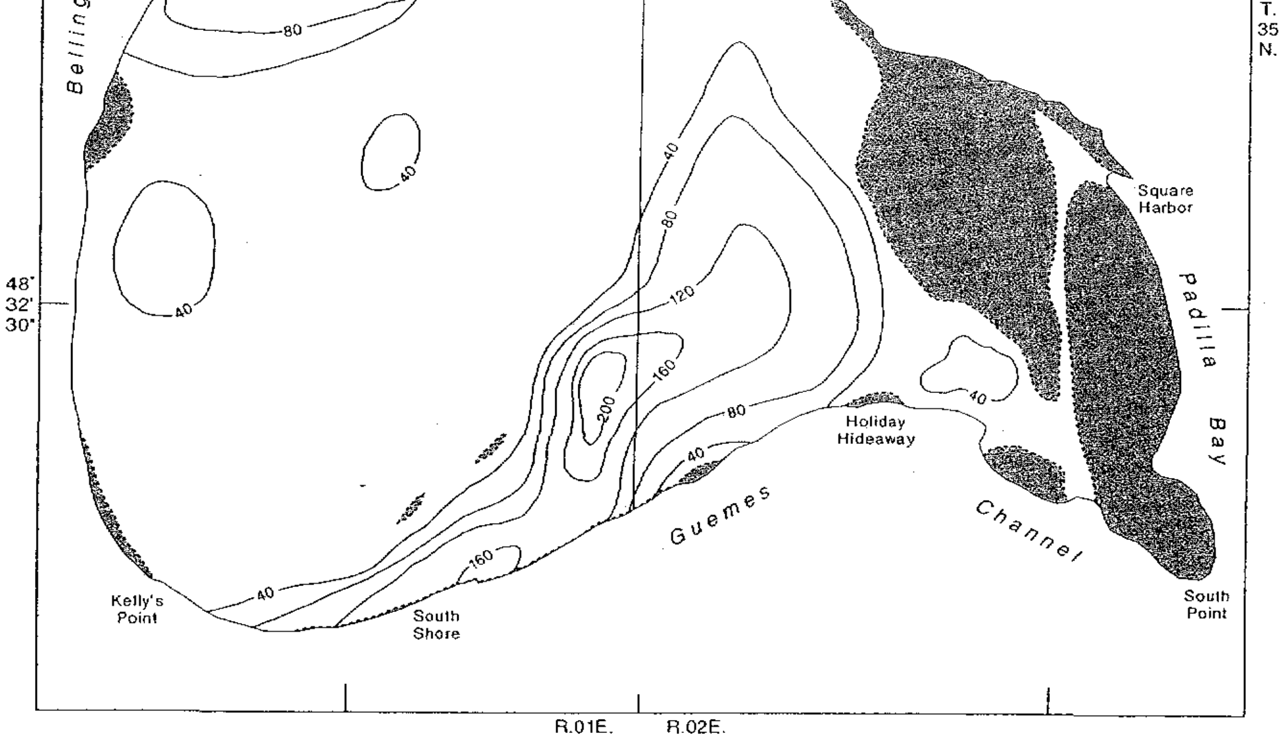

Figure 7.--Extent and thickness of the surficial confining unit.

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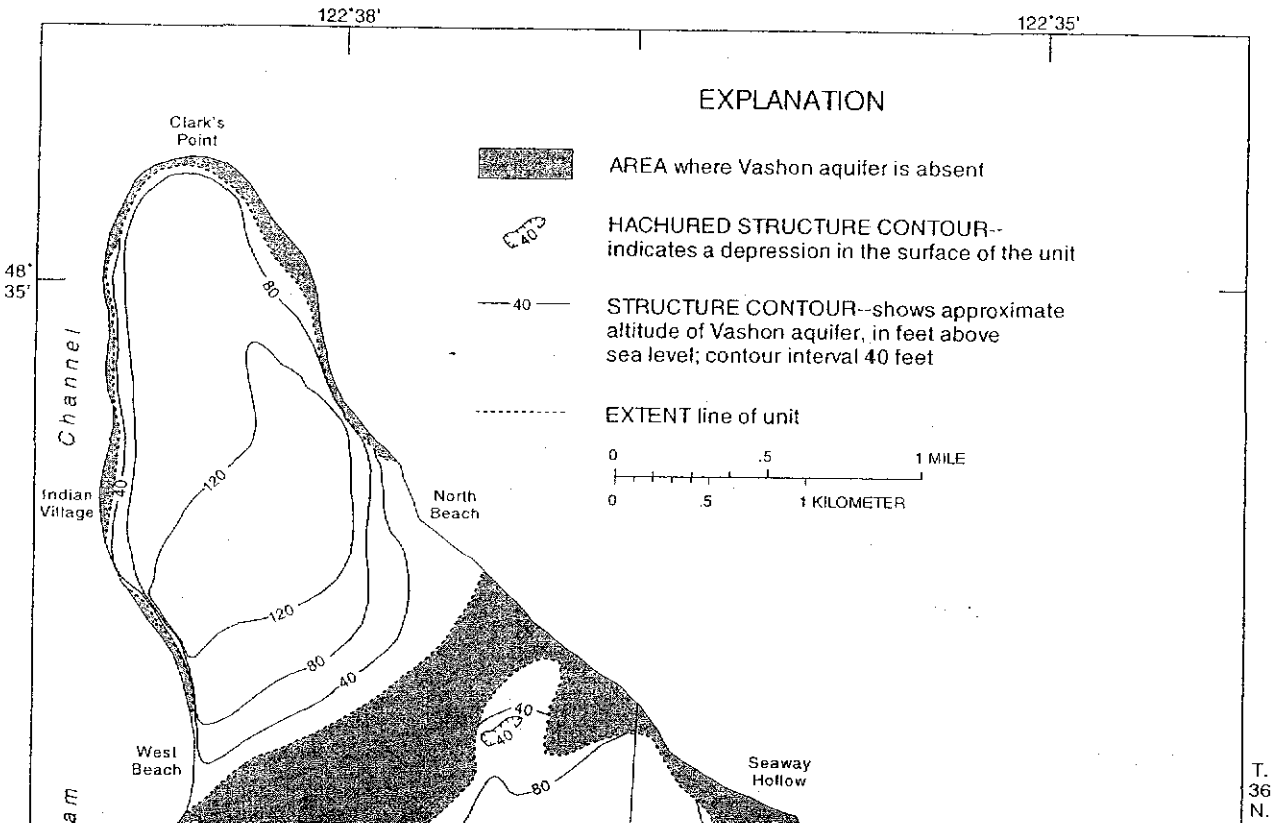
520-21


122°38'
122°35'
48°
35'
EXPLANATION
AREA where Vashon aquifer is absent
HACHURED STRUCTURE CONTOUR--indicates a depression in the surface of the unit
STRUCTURE CONTOUR--shows approximate altitude of Vashon aquifer, in feet above sea level; contour interval 40 feet
EXTENT line of unit
0 .5 1 MILE
0 .5 1 KILOMETER
Clark's Point
Channel
Indian Village
North Beach
West Beach
Seaway Hollow
T. 36 N.

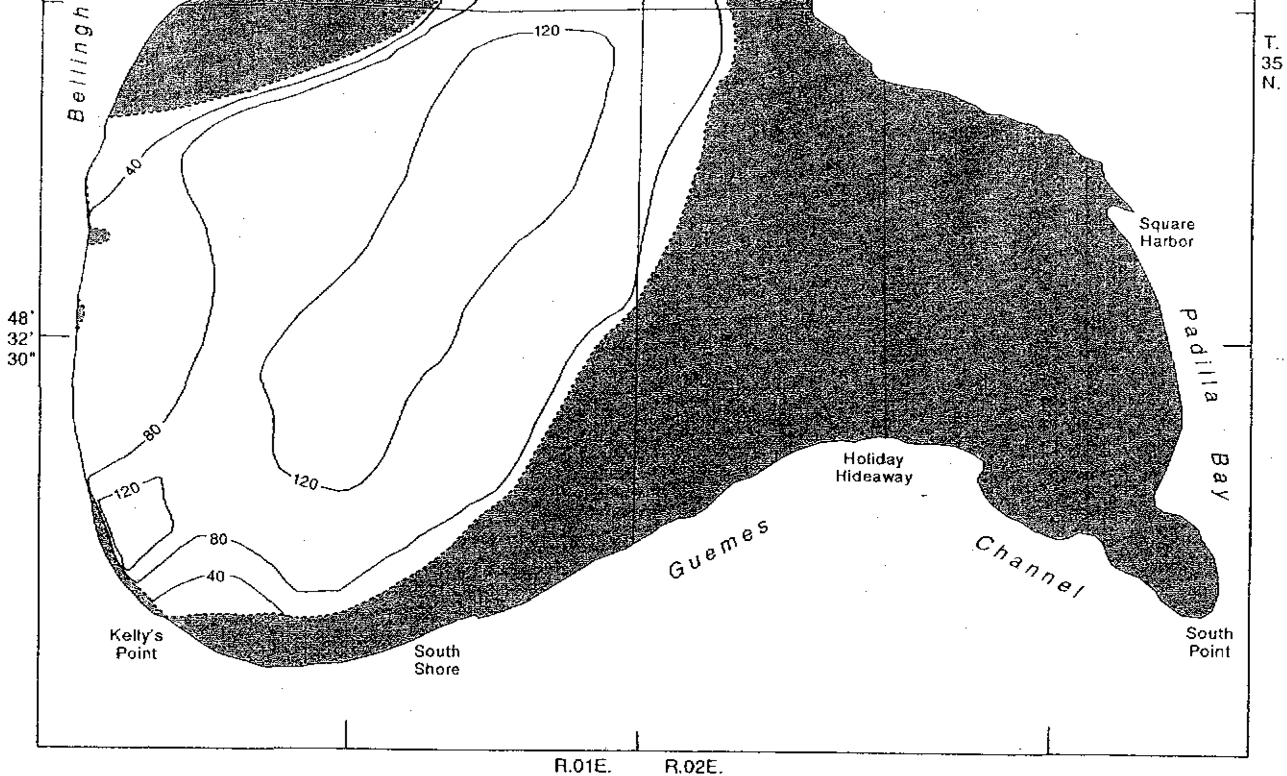


Figure 8.--Extent and altitude of the top of the Vashon aquifer.

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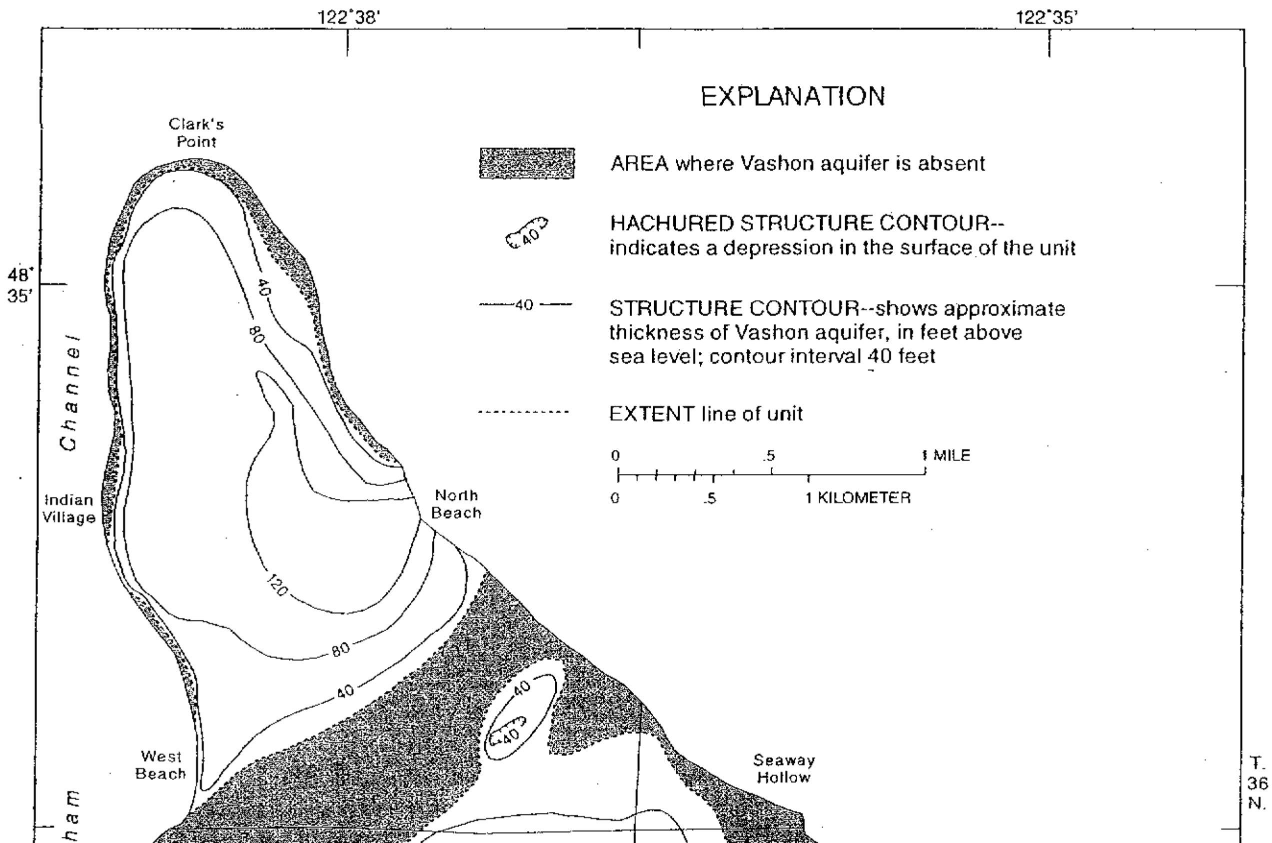

122°38'
122°35'
48°
35'
EXPLANATION
AREA where Vashon aquifer is absent
HACHURED STRUCTURE CONTOUR--
indicates a depression in the surface of the unit
STRUCTURE CONTOUR--shows approximate
thickness of Vashon aquifer, in feet above
sea level; contour interval 40 feet
EXTENT line of unit
0
.5
1 MILE
0
.5
1 KILOMETER
Clark's
Point
Channel
Indian
Village
North
Beach
West
Beach
Seaway
Hollow
40
80
120
T.
36
N.

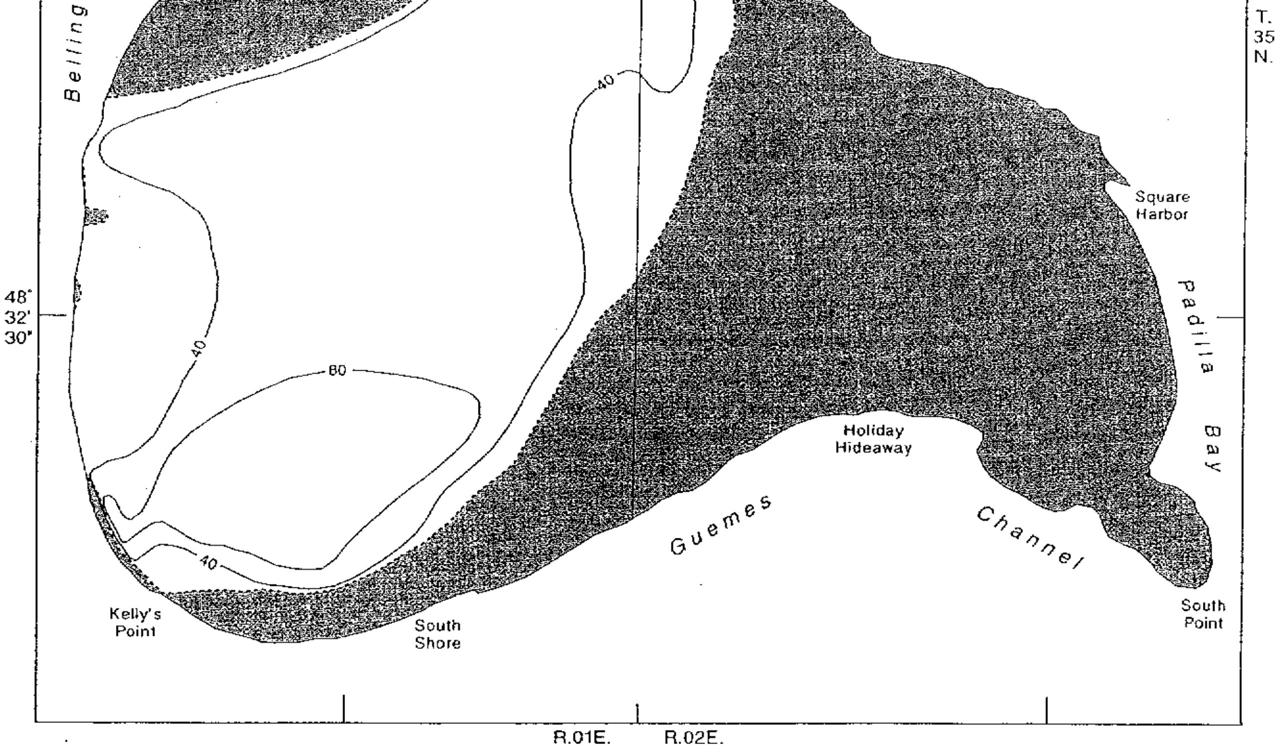


Figure 9.--Extent and thickness of the Vashon aquifer.

0534

520-23

rather than islandwide. The thickness of the unit is commonly 40 to 80 feet, with a maximum thickness slightly greater than 120 feet on the northern part of the island (fig. 9).

The Whidbey confining unit is composed mostly of floodplain clay, silt, fine-grained sand, and peat. A poorly permeable layer of till at the top of the underlying Double Bluff Drift is included with this unit because it has similar hydrologic properties. Generally, the unit is poorly permeable, but it locally contains productive sand lenses; 17 inventoried wells tap productive zones within this unit. The top of the unit ranges from approximately 80 feet above sea level to 80 feet below sea level (fig. 10). The unit occurs at depth throughout much of the island and is commonly 40 to 130 feet thick (fig. 11).

The Double Bluff aquifer consists of sand and gravel outwash and underlies all but the eastern end of the island. In terms of use, the Double Bluff aquifer is the principal aquifer on the island--about half of the inventoried wells on the island obtain water from this unit. The top of the unit ranges from approximately 40 feet above sea level to approximately 160 feet below sea level (fig. 12). The total thickness of the unit is unknown because drilling generally stops once the unit is penetrated sufficiently to yield water

Although more precise methods are available, they require aquifer-test data and (or) analyses of core samples of the unit. Only data from those wells that had a driller's log containing discharge rate, time of pumping, drawdown, static water level, well-construction data, and lithologic log were used.

Two different sets of equations were used to estimate hydraulic conductivity, depending on how the well was finished. For wells that had a screened, perforated, or open-hole interval (a section of a well, usually in bedrock, where no casing or screen exists), the modified Theis equation (Ferris and others, 1962) was first used to estimate transmissivity values. The Theis equation is:

$$s = \frac{Q}{4\pi T} \ln \frac{2.25\ Tt}{r^2 S} \qquad (1)$$

where

- s = drawdown in the well, in feet;
- Q = discharge, or pumping rate, of the well, in ft^3/d;
- T = transmissivity of the hydrogeologic unit, in ft^2/d;

at required rates--commonly 10 to 15 feet below the top of the unit.

The bedrock confining unit is composed of igneous and fine-grained marine sedimentary rocks. Locally it can yield water where the rocks are faulted or fractured, but yields are generally small. Only five inventoried wells, all located on the southeastern end of the island, are completed in this unit. They range in depth from 80 to 403 feet and their yields range from 0.25 to 7 gal/min.

An estimate of the horizontal hydraulic conductivity of each hydrogeologic unit is helpful in understanding the movement and availability of water within the unit. Hydraulic conductivity is a measure of a material's ability to transmit water and is dependent on the size, shape, and arrangement of the particles in unconsolidated materials, or on the degree of fracturing in consolidated bedrock. Because these characteristics vary greatly within each hydrogeologic unit on Guemes Island, hydraulic conductivity values also are expected to vary greatly.

Values of horizontal hydraulic conductivity were estimated for each unit on the basis of the specific capacity of wells completed in that unit. The specific capacity of a well is the ratio of its discharge (yield) to its total drawdown (static water level minus pumping water level).

t = length of time the well was pumped, in days;

r = radius of the well, in feet; and

S = storage coefficient, a dimensionless number.

A computer program was used to solve the equation for transmissivity (T) using Newton's iterative method (Carnahan and others, 1969). Next, the following equation was used to calculate horizontal hydraulic conductivity:

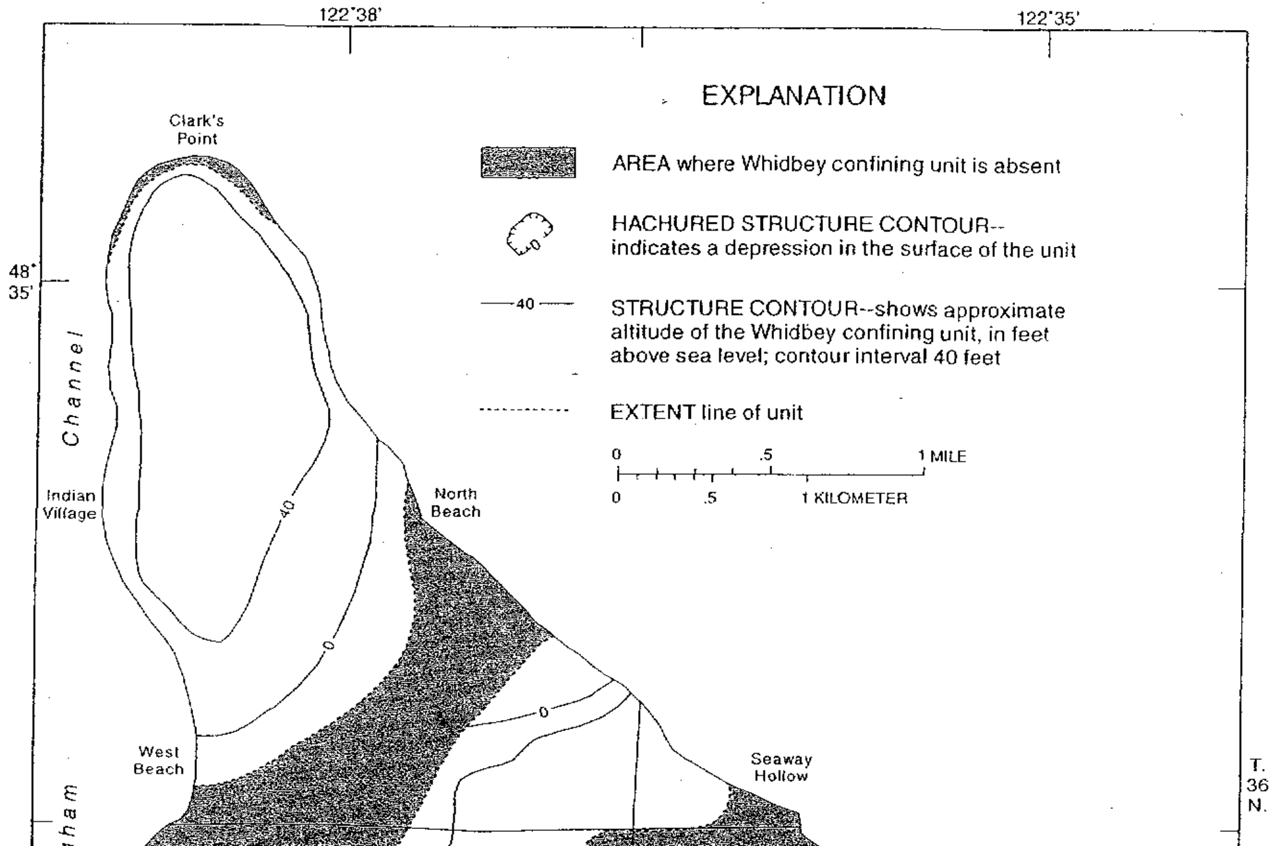
$$K_h = T/b \qquad (2)$$

where

K_h = horizontal hydraulic conductivity of the hydrogeologic unit, in ft/d;

T = transmissivity, as calculated above; and

b = thickness of the hydrogeologic unit, in feet, approximated using the length of the open interval as reported in the driller's report.



122°38'
122°35'
48°
35'
EXPLANATION
AREA where Whidbey confining unit is absent
HACHURED STRUCTURE CONTOUR--
indicates a depression in the surface of the unit
STRUCTURE CONTOUR--shows approximate
altitude of the Whidbey confining unit, in feet
above sea level; contour interval 40 feet
EXTENT line of unit
0
.5
1 MILE
0
.5
1 KILOMETER
Clark's
Point
Channel
Indian
Village
North
Beach
40
0
West
Beach
Seaway
Hollow
T.
36
N.

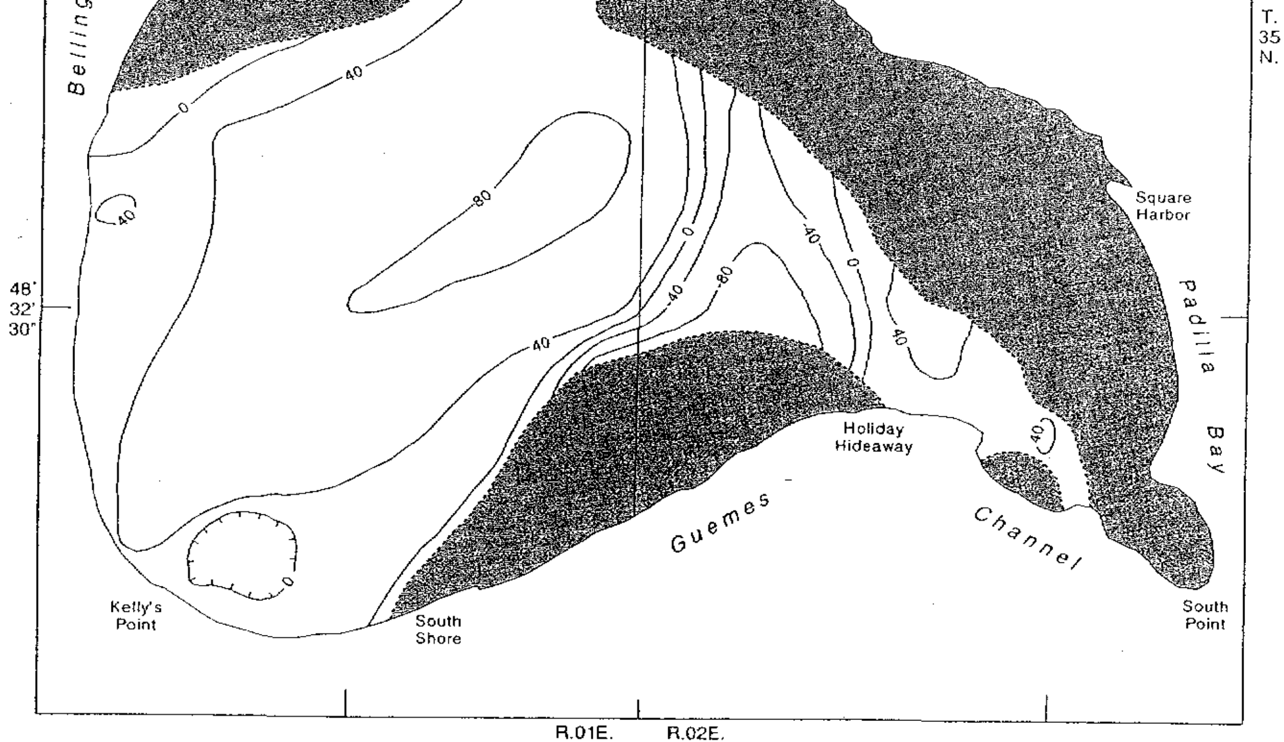


Figure 10.--Extent and altitude of the top of the Whidbey confining unit.

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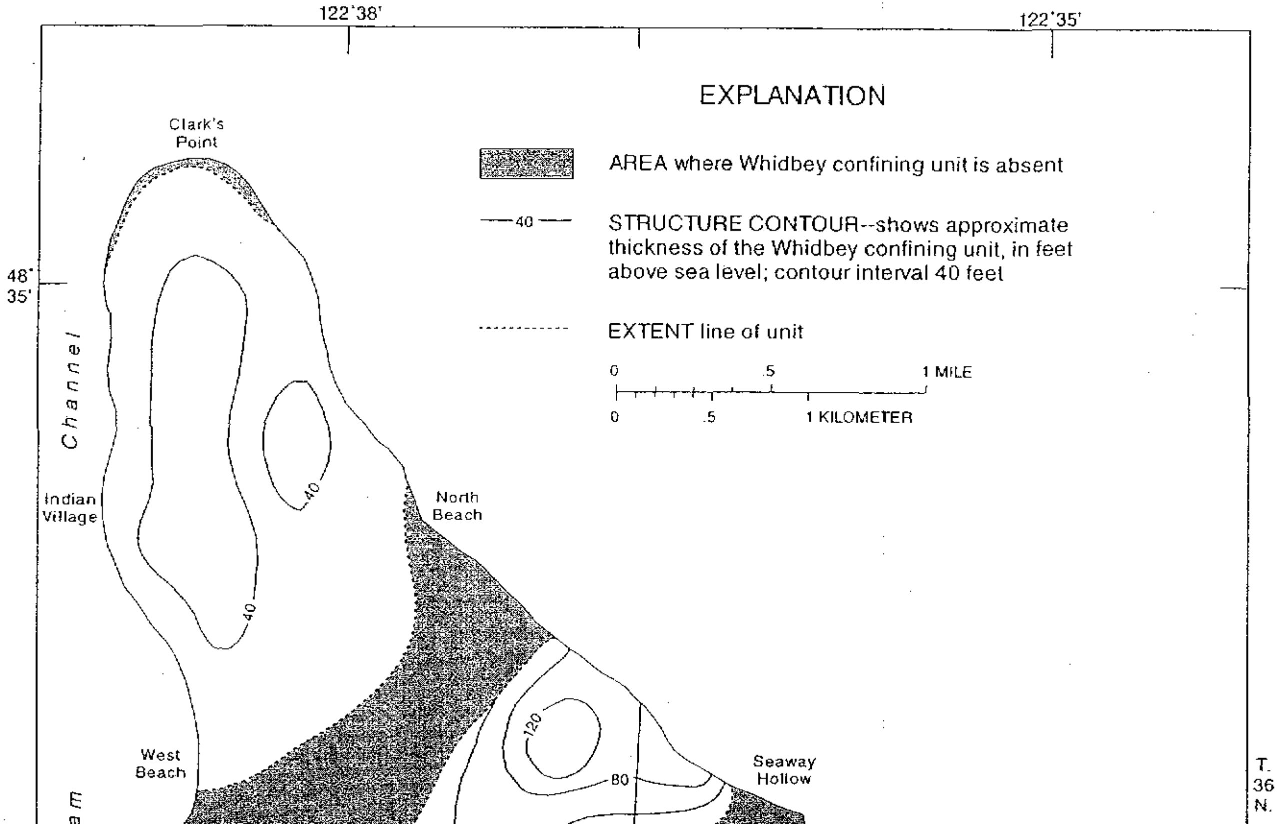

122°38'
122°35'
48°
35'
EXPLANATION
AREA where Whidbey confining unit is absent
40
STRUCTURE CONTOUR--shows approximate thickness of the Whidbey confining unit, in feet above sea level; contour interval 40 feet
EXTENT line of unit
0
.5
1 MILE
0
.5
1 KILOMETER
Clark's Point
Channel
Indian Village
North Beach
40
40
120
80
West Beach
Seaway Hollow
T. 36 N.

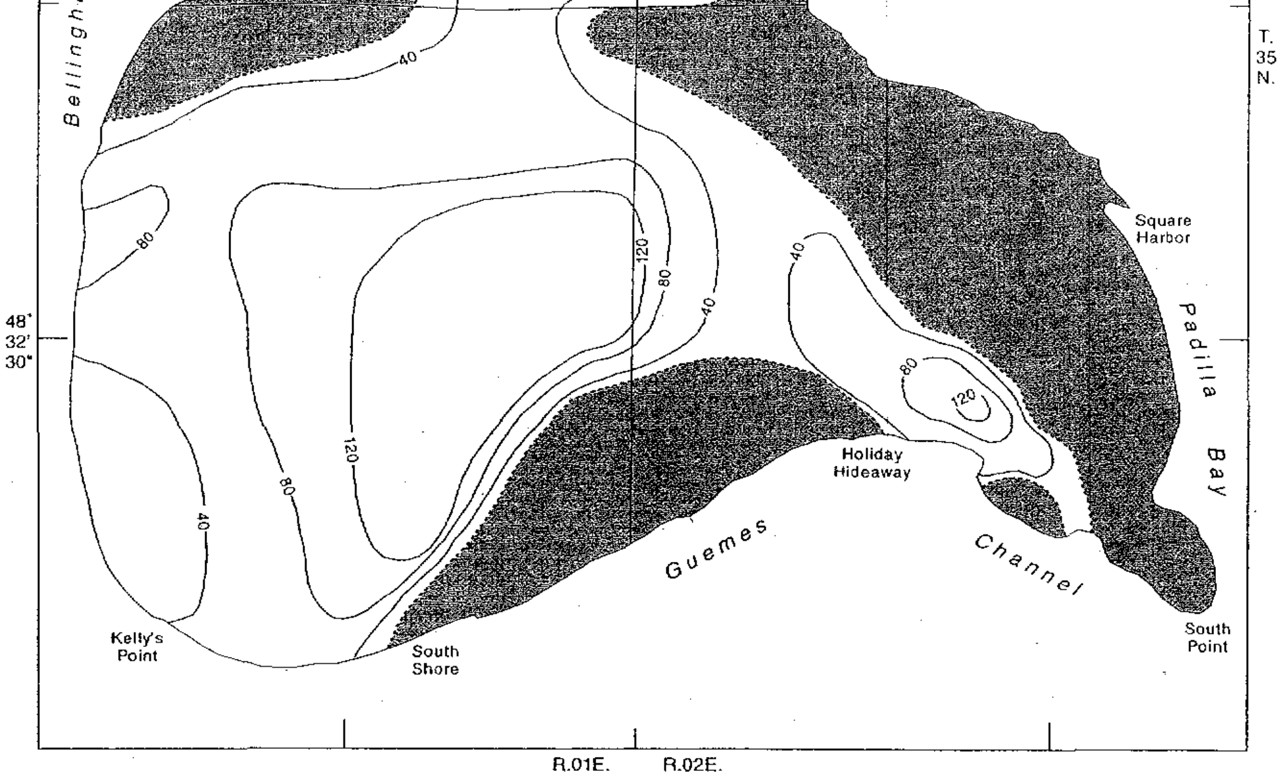
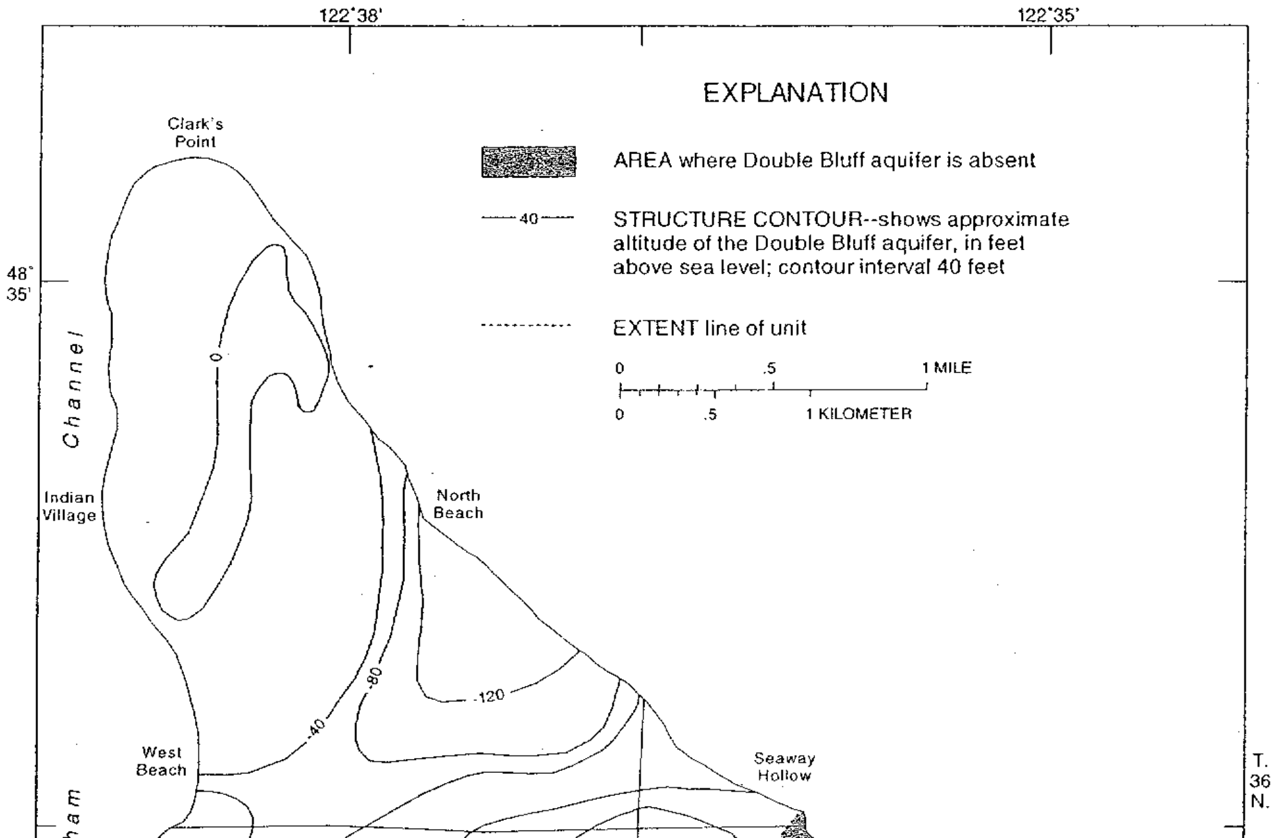


Figure 11.--Extent and thickness of the Whidbey confining unit.

0537

520-26



122°38'
122°35'
EXPLANATION
AREA where Double Bluff aquifer is absent
40
STRUCTURE CONTOUR--shows approximate altitude of the Double Bluff aquifer, in feet above sea level; contour interval 40 feet
EXTENT line of unit
0
.5
1 MILE
0
.5
1 KILOMETER
Clark's Point
48° 35'
Channel
Indian Village
North Beach
0
-40
-80
-120
West Beach
Seaway Hollow
T. 36 N.

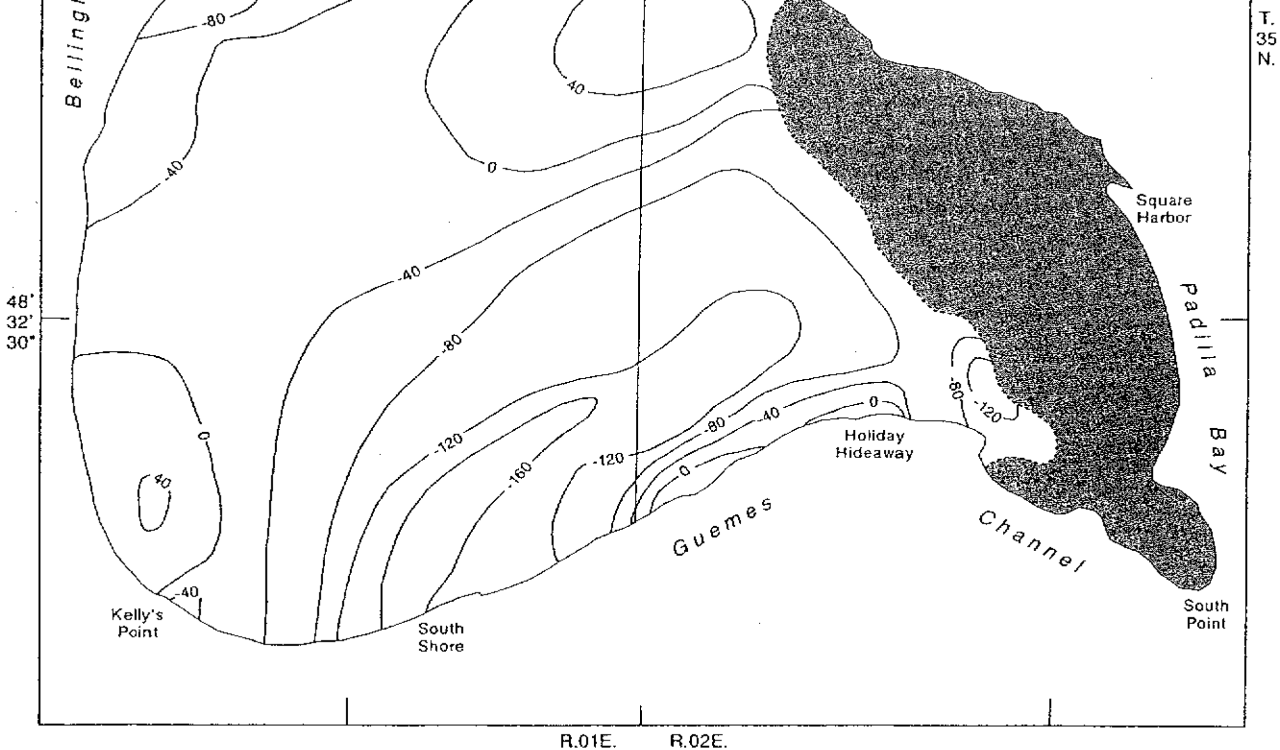


Figure 12.--Extent and altitude of the top of the Double Bluff aquifer.

0538

570-27

The use of the length of a well's open interval to approximate the thickness of a hydrogeologic unit may overestimate values of K_h. Nevertheless, this approximation is necessary because the equations used assume that virtually all flow of water to the well is horizontal. Horizontal flow is much greater than vertical flow in most unconsolidated deposits because the materials typically are layered.

A second equation was used to estimate hydraulic conductivities for wells having only an open end, and thus no vertical dimension to the open interval. Bear (1979) provides an equation for hemispherical flow to an open-ended well just penetrating a hydrogeologic unit. When modified for spherical flow to an open-ended well within a unit, the equation becomes

$$K_h = \frac{Q}{4\pi sr} \qquad (3)$$

where

K_h = horizontal hydraulic conductivity of the hydrogeologic unit, in ft/d;

Q = discharge, or pumping rate of the well, in ft^3/d;

s = drawdown in the well, in feet; and

violating this assumption are likely to be less than those that would occur in trying to fit the Theis equation to the open-ended well geometry.

Individual values of hydraulic conductivity are reported in Appendix 1 and are summarized statistically for Qsc, Qva, Qw, and Qdb in table 2. Specific-capacity data were unavailable for Qb and Br. With the exception of Qsc, the median hydraulic conductivity values presented in table 2 are similar in magnitude to values reported by Freeze and Cherry (1979) for similar materials. Of significance in table 2 is the fact that the median values for the aquifers, 43 ft/d for Qva and 68 ft/d for Qdb, are similar. Although specific-capacity data were available for only one inventoried well completed in Qw, the estimated hydraulic conductivity value of 1.6 ft/d is reasonable for a semi-confining unit. The median value of 23 ft/d for Qsc, on the other hand, is probably skewed upward by the small data set (two wells) and the fact that data for confining beds are usually available only for areas where lenses of productive material exist. Hydraulic conductivity values for Qb would be expected to be similar to those for Qva and Qdb, whereas values for the bedrock would be expected to be much smaller. Median horizontal hydraulic conductivity values for bedrock have been found to be less than 1 ft/d in recent ground-water studies conducted in the Puget Lowland (S. E. Cox and s = drawdown in the well, in feet, and

r = radius of the well, in feet.

Equation 3 is based on the assumption that flow can occur equally in all directions; specifically, that horizontal and vertical hydraulic conductivities are equal. As discussed above, this is not likely to be true for unconsolidated deposits. However, the errors associated with

conducted in the Puget Lowland (S. E. Cox and G. L. Turney, USGS, written commun., 1993).

Precipitation and Recharge

In order to determine the areal and temporal distribution of precipitation, six precipitation gages were installed at various locations on the island in September 1991 and were visited and read weekly from October 1991 through

***Table 2.**--Summary of horizontal hydraulic conductivity values on Guemes Island, by hydrogeologic unit*

[--, not determined; Hydrogeologic unit: Qsc, Surficial confining unit; Qva, Vashon aquifer; Qw, Whidbey confining unit; and Qdb, Double Bluff aquifer]

Hydrogeologic unit	Number of wells	Hydraulic conductivity (feet per day)				
		Minimum	25th percentile	Median	75th percentile	Maximum
Qsc	2	16	--	23	--	30
Qva	10	9.5	25	43	130	900
Qw	1	--	--	1.6	--	--
Qdb	22	1.3	10	68	140	1,200

0539

520-28

December 1992. Gage locations were selected in order to obtain good geographic and topographic distribution across the island. Precipitation during 1992 ranged from 26.47 to 31.88 inches for the six stations. The total precipitation for 1992 at the nearest established weather station, in Anacortes, Wash., was 30.17 inches (National Oceanic and Atmospheric Administration, 1992). Monthly precipitation values at the six Guemes Island stations, tabulated in Appendix 3, were generally similar to values from Anacortes (fig. 13).

Average annual precipitation across Guemes Island ranges from approximately 22 in/yr on the west-central part of the island to approximately 28 in/yr on the easternmost part of the island (fig. 14). Average annual precipitation for the island is about 25 inches.

Precipitation measured at the Anacortes station during 1992 was 14.7 percent higher than the station's 32-year mean (26.31 inches; J. Ashby, Desert Research Institute, Western Regional Climate Center, written commun., 1993). In order to prepare a map showing the areal distribution of precipitation during an average year, the total 1992 precipitation observed at each of the six island stations was reduced by 14.7 percent and plotted on the map, and then the values were contoured.

Recharge of freshwater to the ground-water system

percentage of precipitation going to ground-water recharge decreases as average annual precipitation decreases. To estimate recharge for areas receiving less than 30 inches, the curves were extrapolated, as indicated by the dashed sections of the till and outwash curves in figure 15. Finally, because data existed only for generalized outwash and till in King County, estimates needed to be made for the specific geologic units exposed at land surface on Guemes Island. The Vashon outwash (Qva), the Double Bluff Drift (Qdb), and the Beach deposits (Qb) were assumed to have lithologic and hydrologic characteristics similar to the generalized outwash. Likewise, the Vashon till (Qvt) and Whidbey Formation (Qw) were assumed to have lithologic and hydrologic characteristics similar to the generalized till. Recharge to the Everson drift (Qe) and the overlying peat (Qp), however, was estimated to be half that of the till. Recharge to bedrock was estimated to be 0.5 in/yr, based on regional recharge maps developed during the Puget Sound Regional Aquifer System Analysis (J. J. Vaccaro, U.S. Geological Survey, written commun., 1993) that indicate recharge to bedrock in the Puget Lowland is typically less than 1 in/yr.

To calculate the areal distribution of recharge (fig. 16), the contour map of average annual precipitation (fig. 14) was overlaid on the map of surficial geology (plate 1). The total recharge on the island in an average year was calculated to be about 6 inches. This is the approximate

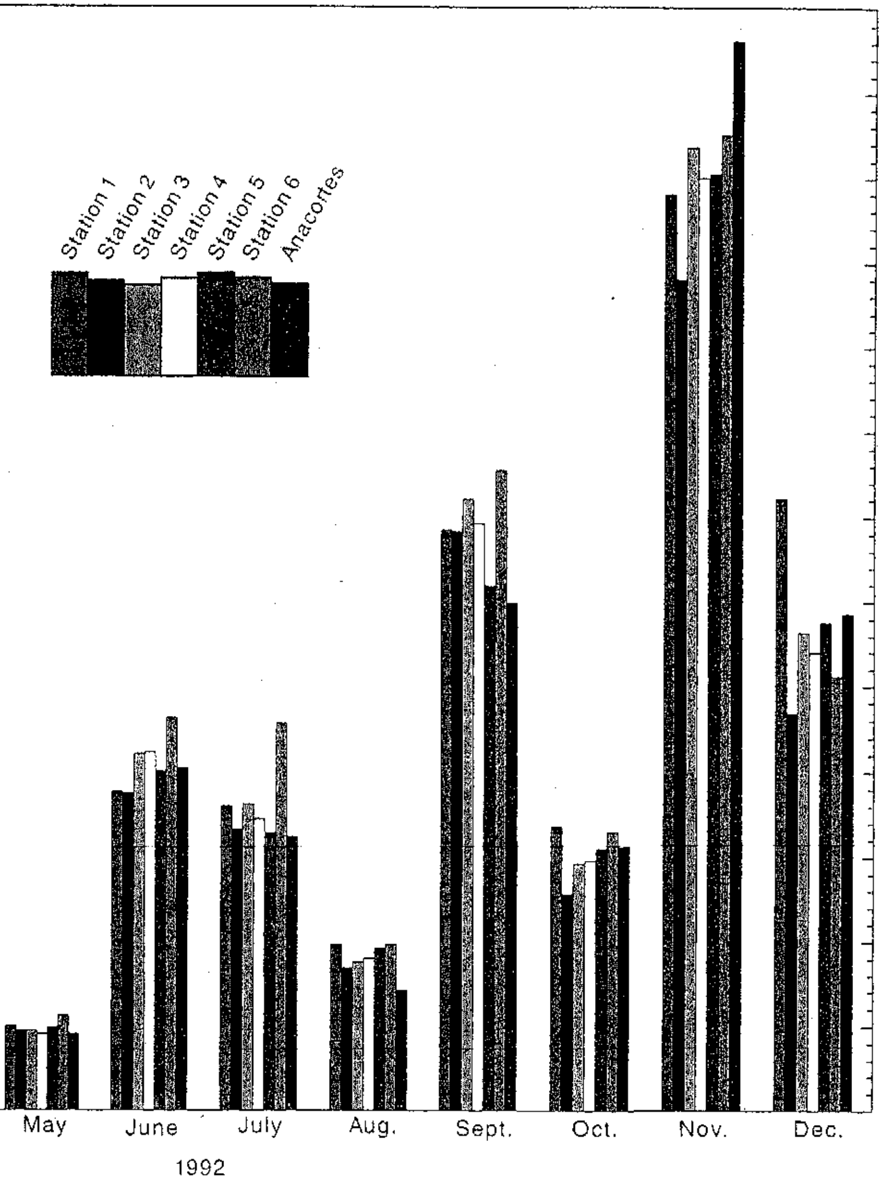
Recharge of freshwater to the ground-water system of Guemes Island is primarily from infiltration of rainfall. Recharge from septic-field leachate and excessive irrigation of lawns and gardens is relatively small. Precipitation recharges everywhere on the island except where ground water is discharging, such as from springs. Most of the recharge occurs in the wet winter months from November through February, when precipitation greatly exceeds evapotranspiration.

The approximate quantity of freshwater recharge to the hydrologic system of Guemes Island was estimated by using relations derived from work in southwestern King County, Wash., by D. G. Woodward (written commun., 1995). These relations are based on the application of a deep percolation (recharge) model developed by Bauer and Vaccaro (1987) that estimates percolation below the root zone. Regression equations determined for King County showed that precipitation and surficial geology were the most important variables in estimating recharge.

The relation of precipitation and ground-water recharge for outwash and till in King County is shown in figure 15. These curves are considered to apply to other areas of the Puget Lowland, including Guemes Island, where geology, vegetation, and climate are similar. The calculated to be about 6 inches. This is the approximate quantity of water that percolates below the root zone; it is not indicative of the actual quantity of water that reaches the island's deeper hydrogeologic units.

Compared with estimates of recharge made in other areas of western Washington, the 6 inches of recharge for Guemes Island is relatively small because of the island's lower average annual precipitation and the lower permeabilities of its surficial geologic materials. For example, recharge in east King County using the same technique was estimated to be 31 in/yr (Turney and others, 1995) and in Thurston County recharge was estimated to be 28 in/yr (Dion and others, 1994). However, annual precipitation in the east King and Thurston County study areas is approximately 57 and 51 inches, respectively, and only 55 and 35 percent of the surficial geologic materials are considered to be of low permeability.

The map showing the distribution of recharge (fig. 16) indicates that the areas of the island receiving the largest quantities of recharge (greater than 10 inches) generally are located in near-shore areas where coarse-grained units are exposed. In terms of recharge to the island's ground-water system, however, relatively high recharge in near-shore areas will have little effect on



nd (stations 1-6; see figure 14 for locations) and at Anacortes,

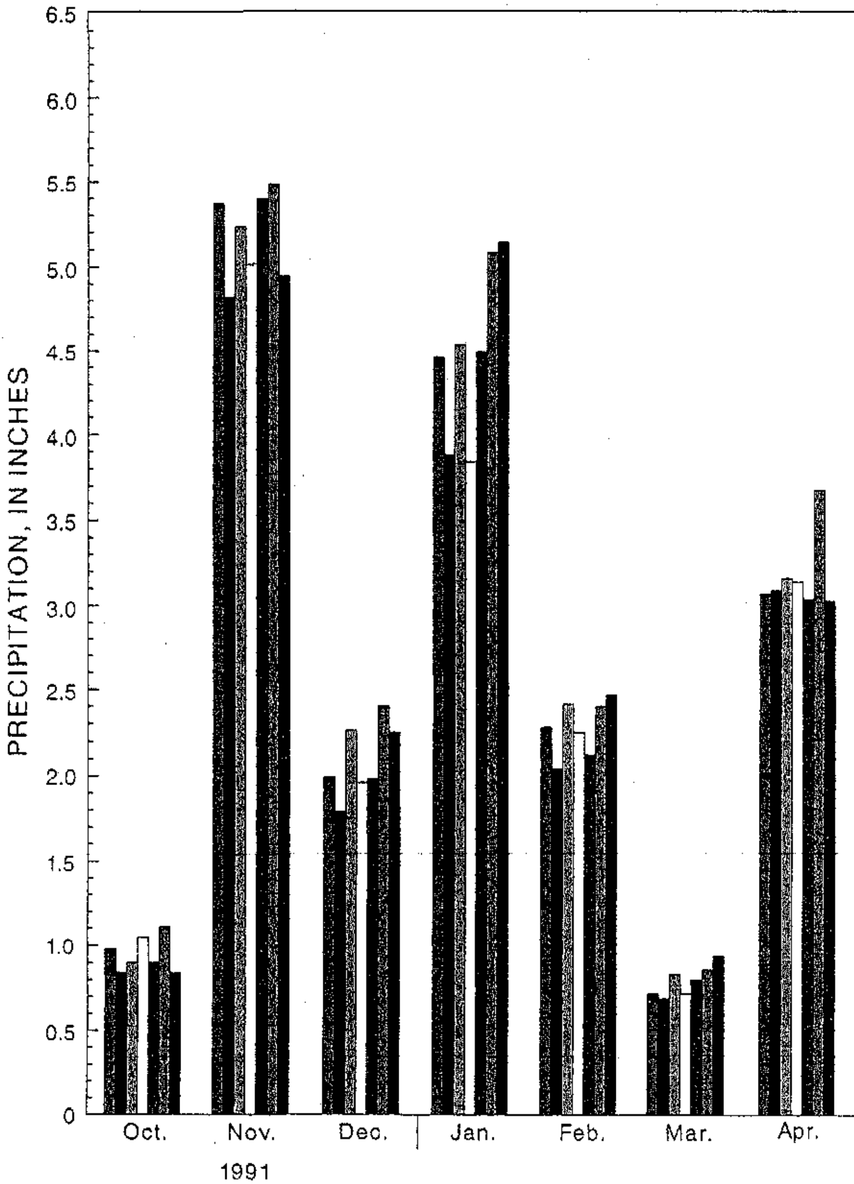


Figure 13.--Monthly precipitation measured on Guemes Isla
October 1991 through December 1992.

520-30

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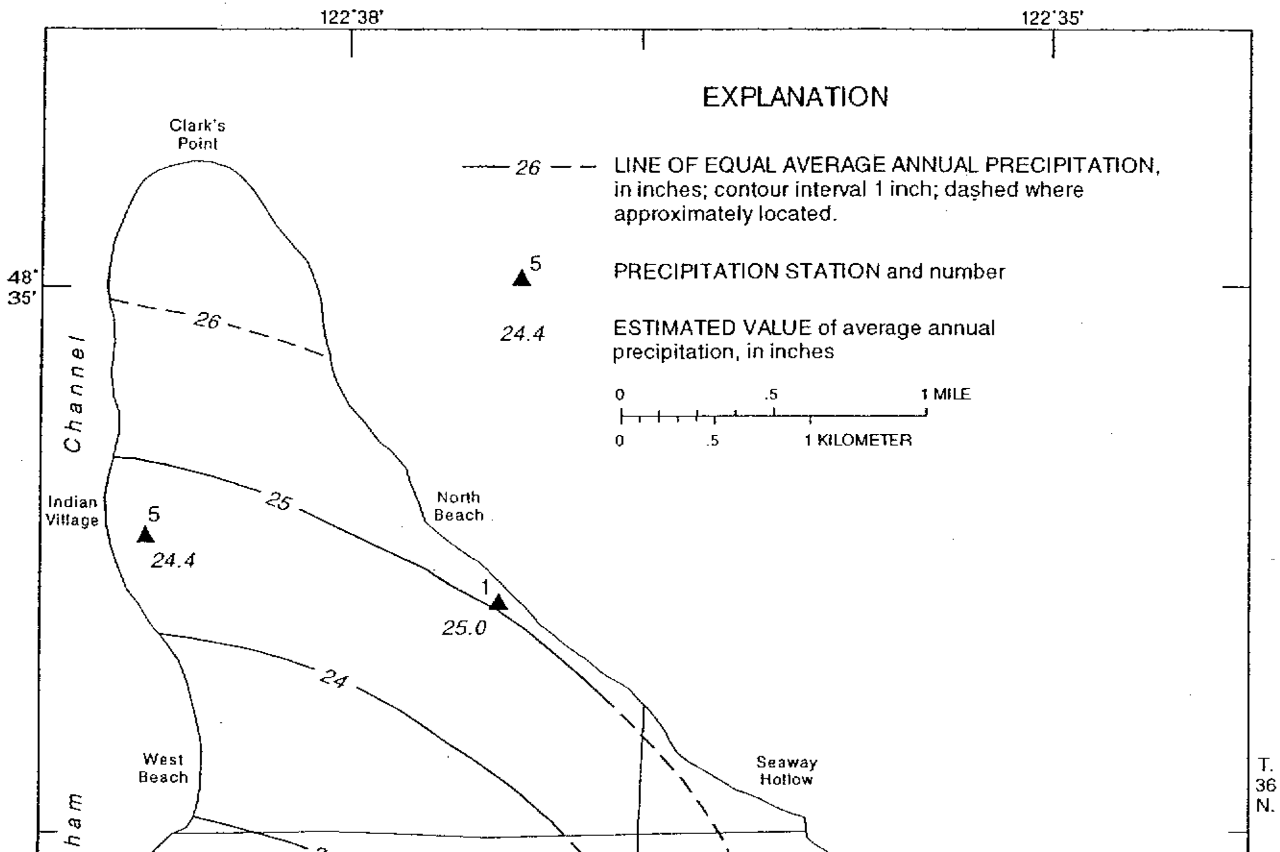
122°38'
122°35'
48°
35'
EXPLANATION
26 — — LINE OF EQUAL AVERAGE ANNUAL PRECIPITATION, in inches; contour interval 1 inch; dashed where approximately located.
5 PRECIPITATION STATION and number
24.4 ESTIMATED VALUE of average annual precipitation, in inches
0 .5 1 MILE
0 .5 1 KILOMETER
Clark's Point
Channel
Indian Village
North Beach
West Beach
Seaway Hollow
26
25
24
5
24.4
1
25.0
T. 36 N.

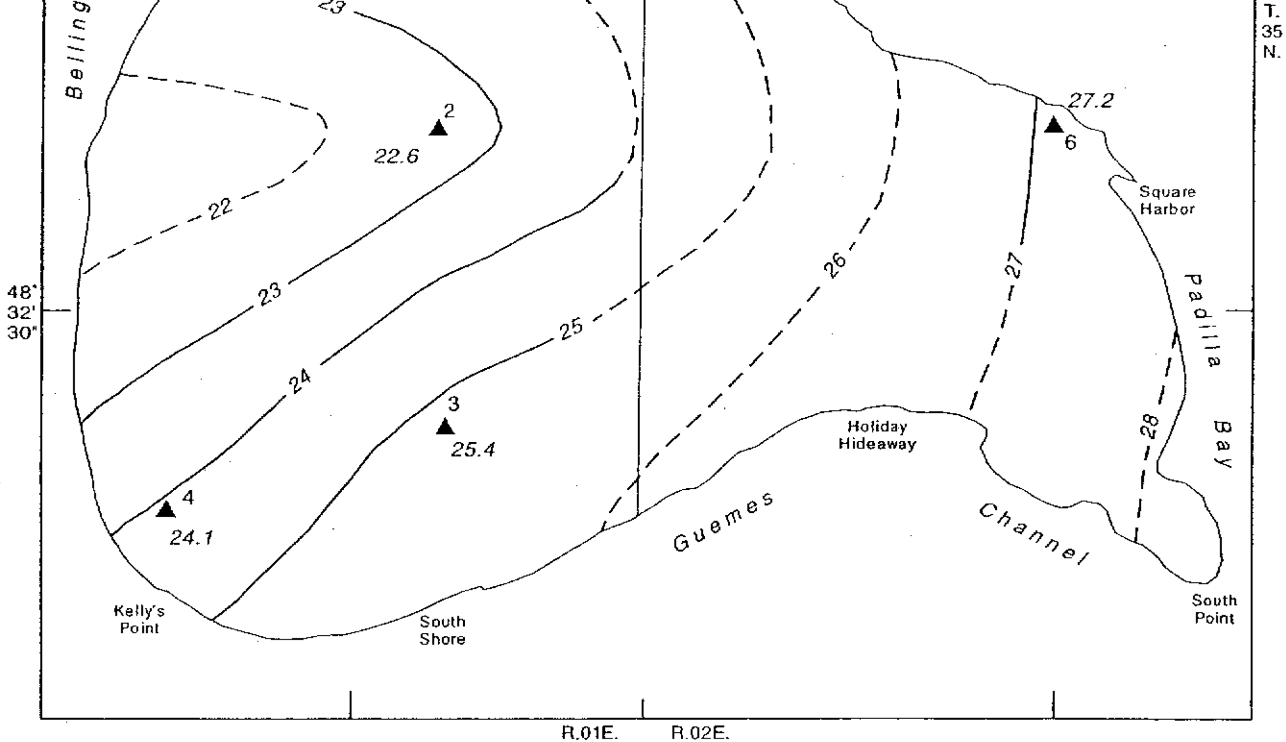

Figure 14.--Areal distribution estimate of average annual precipitation.

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520-31

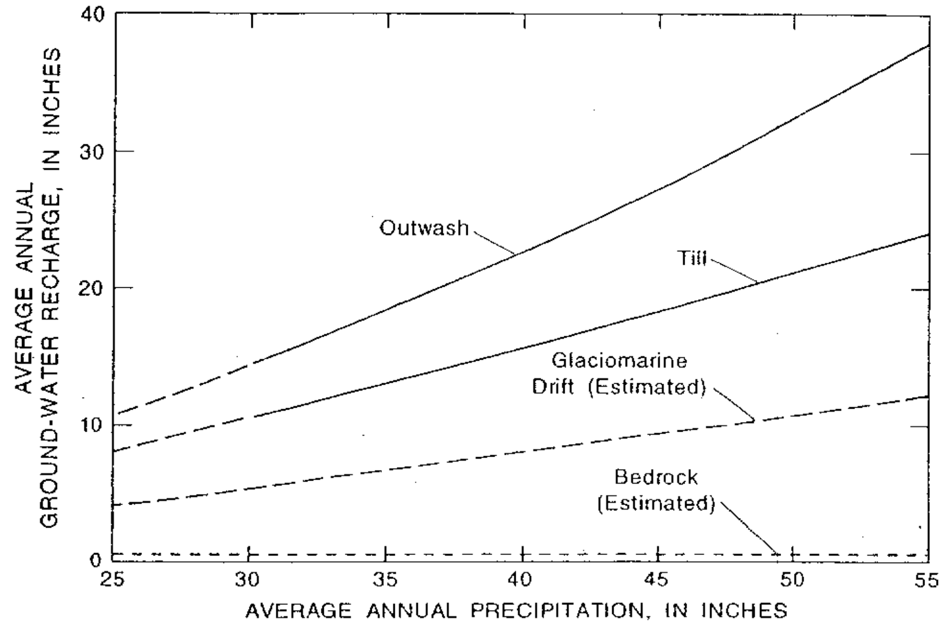


Figure 15.--Relation of precipitation to ground-water recharge on Guemes Island.

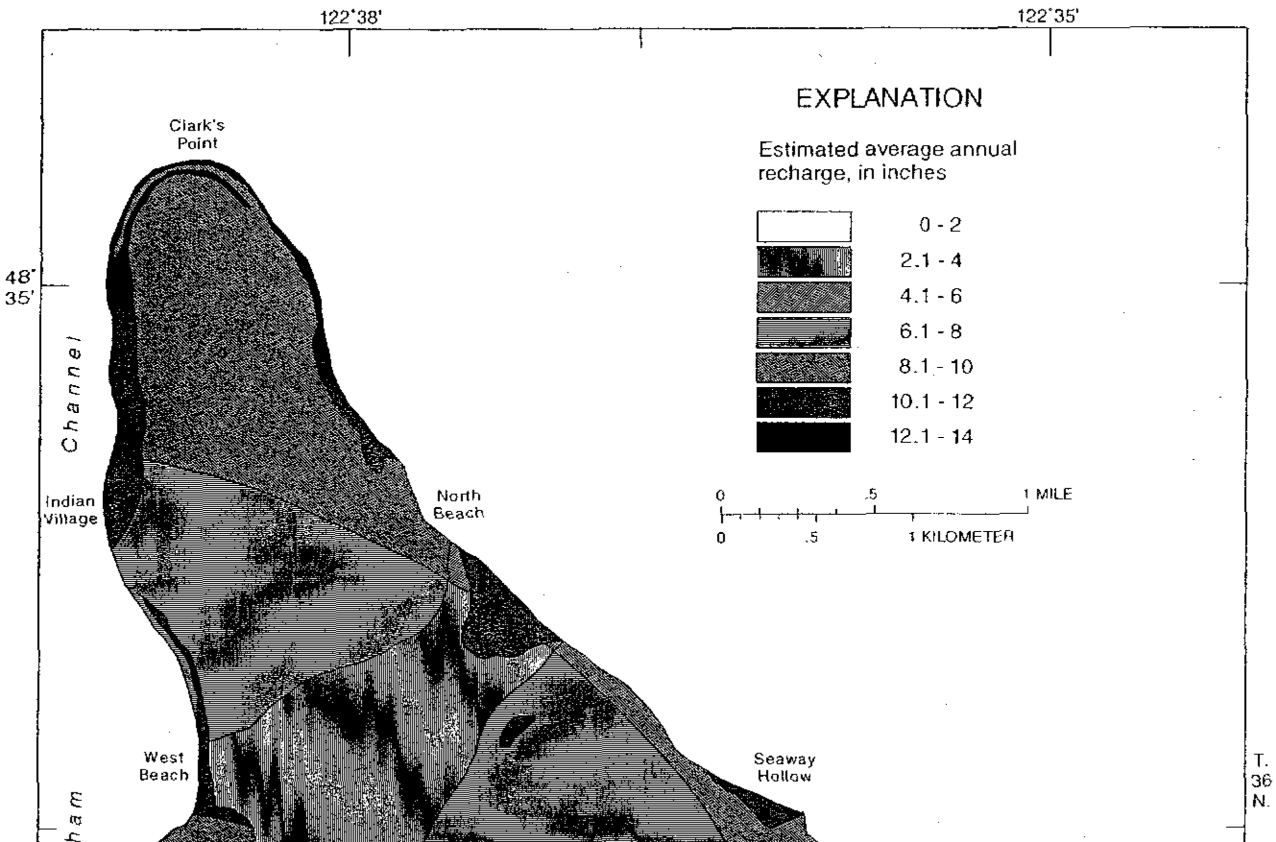
aquifers before the recharge water discharges to the sea. Areas receiving the smallest quantities of recharge (less than 6 inches) include the eastern end of the island where bedrock is exposed and the south-central and northwest-central parts of the island where fine-grained glaciomarine drift is exposed.

No attempt was made to determine the fate of recharge water in quantitative terms once it becomes part of the ground-water system. Some of the recharge water may immediately discharge to drainage ditches, and some may enter the deeper flow system to recharge the island's principal aquifers and not be discharged for months or years. Recharge to the island's principal aquifer (Qdb) would be dependent to a large extent on the vertical hydraulic conductivity values of overlying units. Such a determination would require a three-dimensional ground-water flow model.

Ground-Water Withdrawals

A summary of ground-water withdrawals during 1992 on Guemes Island, compiled by water-use category, is shown in table 3. Quantities of withdrawals were derived from information provided by the Skagit County Departments of Health, Planning, and Transportation, water system purveyors, U.S. Census Bureau, U.S. Department of Agriculture's Soil Conservation Service, and island residents. Water use was divided into three categories--livestock, public supply, and domestic self-supplied. Public supply and domestic self-supplied are further subdivided into year-round and seasonal use. Public supply has a third subdivision that includes ground water used for municipal purpose (fire department use, for example) or is lost due to pipe breakage, leaks, or flushing of lines. As shown in table 3, approximately 65 acre-feet of water was withdrawn through wells in 1992. About 70 percent of the total quantity was used for domestic self-supply, 28 percent for public supply, and 2 percent for livestock.

The livestock category includes ground-water withdrawals used for watering 178 cattle and 12 horses; these numbers were estimated on the basis of telephone surveys and actual field counts. Withdrawals for livestock were estimated by multiplying the cattle and horse populations by 7 and 12 gal/d, respectively, adding those numbers together, and then by multiplying the total by 365 days. Although the island's deer population and other wildlife consume water from stock troughs, the quantity was considered negligible for purposes of this study.


122°38'
122°35'
48° 35'
EXPLANATION
Estimated average annual recharge, in inches
0 - 2
2.1 - 4
4.1 - 6
6.1 - 8
8.1 - 10
10.1 - 12
12.1 - 14
0 .5 1 MILE
0 .5 1 KILOMETER
Clark's Point
Channel
Indian Village
North Beach
West Beach
Seaway Hollow
T. 36 N.

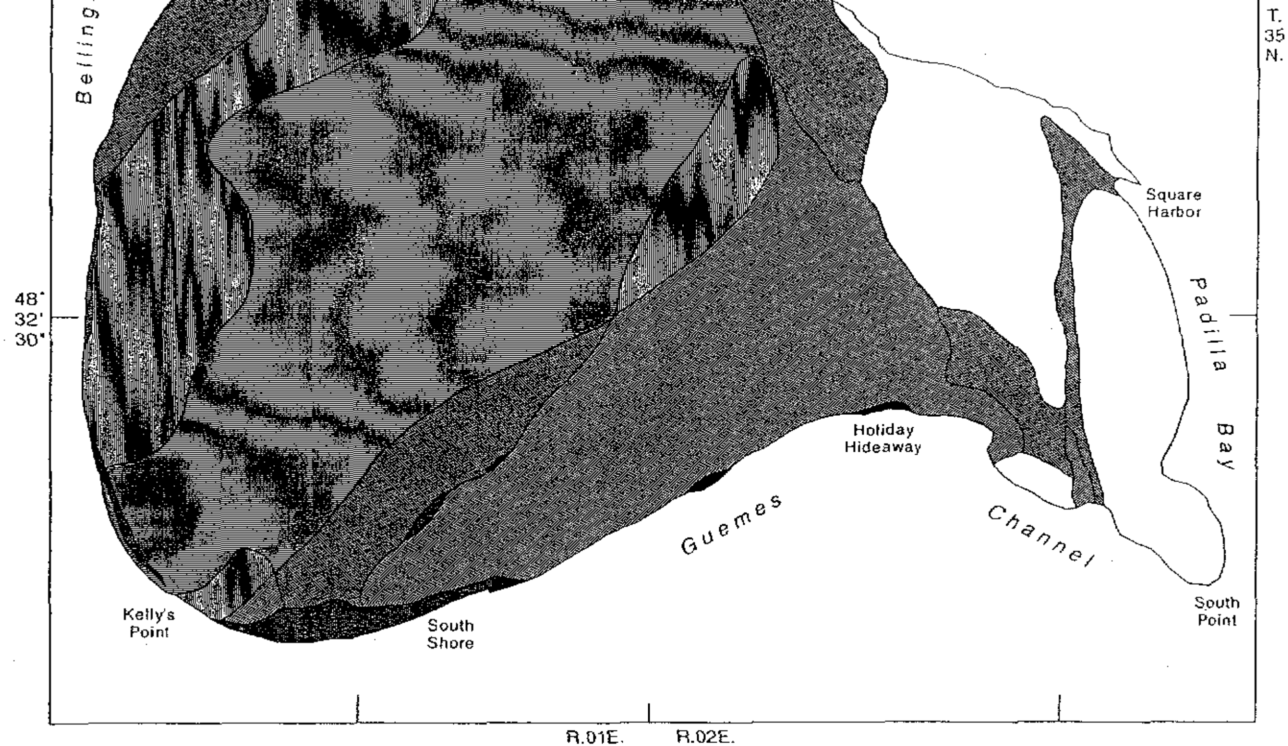


Figure 16.--Estimated areal distribution of recharge

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Table 3.--Estimated ground-water withdrawals on Guemes Island during 1992

Use category	Quantity		Percent
	Gallons	Acre-feet	
LIVESTOCK	462,000	1.4	2
PUBLIC SUPPLY			
Year-round residents	3,818,000	11.7	18
Seasonal residents	1,584,000	4.9	8
Reported transmission losses and municipal use	552,000	1.7	2
Subtotal	5,954,000	18.3	28
DOMESTIC SELF-SUPPLIED			
Year-round residents	9,709,000	29.8	46
Seasonal residents	4,930,000	15.1	24
Subtotal	14,639,000	44.9	70
Total	21,055,000	64.6	100

Public supply on Guemes Island includes ground-water withdrawals by 12 single-well systems with 5 to 17 connections, a 2-well system with 32 connections, and a 3-well system with 85 connections. Four of the larger distribution systems are metered. Each water supplier provided data on ground-water withdrawals, population served, and how that population was divided between year-round and seasonal users.

Withdrawals for each non-metered public-supply system were determined by adding together the quantity of water used at each hookup (service) on each non-metered system during the year. The quantity used at each service was calculated using the following formula:

$$W = 70(nd) \qquad (4)$$

where

W = withdrawal for the year, in gallons,

n = the number of people using the service, and

d = the number of days per year the service was used.

Number of days of service was assumed to be 365 for year-round residents and an estimate provided by each water system was used for the number of days for seasonal users. The factor of 70 represents a gallons-per-day-per-capita value for Guemes Island based on records of water use provided by the purveyor of the island's largest water system.

The domestic self-supplied category includes ground-water withdrawals for the year-round and seasonal residents who are not served by one of the public-supply systems. The same equation (4) presented above was used to determine withdrawals. For seasonal residents, however, the number of days of service (d) was estimated to be 42 by consensus of water system purveyors. In order to determine the number of people served in this category, it was necessary to determine the island's seasonal and year-round populations first and then to subtract from those numbers the number of people served by public-supply systems.

A population figure reflecting seasonal shifts was estimated using several sources of information. The year-round population for 1992, estimated to be 535, was projected from the 1990 U.S. Census Bureau figure of 496 by adding the number of housing unit increases on the island from 1990 to 1992 (35) multiplied by the Census Bureau's factor (calculated for Guemes Island) for permanent residents per housing unit (1.12). According to public-supply system records, about 25 percent of the peak population served is year-round, indicating that 75 percent is seasonal. Therefore, if the island's year-round population is 535, the peak population is estimated to be 2,140 (4 x 535), and the difference of 1,605 is the seasonal population. Guemes Island ferry traffic data and monthly water-use data provided by various water systems indicate that the island's peak population occurs between Memorial Day and Labor Day.

Approximate Water Budget of the Island

An approximate water budget, or distribution of precipitation, for a typical year on the island is presented in table 4. It includes estimates of component values, possible errors associated with each component value, and a likely range of values for each component. This water budget serves as a simple illustration of the fate of precipitation by roughly quantifying the distribution of water in the island's hydrologic system: precipitation, evapotranspiration, recharge, and runoff. Because errors associated with estimation of component values may be considerable, likely ranges of values are presented.

Table 4.--Approximate water budget of Guemes Island, reflecting uncertainties in estimation of component values
[--, no value]

	Estimated	Possible error due to	Likely range of component values

Hydrologic component	quantity (inches per year)	uncertainties in estimation (percent)	reflecting uncertain-ties in estimation (inches per year)
Precipitation	25	[1]±15	21-29
Fate of precipitation:			
Evapotranspiration	17	[2]±30	12-22
Recharge (gross)	6	[3]±75	2-10
Runoff (residual)	2	[5]±120	0-4
Total	25	--	--
Fate of recharge:			
Withdrawal by wells	.2	[4]±40	.1-.3
Natural discharge (net recharge)	5.8	[5]±115	0-12
Total	6	--	--

[1] From Winter (1981).

[2] From H. Bauer (U.S. Geological Survey, written commun., 1994).

[3] From N. Dion and J. Vaccaro (U.S. Geological Survey, written commun., 1993).

[4] Estimated during this study.

[5] Accumulated errors.

A value for potential evapotranspiration was estimated by using the Thornthwaite energy-budget method as described by Dunne and Leopold (1978), and then actual-evapotranspiration was calculated by performing soil-moisture budget calculations as described in Jones (1992). Variables used for these estimations include average monthly precipitation and temperatures from Anacortes; estimated root depths for forest and grassland in the island's dominant soil types; and soil-moisture content. Average annual evapotranspiration was estimated to be 17 in/yr (table 4), or 12-22 in/yr based on estimation errors of as much as 30 percent (H. Bauer, U.S. Geological Survey, written commun., 1994).

The value of 2 inches for runoff (table 4) is a residual; that is, it represents the quantity that remains after evapotranspiration (17 inches) and recharge (6 inches) are subtracted from precipitation (25 inches). Similarly, the value of 5.8 inches for natural discharge from the ground-water system also is a residual; it represents the remainder when the estimated quantity withdrawn by wells (0.2 inches) is subtracted from recharge (6 inches). The large cumulative errors associated with the runoff and natural discharge are evident in their likely ranges of values: 0-4 and 0-12 in/yr, respectively (table 4).

The water budget indicates that a large quantity of

Ground-Water Levels

Several types of water-level data were collected during the course of this investigation, including (1) historical water-level measurements made in several wells as part of earlier seawater-intrusion studies; (2) water levels measured during the inventory phase of this study in October 1991; (3) monthly water-level measurements made in 20 selected observation wells across the island from December 1991 through December 1992; and (4) measurements of water levels in two coastal wells at 5-minute intervals for up to 48 hours to determine if water levels in those wells were affected by ocean tides.

Comparisons of historical and recent water-level measurements made in several wells on the island do not indicate any significant long-term water-level changes. However, earlier measurements made in 1967 and 1978 (Walters, 1971; Dion and Sumioka, 1984) are from too few wells (five total) to assess adequately the islandwide long-term water-level fluctuations.

Water-level measurements made during the inventory phase of this study were used to construct maps of generalized water-level altitudes for the island's two principal aquifers, Qdb (fig. 17) and Qva (fig. 18). For reasons pointed out in the Study Methods section, the water-level precipitation goes to evapotranspiration and that a smaller quantity goes to recharging the island's ground-water system. The smallest quantity of precipitation goes to runoff. Of the water that goes to recharge, only a small fraction goes to pumped wells.

Although ground-water withdrawals account for only a small part of the annual recharge to the system, increased withdrawals could have significant impacts on the system for several reasons. Bredehoeft and others (1982) point out that any additional withdrawal or discharge superimposed on a previously stable system must be balanced by (1) an increase in recharge, (2) a decrease in discharge, (3) a loss of storage within the aquifer (reflected by lowering water levels in wells), or (4) by a combination of these factors. The possibility of increased natural recharge (increased infiltration of precipitation) is unlikely because it would involve major changes in regional weather patterns or increased infiltration rates. Likewise, a decrease in discharge (by pumping wells) is unlikely, because it would necessitate a decrease in water use. The third factor, a loss in fresh ground-water storage, is the one most likely to occur in response to increased withdrawals on the island. Long-term water-level data would be needed, however, in order to verify such changes in storage.

pointed out in the Study Methods section, the water-level altitudes shown in figures 17 and 18 are probably only accurate to plus or minus 10 feet. This helps explain why some of the water levels shown are slightly below sea level, a condition that would not be expected under natural conditions. Because of this uncertainty, the water-level maps were constructed to show areas of similar water-level altitudes rather than trying to contour the available point data.

Water levels in aquifer Qdb were generally 13 to 30 feet above sea level in the central part of the island and generally less than 13 feet in near-shore areas (fig. 17). Water levels in overlying aquifer Qva were generally 61 to 80 feet above sea level near the central part of the island and less than 30 feet in near-shore areas (fig. 18). The wells in aquifer Qdb were distributed much more broadly than those in aquifer Qva.

Monthly water-level measurements were made in 20 selected wells to determine seasonal variations in hydraulic heads in the productive hydrogeologic units (Appendix 4). Representative hydrographs of ground-water levels for wells completed in Qdb and Qva are shown in figures 17 and 18. Hydrographs for wells completed in Qdb show

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