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

Ground-Water Age, Flow, and Quality Near a Landfill, and Changes in Ground-Water Conditions from 1976 to 1996 in the Swinomish Indian Reservation, Northwestern Washington

Water-Resources Investigations Report 98-4014

Prepared in cooperation with
Swinomish Indian Tribal Community

USGS
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By B.E. Thomas and S.E. Cox

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1998

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONTENTS

FIGURES

FIGURES--Continued

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.2642	liter per day

CONVERSION FACTORS AND VERTICAL DATUM--Continued

Temperature: To convert temperature given in this report in degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation: °C = 5/9(°F-32).

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, formerly called Sea Level Datum of 1929.

Altitude: In this report, "altitude" is measured in feet above sea level.

Ground-water Age, Flow, and Quality Near a Landfill, and Changes in Ground-water Conditions From 1976 to 1996 in the Swinomish Indian Reservation, Northwestern Washington

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ABSTRACT

This report describes the results of two related studies: a study of ground-water age, flow, and quality near a landfill in the south-central part of the Swinomish Indian Reservation; and a study of changes in ground-water conditions for the entire reservation from 1976 to 1996. The Swinomish Indian Reservation is a 17-square-mile part of Fidalgo Island in northwestern Washington. The ground-water flow system in the reservation is probably independent of other flow systems in the area because it is almost completely surrounded by salt water.

There has been increasing stress on the ground-water resources of the reservation because the population has almost tripled during the past 20 years, and 65 percent of the population obtain their domestic water supply from the local ground-water system. The Swinomish Tribe is concerned that increased pumping of ground water might have caused decreased ground-water discharge into streams, declines in ground-water levels, and seawater intrusion into the ground-water system. There is also concern that leachate from an inactive landfill containing mostly household and wood-processing wastes may be contaminating the ground water.

The study area is underlain by unconsolidated glacial and interglacial deposits of Quaternary age that range from about 300 to 900 feet thick. Five hydrogeologic units have been defined in the unconsolidated deposits. From top to bottom, the hydrogeologic units are a till confining bed, an outwash aquifer, a clay confining bed, a sea-level aquifer, and an undifferentiated unit.

The ground-water flow system of the reservation is similar to other island-type flow systems. Water enters the system through the water table as infiltration and percolation of precipitation (recharge), then the water flows downward and radially outward from the center of the island. At the outside edges of the system, ground water flows upward to discharge into the surrounding saltwater bodies. Average annual recharge is estimated to be about 3 inches, or 12 percent of the average annual precipitation.

Ground water in the outwash aquifer near the landfill is estimated to be between 15 and 43 years old. Some deeper ground waters and ground water near the discharge areas close to the shoreline are older than 43 years.

Analysis of water-quality data collected for this study and review of existing data indicate that material in the landfill has had no appreciable impact on the current quality of ground water outside of the landfill. The water quality of samples from seven wells near to and downgradient from the landfill appears to be similar to the ground-water quality throughout the entire study area. The high iron and manganese concentrations found in most of the samples from wells near the landfill are probably within the range of natural concentrations for the study area.

Ground-water pumping during the past 20 years has not caused any large changes in ground-water discharge to streams, ground-water levels, or seawater intrusion into the ground-water system. Ground-water discharge into Snee-oosh Creek and Munks Creek had similar magnitudes in the summers of 1976 and 1996; flows in both creeks during those summers ranged from 0.07 to 0.15 cubic feet per second. Ground-water levels changed minimally between 1976 and 1996. The average water-level change for 20 wells with more than 10 years between

measurements was -0.7 feet and the two largest water-level declines were 6 and 9 feet. No appreciable seawater intrusion was found in the ground water in 1996, and there was no significant increase in the extent of seawater intrusion from 1976 to 1996. Median chloride concentrations of water samples collected from wells were 22 milligrams per liter in 1976 and 18 milligrams per liter in 1996.

INTRODUCTION

The Swinomish Indian Reservation is on part of Fidalgo Island in northwestern Washington (figs. 1 and 2). The reservation is about 17 mi^2 and it is bounded by saltwater on almost all sides. The Swinomish Indian Tribal Authority is interested in protecting the ground-water resources of its reservation for the beneficial uses of the members of the Tribe. About 65 percent of the population obtain their water supply from the local ground-water system. An increase in population in the reservation from about 1,750 in 1976 to 4,700 in 1996 has placed increasing stress on the quantity and quality of the ground water. A thorough understanding of the ground-water system is needed to wisely manage this limited resource.

The overall hydrologic budget, ground-water flow system, and ground-water quality of the Swinomish Indian Reservation were investigated by Drost (1979) in 1975-76. In 1990, a more focused investigation (Embrey and Jones, 1997) described a sea-level aquifer that was not identified by Drost (1979). The water resources and ground-water system are adequately described by Drost (1979) and Embrey and Jones (1997), but some additional information is needed. The Tribe is concerned that increased pumping of ground water might have caused decreased ground-water discharge into streams, declines in ground-water levels, and seawater intrusion into the ground-water system. There is also concern that leachate from an inactive landfill containing mostly household and wood-processing wastes may be contaminating the ground water. In April 1996, the U.S. Geological Survey began a study in cooperation with the Swinomish Indian Tribal Authority to provide information needed to address these concerns.

Purpose and Scope

The purpose of this report is to describe the results of two related studies: a study of ground-water age, flow, and quality near a landfill in the south-central part of the Swinomish Indian Reservation; and a study of changes in ground-water conditions for the entire reservation from 1976 to 1996. Data were collected during July to September 1996, historical data were compiled for comparisons with the 1996 data, and all the data were analyzed to achieve the following objectives:

1.) To describe ground water near the landfill, including the age of ground water, most likely flow directions, general rate of flow, and quality of water; and

2.) To determine if ground-water conditions in the study area changed from 1976 to 1996.

To provide background information for understanding the results of the two studies, the ground-water flow system of the study area was briefly described using existing data and information and data collected for the two studies. The scope of the study at the ground water near the landfill was to collect water samples from existing wells near the landfill and to analyze the samples for constituents related to ground-water age, flow, and quality. The scope of the study of changes in ground-water conditions was to collect data from existing wells or streams that could be compared with data collected in 1976 (Drost, 1979). The ground-water conditions that are important to the Swinomish Indian Tribal Authority and that were most suitable for comparisons were ground-water discharge, ground- water levels, and extent of seawater intrusion.

Physical Setting

The Swinomish Indian Reservation is on part of Fidalgo Island in northwestern Washington (figs. 1 and 2). The total area of the reservation is about 17 mi^2. The study area is about 10.5 mi^2; excluded from the study area is about 6.5 mi^2 of low-lying tideflats or recent floodplain deposits in the northeastern part of the reservation. The reservation is bounded by salt water on almost all sides; Padilla Bay is on the north, Swinomish Channel is on the east, and Skagit Bay and Similk Bay are on the south and west. A narrow neck of land connecting to the remainder of Fidalgo Island is on the northwest.

The study area is an elongate, north-south trending remnant of a glacial drift plain. The average dimensions are about 6.5 mi long and 2.5 mi wide. The land surface is mostly glacial till and ranges in altitude from sea level to about 330 ft. Most of the study area has moderate slopes of less than 15 percent.

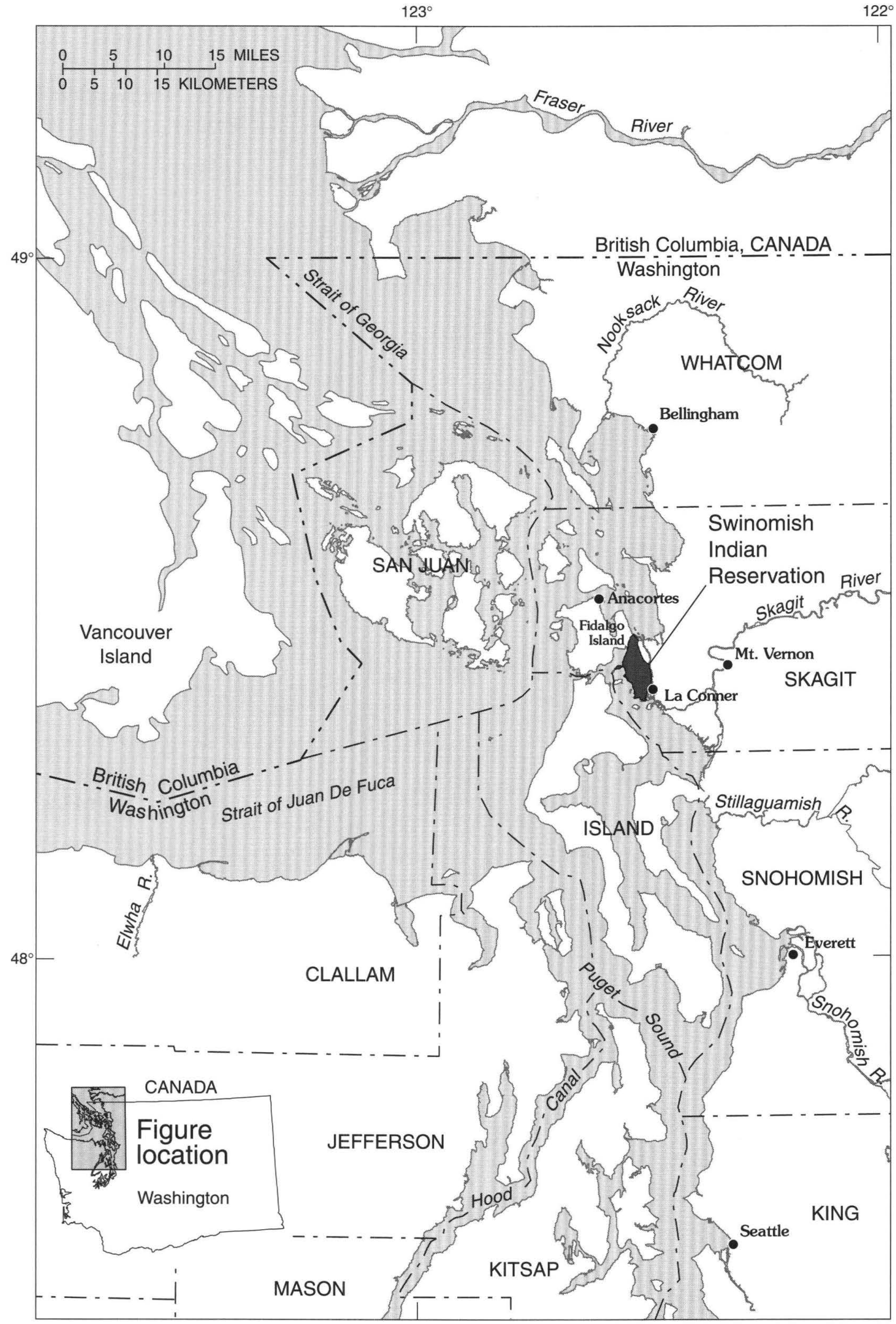


Figure 1. Location of the study area, Skagit County, Washington.

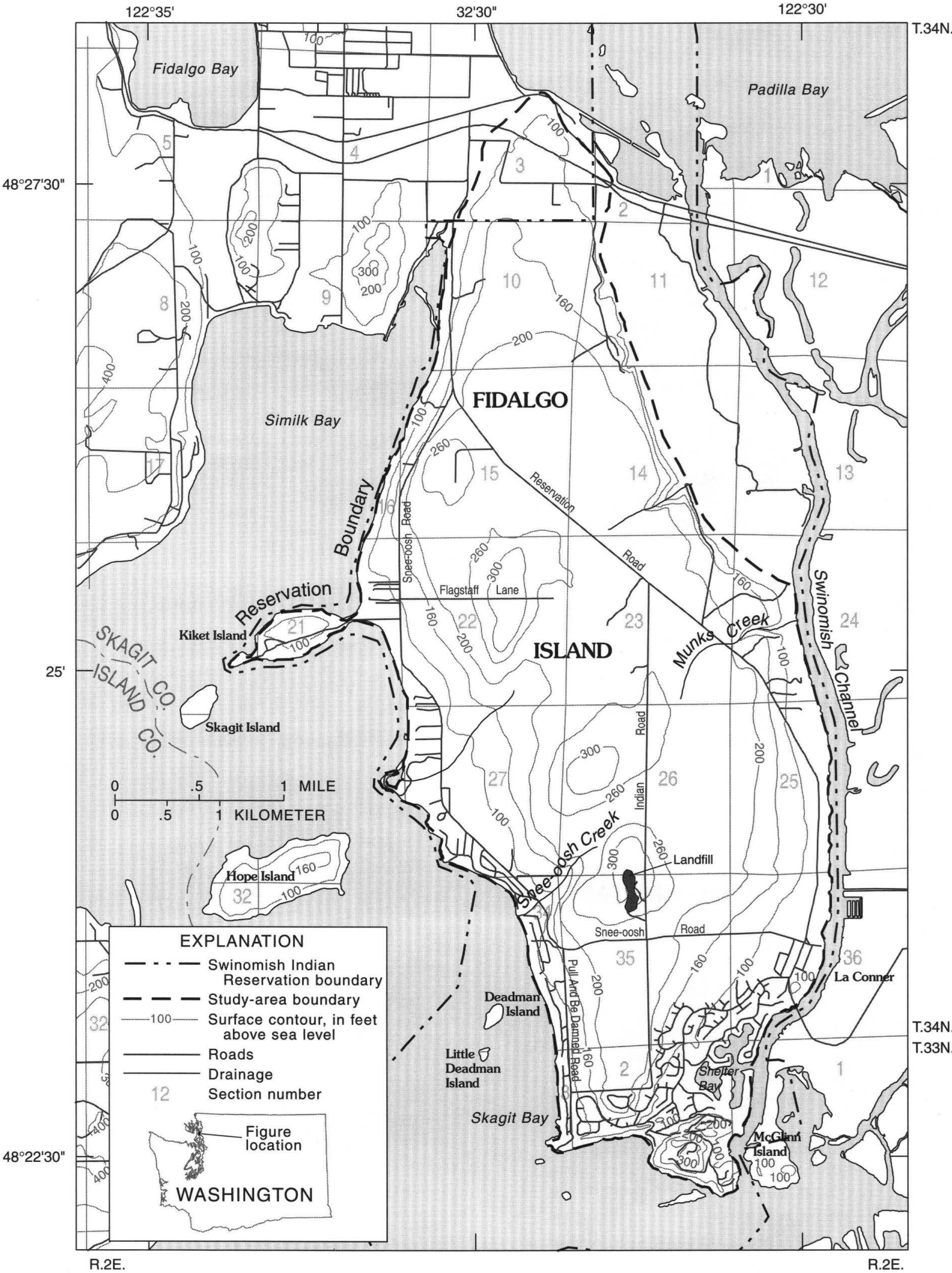


Figure 2. Physical and cultural features of the study area.

The climate of the study area is temperate marine, with cool, wet winters and warm, dry summers. It was assumed that data from the National Weather Service station at Anacortes, Wash. (fig. 1), represents the weather and climate of the reservation. The average annual precipitation is 25.3 in. Between 1921 and 1996, annual precipitation at Anacortes was moderately variable with the least precipitation of 16 in. in 1929 and 1952, and the greatest precipitation of 39 in. in 1990 (fig. 3).

There are no appreciable increasing or decreasing trends in annual precipitation during the entire record (fig. 3). However, the year prior to the data-collection effort (July 1995 to June 1996) had 35.33 in. of precipitation, which is 140 percent of the long-term annual average.

The distribution of precipitation varies throughout a typical year, and 40 percent of the annual precipitation is during the winter, December through February. Summers are typically dry, with only 12 percent of the annual precipitation in June through August (National Oceanic and Atmospheric Administration, 1982).

Air temperatures are moderate throughout a typical year. The average monthly maximum temperature ranges from 44 degrees in January to 72 degrees in July; the average monthly minimum temperature ranges from 34 degrees in January to 52 degrees in July and August.

Cultural Setting

The population of the study area has increased from 1,750 in 1976 to about 4,700 in 1996. About 1,600 people live in the Shelter Bay community, and most of the remaining population resides along the western shoreline of the reservation (fig. 2) (Lauren Rich, Swinomish Indian Tribal Community, oral commun., March 1997).

Most of the reservation is used for permanent and seasonal residences. Commercial activities are minimal: the Tribal administrative center, a fish processing plant, a marina, a log-storage yard, commercial campgrounds, a few small businesses such as a motorcycle repair shop, and a few restaurants. The 6.5 mi^2 of the reservation not included in the study is about 75 percent tideflats and 25 percent agricultural land.

The community of Shelter Bay obtains all its water from the City of La Conner. The remainder of the reservation depends on the local ground-water system for water supply. The Tribe operates two public-supply wells that serve about 1,000 people; they augment the water supply during periods of high demand by purchasing some water from the City of Anacortes. Individual domestic wells and small community wells provide water to the remaining 2,100 people on the reservation (Lauren Rich, Swinomish Indian Tribal Community, oral commun., March 1997).

Well-Numbering System

The well-numbering system used by the U.S. Geological Survey in the State of Washington is based on the rectangular subdivision of public land, which indicates township, range, section, and 40-acre tract within the section. For example, in well number 34N/02E-15R03 (fig. 4), the characters preceding the hyphen indicate the township (T. 34N) and range (R. 02E) north and east of the Willamette base line and meridian, respectively. The first number following the hyphen (15) indicates the section, and the letter (R) designates the 40-acre tract within that section (fig. 4). The last number (03) is the serial number of the well and indicates that this is the third well inventoried in that 40-acre tract.

METHODS OF INVESTIGATION

To achieve the objectives of the study, data were collected during the summer of 1996 from two streams and from selected wells on the reservation. Data-collection sites were selected to obtain the best possible areal coverage of the reservation, to allow comparison of 1996 data with data collected in 1976, and to describe ground-water flow and quality near the landfill.

To compare ground-water discharge in 1996 with discharge in 1976, data were collected from Munks Creek and Snee-oosh Creek once each month in July, August, and September 1996 (fig. 5). During the summer, all the flow in these creeks is ground-water discharge (Drost, 1979, p. 29). The data-collection sites were within about 100 ft of the sites used by Drost (1979) in 1976. Discharge was measured with both a Price pygmy meter and a Parshall flume. The pygmy-meter measurements are reported in this report, because the flume measurements were within 20 percent of the pygmy-meter measurements, and a Price pygmy meter was used for the measurements in 1976. Specific conductance, pH, dissolved-oxygen concentration, and water temperature were measured at each site by placing the meter probes directly in the water current.

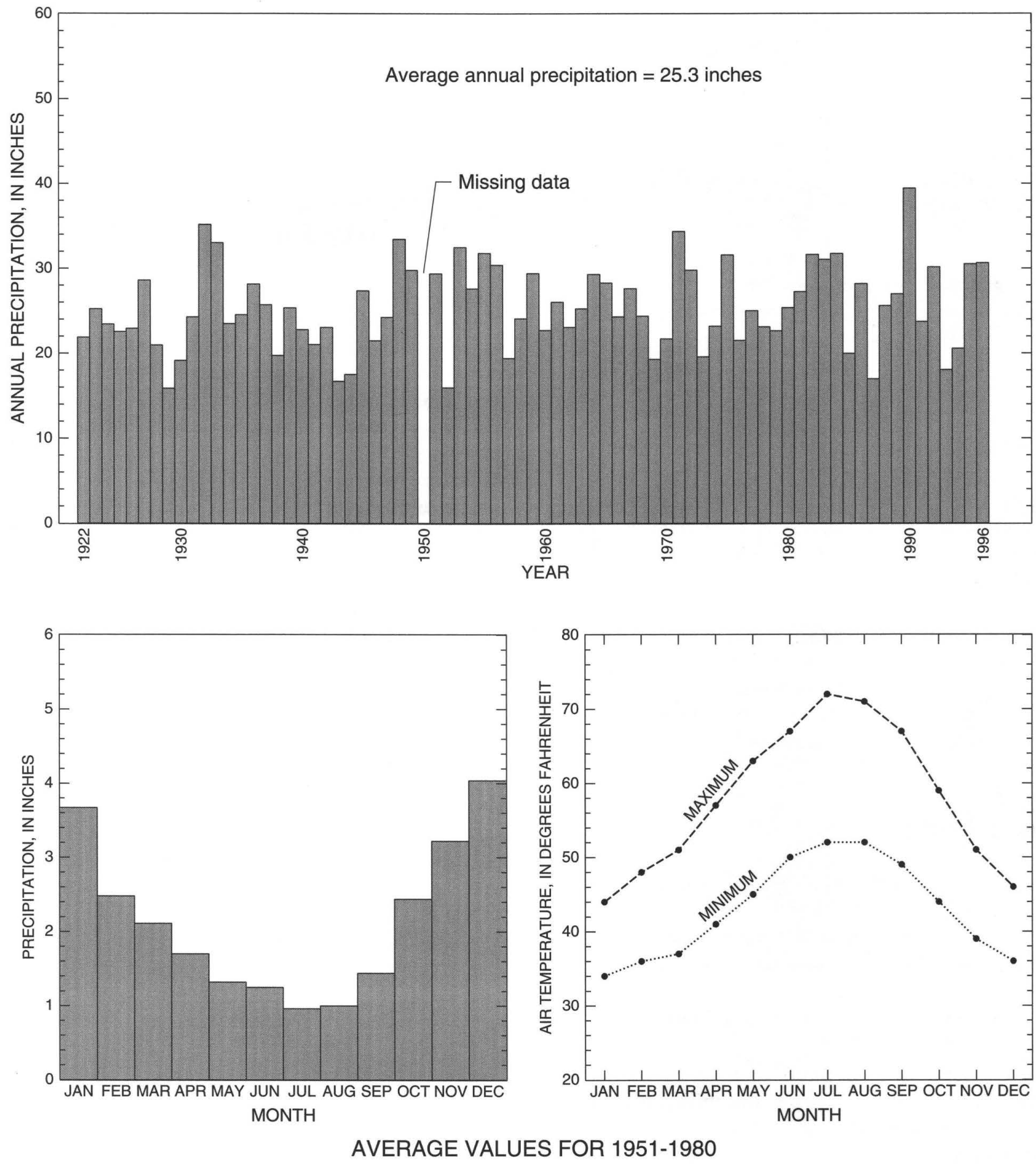


Figure 3. Historical annual precipitation, average monthly precipitation, and average monthly air temperature at the National Weather Service station in Anacortes, Washington.

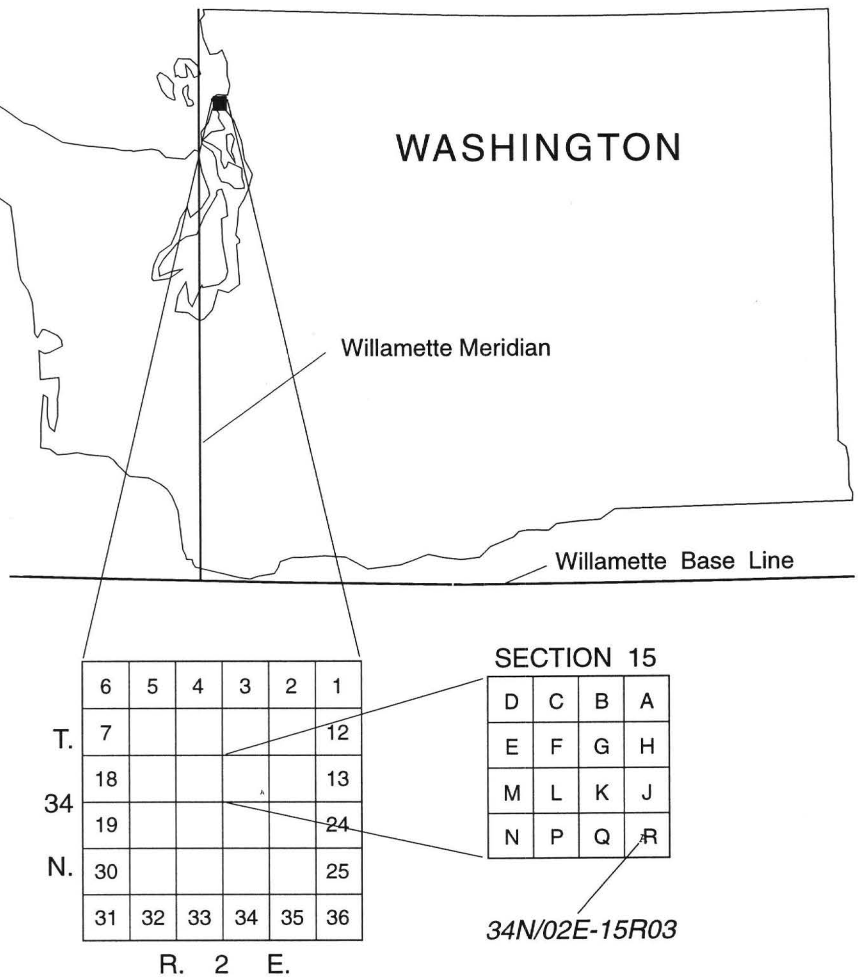


Figure 4. Well-numbering system used by the U.S. Geological Survey in the State of Washington.

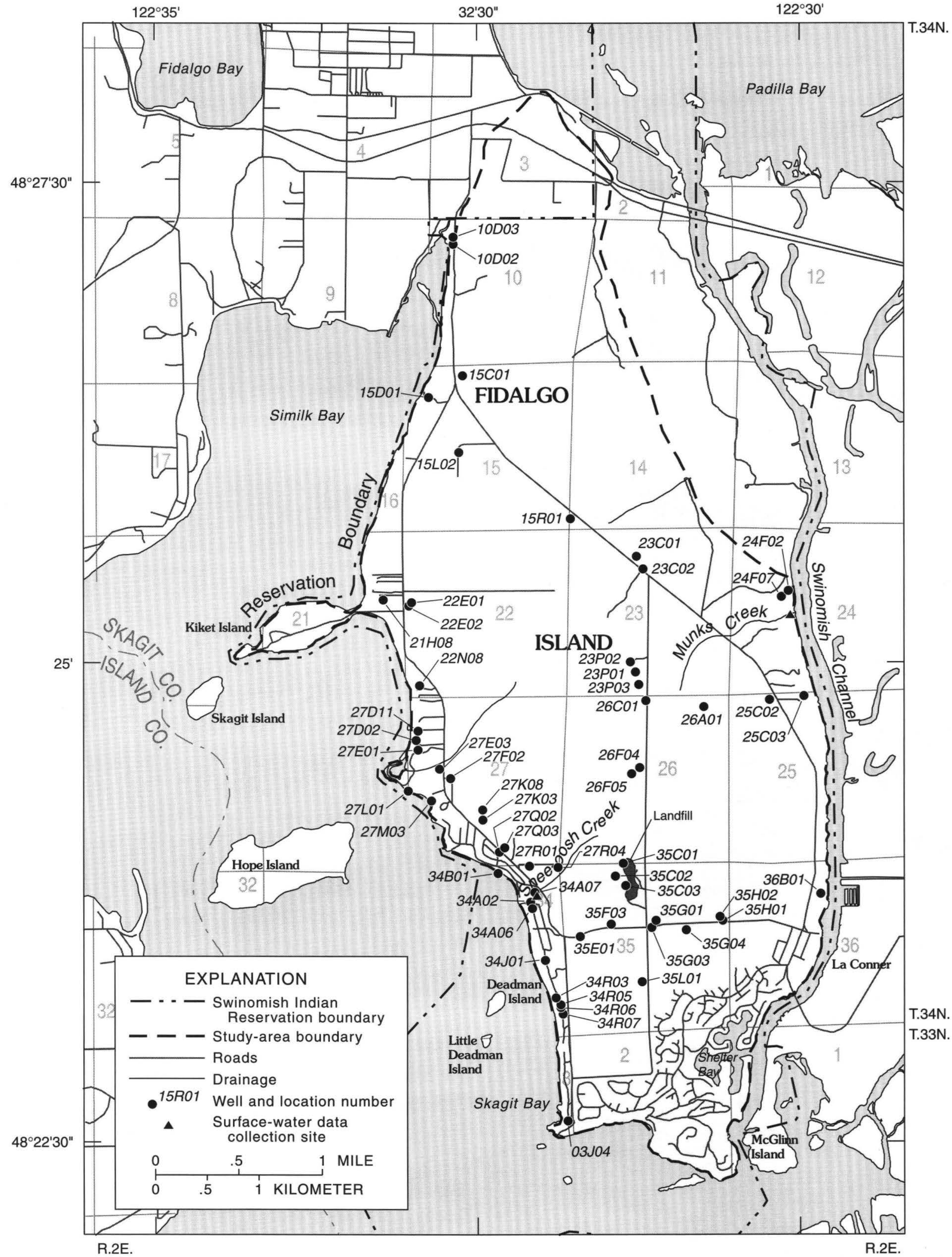


Figure 5. Locations of wells inventoried in 1996 and surface-water data collection sites.

An inventory of 58 wells on the reservation was conducted to collect data needed to determine ground-water levels and extent of seawater intrusion (fig. 5). Data collected previously at an additional 139 wells were also used to augment the analysis (fig. 6). These additional wells were in the USGS National Water Information System (NWIS) data base prior to this study. Data for the 58 wells inventoried in this study were entered in the NWIS data base, and data for both sets of wells are listed in appendixes A and B.

Locations of the inventoried wells were determined by plotting the wells on 1:24,000 topographic maps and digitizing the latitude and longitude. Land-surface altitudes were determined by plotting the wells on a 1:9,600 scale topographic map (Walker and Associates, Seattle, Wash., written commun., 1969) and interpolating the altitude from contours on the map. Water levels were measured in 19 wells, and water samples were collected from 35 wells. Data could not be collected at some wells because either they were destroyed, permission was denied by some owners, the physical condition of the well prohibited access, or the well was pumping, which prevented the measurement of a static water level.

The water-level data collected during the well inventory were intended to be used for estimating ground-water flow directions and for determining possible long-term changes in water levels by comparing the data with historical water-level data. A water-level map sufficient for estimating flow directions could not be constructed from the 19 water levels measured in this study. Therefore, 125 water levels measured during 1948 to 1990 were added to the water-level data base to give a more complete areal coverage of the study area. Seasonal and long-term changes in the historical water-level data were small enough to allow the use of water levels measured during different times. Maximum seasonal fluctuations measured in 21 wells during 1975-76 averaged 3.4 ft, and the largest fluctuation was 9 ft (Drost, 1979). Water-level changes for 20 wells (with more than 10 years between measurements) between 1976 and 1996 averaged -0.7 ft, and only 2 wells had more than a 5-ft change.

The combined water-level data for 144 wells were plotted on the study-area map, but they still did not provide an adequate areal distribution to construct a water-level map. A water-table map constructed by Drost (1979) using geophysical methods was, therefore, used as a base map, and the water-table contours were modified slightly, using the water-level data from this study.

To determine the extent of seawater intrusion and possible increases in seawater intrusion from 1976 to 1996, chloride concentrations in ground-water samples were evaluated. Thirty water samples collected in 1976 had available chloride concentrations, and samples were collected from 35 wells during the well inventory in this study for determination of chloride concentrations. Thirteen wells had samples collected in both 1976 and 1996.

At the inventoried wells, beakers and sample bottles were filled directly with unfiltered-whole water from the water faucet nearest the well and ahead of any water treatment such as disinfection, softening, or filtration. Specific conductance was measured with a meter in the beakers at the well site. Analysis of dissolved chloride required that the water samples be filtered; therefore, the water-sample bottles were taken to the USGS-WRD laboratory in Tacoma, Wash., and the water was filtered through a 0.45-micron membrane filter to a new bottle. The filtered-sample bottles were then sent to the USGS National Water Quality Laboratory (NWQL) in Arvada, Colo., for analysis of dissolved chloride by ion-chromatography.

Ground-water age, flow, and quality near the landfill were evaluated by analyzing water samples collected from nine wells near the landfill, and using existing data and information (fig. 7). The wells available for sampling were limited to existing domestic and observation wells. The resulting locations and depths of the nine wells were not suitable for determining directions and rates of ground-water flow with ground-water-age data (fig. 7), but the age data can still be used to improve the general understanding of ground-water recharge near the landfill. Because of these sampling limitations, ground-water flow directions were estimated using the water-table map constructed by Drost (1979) and modified in this study. Ground-water quality near the landfill was evaluated by analyzing water samples from the nine wells. In addition, existing water-quality data collected from three observation wells near the landfill were also used in the evaluation (Q. Brown, Bureau of Indian Affairs, Portland, Oreg., written commun., March 1996).

Ground-water age near the landfill was estimated using laboratory analyses for the environmental tracers, tritium and chlorofluorocarbons (CFC's). Ground-water quality was evaluated using laboratory analyses of concentrations of nutrients, dissolved organic carbon, major ions, dissolved iron, dissolved manganese, and volatile organic compounds (VOC's).

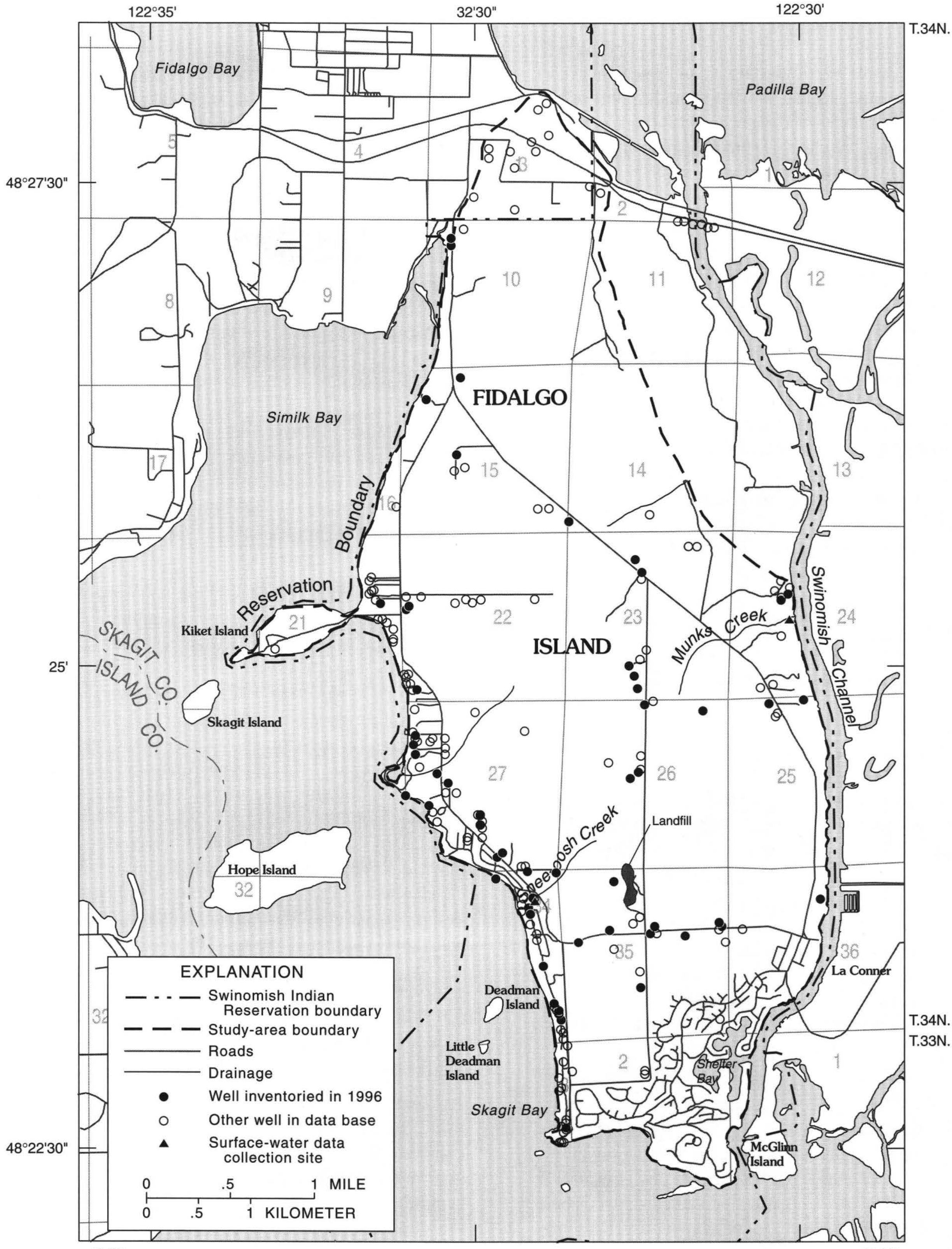


Figure 6. Locations of wells inventoried in 1996, other wells in the data base, and surface-water data collection sites.

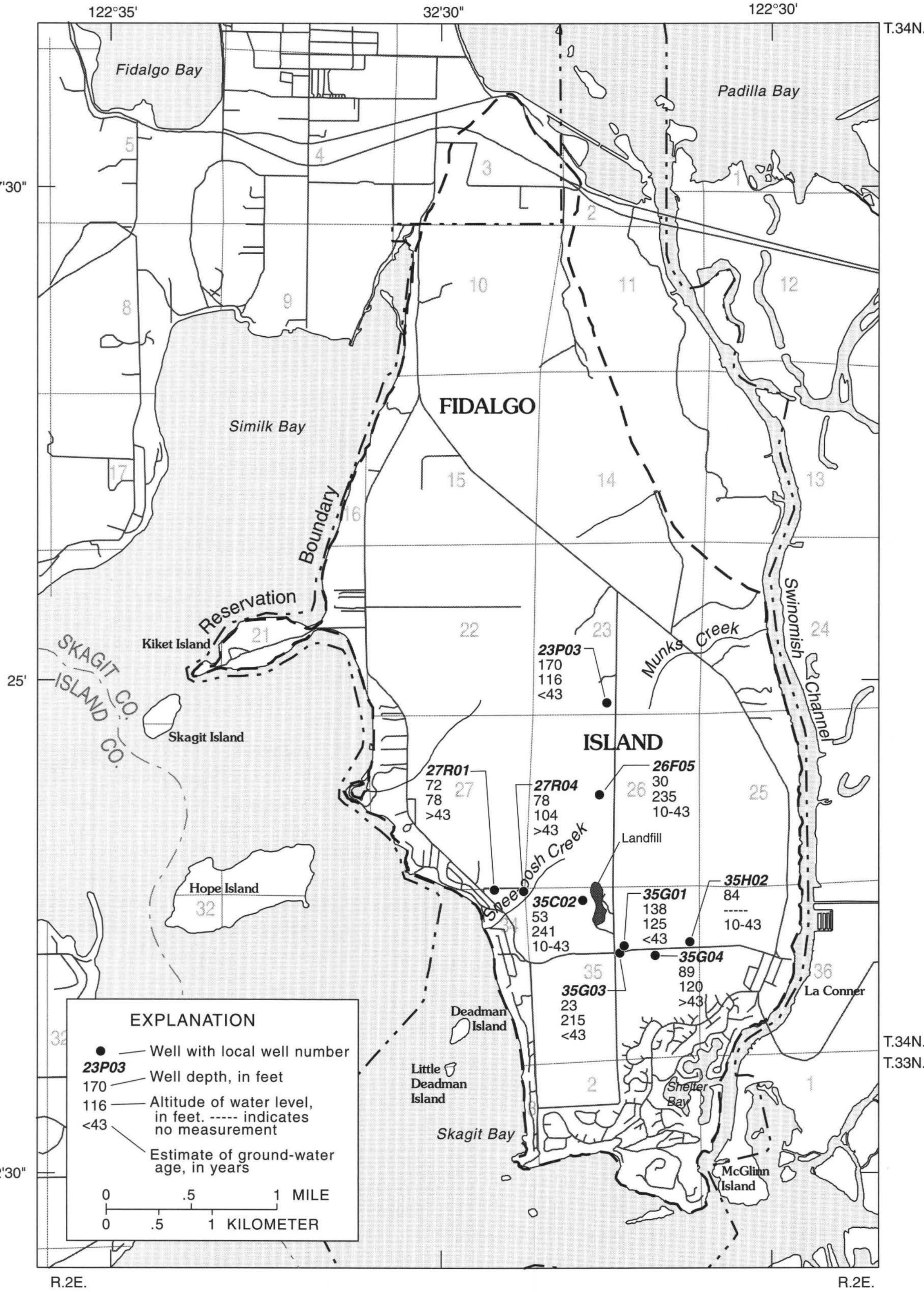


Figure 7. Locations of wells used to collect detailed water-chemistry and ground-water age data.

Standard USGS methods were used for collecting, treating, and preserving the ground-water quality samples (M. Sylvester, U.S. Geological Survey, written commun., 1990; and Pritt and Jones, 1989). The pH, specific conductance, temperature, and dissolved-oxygen concentration were measured in the field following procedures described by Wood (1981). Alkalinity was assessed in the field by analyzing for bicarbonate and carbonate concentrations following the incremental titration method described by Sylvester and others (M. Sylvester, U.S. Geological Survey, written commun., 1990).

Seven of the nine wells selected for sampling had submersible or centrifugal pumps; temporary submersible pumps were installed in two unused wells. Water samples were collected from the pump discharge line or a faucet located as near to the wellhead as possible and ahead of any water treatment such as disinfection, softening, or filtration. Large holding tanks were present at two wells (34N/02E-27R04 and 34N/02E-35H02), which precluded the measurement of some unstable characteristics (pH, temperature, dissolved oxygen, and alkalinity) at those sites. Water was fed from the discharge line or faucet through nylon tubing to a flow chamber where pH, temperature, specific conductance, and dissolved-oxygen concentration were monitored continuously. The well was considered adequately purged when at least three casing volumes had been pumped out and the flow chamber readings were constant for 10 minutes; at that point, the field measurements were noted, and the whole-water and filtered samples were collected. Water samples to be analyzed for inorganic constituents were filtered through a 0.45-micron membrane filter. Water for dissolved organic carbon was filtered through a 0.45-micron silver membrane filter. All other analyses were made with unfiltered water.

All laboratory analyses for the ground-water quality samples were done at the USGS NWQL. Analytical procedures used by the NWQL are described by Fishman and Friedman (1989) and Wershaw and others (1987).

Tritium was analyzed by gas counting following electrolytic enrichment at the University of Miami Tritium Laboratory using the procedures described by Ostlund and Dorsey (1977). Results were reported in picoCuries (pCi) per liter and converted to the more commonly used tritium units (TU). One TU is defined as one tritium atom in 10^{18} hydrogen atoms and is equivalent to 3.24 pCi per TU.

Chlorofluorocarbon (CFC) samples were collected and analyzed in triplicate, following the procedures outlined by Busenburg and Plummer (1992). Because there is a substantial potential for atmospheric contamination when measuring dissolved gases at the parts per quadrillion level (picograms per kilogram) three replicate samples were collected at each location and analyzed individually. Chlorofluorocarbon determinations were done using purge-and-trap gas chromatography and electron capture detection by the USGS CFC Laboratory in Reston, Va. The results are reported as picograms per kilogram of water (pg/kg).

To augment the analysis of CFC's, several other water-quality samples were also collected. A water sample was collected from well 34N/02E-35G01 for analysis of volatile organic compounds (VOC's) because CFC's and other VOC's can be found in very high concentrations near landfills where refrigerators have been buried. If refrigerators or other CFC sources have leached CFC's into ground water, the use of CFC's as an age-dating technique would be inappropriate. The VOC sample was analyzed by NWQL using purge-and-trap procedures described by Rose and Schroeder (1995). Concentrations of dissolved methane, nitrogen, argon, and carbon dioxide were measured by gas chromatography at the USGS CFC Laboratory in Reston, Va; these data were used to help interpret the estimates of ground-water age from CFC data.

Quality assurance procedures used for this study included meter calibration, duplicate samples, and blind standard-reference samples. To ensure the accuracy of field pH and specific-conductance measurements, meters were calibrated daily with known standards. Dissolved-oxygen meters were calibrated daily using the water-saturated air technique. Duplicate chloride samples were collected at six wells during the field inventory. One of the nine wells sampled near the landfill was sampled in duplicate for nutrients, major ions, total organic carbon, and tritium. All of the CFC samples were analyzed in triplicate. Standard reference samples of various concentrations of major ions and nutrients were inserted as blind samples into the sample runs at least twice weekly by the Quality Systems Section of the NWQL.

Review of the analytical and quality-assurance data indicate that the water-quality data collected for this project were within acceptable limits of bias and variability and were suitable for their purposes. Blank distilled water samples submitted in May and December of 1996, showed only trace concentrations of ammonia at 0.019 milligrams per liter (mg/L). Analytical accuracy determined from blind standard reference data was acceptable for all common ion and nutrient data except calcium, which was rated satisfactory. The difference in the sum of cations and anions for the nine common-ion analyses ranged from 0.2 to 3.8 percent, with a median of 1.2 percent, and all differences were acceptable. Variability within the duplicate samples was small. The average absolute difference between field and duplicate chloride concentrations for the six samples was 0.5 mg/L, and the largest difference was 1.0 mg/L. The differences between the field and duplicate analyses of nutrients and common ions were all less than 10 percent; two-thirds of the duplicate analyses were identical. Only tritium and total organic carbon showed large differences in duplicate samples; tritium values were 0.3 and 0.6 TU, and total organic carbon concentrations were 1.0 and 1.8 mg/L. However, the tritium analyses are near the detection limit of 0.1 TU, and the estimate of precision for the measurements (one standard deviation) was 0.26 TU; thus, the difference in the tritium analyses is not considered substantial.

GROUND-WATER FLOW SYSTEM

The ground-water flow system in the study area is briefly described to provide background information for understanding the results of the two studies described in this report—ground-water age, flow, and quality near the landfill; and changes in ground-water conditions from 1976 to 1996. A conceptual model describes an overall framework of the ground-water flow system. The flow system is described in more detail in subsequent sections on the basis of previous studies of the study area and some of the data collected for this study.

Conceptual Model

Hydrologic Budget

A hydrologic budget describes the amount and distribution of water that moves through a hydrologic system. Under natural conditions, a hydrologic system is in a state of dynamic equilibrium. On a long-term basis, inflow to the system (precipitation) is equal to outflow (evapotranspiration, surface-water outflow, and ground-water discharge by subsurface outflow). There is little or no change in the amount of water in storage at land surface, in the unsaturated zone, or in the ground-water reservoir.

Precipitation falling on land surface in the study area will (1) run off directly into surrounding saltwater bodies via streams, (2) be intercepted by vegetation or remain on the land surface and then be evapotranspired, or (3) infiltrate to the unsaturated zone (fig. 8). Some water in the unsaturated zone percolates downward to recharge ground water, and some is transpired by plants or moves upward by capillary action and is evaporated from land surface.

The average annual hydrologic budget for the study area is expressed in the following equation:

$$P = ET + SWR + GWR \quad , \qquad (1)$$

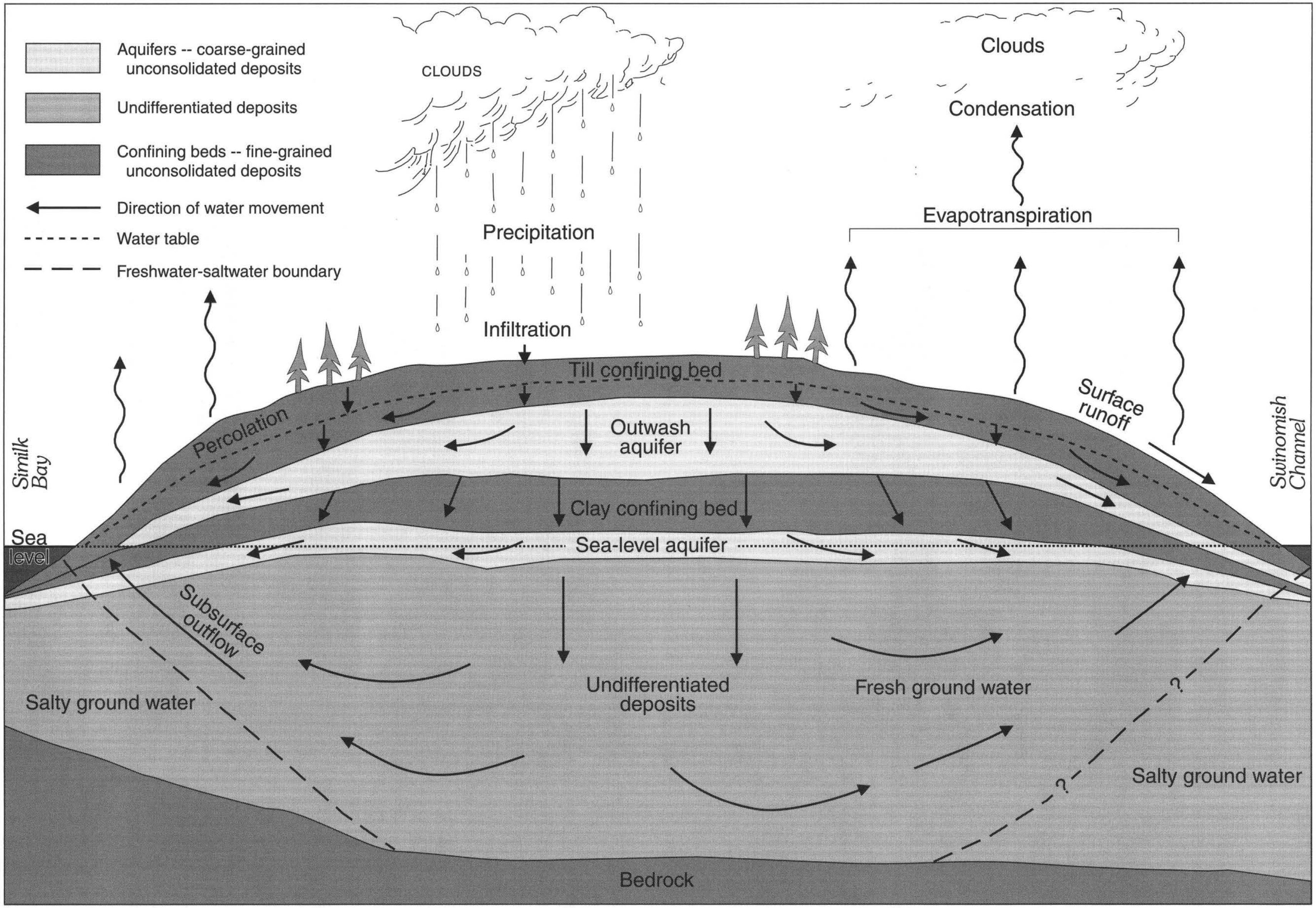
where

- P is precipitation, in inches;
- ET is evapotranspiration, which is the sum of interception of water and subsequent evaporation, evaporation from soils, and transpiration, in inches;
- SWR is surface-water runoff, in inches; and
- GWR is ground-water recharge; in inches.

Assumptions in this equation are that (1) there are no changes in storage, (2) ground-water recharge equals ground-water discharge, and (3) the surface-water runoff component is a combination of surface runoff of water and shallow subsurface flow. Also, streamflow is not shown in the equation, but it is a combination of parts or all of surface-water runoff and ground-water discharge. Precipitation, P, is the source of all water in the equation, and for any given value of P, a decrease in one right-side component must be balanced by an increase in one of the other right-side components. For example, if surface-water runoff is increased because of urbanization and paving of part of the watershed, one of the other components, such as ground-water recharge or evapotranspiration will be decreased.

Ground-Water Boundaries and Flow

The ground-water flow system in the Swinomish Indian Reservation is probably independent of other flow systems in the area because it is almost completely surrounded by salt water (fig. 2). The only area where salt water does not form a boundary with the system is the northwest side of the reservation, where a small amount of ground water probably flows in a northwest direction out of the study area. The conceptual ground-water flow patterns for a cross section of the center of the study area (looking from south to north) are similar to island flow systems (fig. 8). Water enters the system through the



NOT TO SCALE

Figure 8. Simplified conceptual model of hydrologic conditions in the Swinomish Indian Reservation.

water table as infiltration and percolation of precipitation (recharge), then the water flows downward and radially outward from the center of the island. At the outside edges of the system, ground water flows upward to discharge into the salt water of Similk Bay and Swinomish Channel (figs. 2 and 8). Most ground-water flow is parallel to the lower boundary, which is a freshwater-saltwater boundary caused by the density differences between freshwater and salt water. Flow patterns are altered by the different permeabilities of aquifers and confining beds; flow is mostly horizontal in aquifers and flow is mostly vertical in confining beds.

An independent ground-water system is the most likely conceptual model, on the basis of available data and hydrologic concepts. A less likely alternative is that the system is not independent, and ground water flows from the east in a deep confined aquifer under the Swinomish Channel and into the ground-water system. This alternative is possible because the Swinomish Channel is only about 15 ft deep, and available data are not sufficient to prove or disprove it.

Hydrologic characteristics supporting an independent ground-water system above sea level are the radial ground-water flow patterns and saltwater boundaries surrounding the study area. Below sea level, the characteristics of the ground-water system are uncertain, and a deep confined aquifer could exist. Geophysical data show that unconsolidated deposits extend to several hundred feet below sea level. No wells have been drilled deeper than 100 ft below sea level; therefore, the geology, ground-water levels, and chloride concentrations below that level are unknown.

The available data and hydrologic conditions to the east of the study area are not conclusive, but do not support the alternative model of ground-water flow under the Swinomish Channel. East of the study area, the geologic units are several hundred feet thick and are mostly fine-grained deltaic deposits; the topography is flat for about 10 mi to potential recharge areas in the hills and mountains to the east; and the Skagit River, a regional ground-water discharge area, is between the hills and mountains and the study area. These hydrogeologic conditions make it unlikely that a large enough hydraulic gradient could be established in a deep aquifer to move the ground water under the Skagit River, under 10 mi of flat terrain, and under the Swinomish Channel. Even if this deep confined aquifer exists, it would have little effect on the ground-water system above sea level. The principal effect would be some upward flow into the sea-level aquifer. A benefit of a deep confined aquifer with flow under the Swinomish Channel is that the aquifer would be a source of water for future ground-water development.

Hydrogeologic Units

The study area is underlain by unconsolidated glacial and interglacial deposits of Quaternary age. The deposits range from 400 to 900 ft thick under the north, central, and east sides of the study area and from 100 to 400 ft thick under the west and south sides. Bedrock crops out in about 5 percent of the study area at the extreme southern end. The bedrock is predominantly sedimentary and metamorphic rocks of Tertiary age (Drost, 1979). Five hydrogeologic units have been identified in the unconsolidated material (Embrey and Jones, 1997)—a till confining bed, an outwash aquifer (identified as "stratified drift" in Drost (1979), a clay confining bed, a sea-level aquifer, and a lower unit of undifferentiated deposits (Drost, 1979; and Embrey and Jones, 1997). The definition of the aquifers and confining beds was made on the basis of lithology and relative position of the geologic deposits in the study area. The aquifers are primarily coarse-grained glacial or alluvial deposits. The confining beds are primarily fine-grained lake deposits or glacial till.

The following discussion describes the origin, lithology, water use, hydraulic properties, areal extent, and thickness of each hydrogeologic unit. The hydraulic properties of a hydrogeologic unit can be represented by the normalized specific capacity of wells completed in the unit. Normalized specific capacity of a well is the yield (gallons per minute) divided by drawdown (feet), divided by feet of open interval in the well. Embrey and Jones (1997) compiled median values of the normalized specific capacities of wells completed in each unit and those values are reported here.

The till confining bed is a glacial deposit of compact, unsorted sand, gravel, and boulders in a matrix of silt and clay. The till unit also contains lenses of sand and gravel that can yield usable amounts of water to wells for domestic water supply. The median normalized specific capacity is 0.08 (gal/min)/ft/ft. Because the specific capacities are based on domestic water-supply wells, which drillers prefer to complete in lenses of sand and gravel, the median value of 0.08 is biased; typical values for wells that were completed throughout the till unit would be much smaller. The till unit covers the surface of about 85 percent of the study area and ranges in thickness from a few feet to about 150 ft along the western shoreline (Drost, 1979).

The outwash aquifer that underlies the till confining bed was deposited by glacial meltwater during a glacial advance. It is moderately to well-sorted sand and gravel, with some lenses of clay and silt. Most of the productive wells on the reservation obtain their water from this aquifer. The median normalized specific capacity is 1.0 (gal/min)/ft/ft. The outwash aquifer underlies most of the study area and crops out in about 5 percent of the study area in isolated pockets in the center and the northwest parts. It has an average thickness of about 60 ft, with a maximum thickness of about 150 ft in the center of the study area.

The clay confining bed lies beneath the outwash aquifer. It is mostly clay and silt of nonglacial origin, with some lenses of fine sand, sand and gravel, and peat-like material. A few wells are completed in this unit, but like wells in the till confining bed, yields are small and it is not suitable for large-scale withdrawals. The median normalized specific capacity is 0.03 (gal/min)/ft/ft. For wells in the clay confining bed there is also a bias in specific capacities; typical values for wells that were completed throughout the clay unit would be much smaller. The clay confining bed underlies the entire study area and has an average thickness of about 100 ft.

The sea-level aquifer is mostly coarse sand and gravel of glacial or nonglacial origin. The Tribe has two public-supply wells (34N/02E-15R02 and 34N/02E-15R03) completed in this aquifer that supply water to about 1,000 people. The median normalized specific capacity computed with data from five wells in this unit is 0.6 (gal/min)/ft/ft. The extent and thickness of this unit are not well known because of meager data. Near the Tribe's well field, the aquifer extends to at least a one-half mile radius from the wells, and the thickness is about 20 ft. The extent and thickness of the sea-level aquifer in other areas of the reservation are unknown.

The lower undifferentiated hydrogeologic unit contains glacial and nonglacial unconsolidated deposits between the sea-level aquifer and bedrock. No information is available on the lithologic or the hydraulic properties of the unit, because no known wells have been drilled into this unit. The lower undifferentiated unit underlies most of the study area and in most areas, the thickness is several hundred feet.

Recharge

Recharge to ground water in the study area is from infiltration and percolation of precipitation. Average annual ground-water recharge was estimated to be about 3 in., or 12 percent of the average annual precipitation. A chloride mass-balance method was used to estimate recharge. An alternate method, based on ground-water ages estimated in this study, was used as an independent check, but the mass-balance method was assumed to be more accurate and reliable.

The results of both recharge methods were assumed to represent average annual conditions. Both methods used concentrations of constituents in ground water in 1996; however, those constituent concentrations are a result of recharge, ground-water flow, and discharge over many years. The chloride concentrations used in the chloride mass-balance method have remained fairly constant during the past 20 years. Also, the ground-water age method integrates annual recharge amounts during the past 15 to 40 years.

The chloride mass-balance method uses the assumption that precipitation is the only source of chloride in ground water and in surface-water runoff. Human sources such as septic systems and animal sources such as cow manure contribute minimal amounts of chloride to the water in the study area, and natural sources such as evaporite rocks or connate seawater are not present in the hydrogeologic units above sea level. A mass balance of chloride in precipitation, surface runoff, and ground water is expressed in the following equation (Maurer and others, 1996; Prych, 1995):

$$P \times C_p = \left(GWR \times C_g\right) + \left(SWR \times C_p\right) \quad , \qquad (2)$$

where

GWR is annual ground-water recharge, in inches;

P is annual precipitation, in inches;

SWR is annual surface-water runoff, in inches;

C_g is concentration of chloride in ground water, in milligrams per liter; and

C_p is concentration of chloride in precipitation, in milligrams per liter.

Rearranging the terms in equation (2) and solving for GWR gives:

$$GWR = \frac{(P \times C_p) - (SWR \times C_p)}{C_g} , \qquad (3)$$

Values used in the equation were 25 in. for precipitation, 1.6 to 5.0 in. for surface-water runoff, 1.9 mg/L for concentration of chloride in precipitation, and 14 mg/L for concentration of chloride in ground water. The range of surface-water runoff resulted in a range of recharge of 2.7 to 3.2 in., which rounds to 3 in.

Precipitation is the average annual amount at the National Weather Service station at Anacortes, Wash. The chloride concentration in precipitation is the average value of data collected during October 1996 to February 1997 from three sites in nearby Island County (H.H. Bauer, U.S. Geological Survey, written commun., 1997). The chloride concentration in ground water is the median value of 13 water samples collected in 1996 from wells that are more than 1,500 ft from the shoreline and that have well bottoms at altitudes above sea level.

Measurements of annual surface-water runoff were not available so a range of feasible values was used. Drost (1979, p. 26) estimated runoff to be 3.3 in. on the basis of measurements of flow in Munks Creek and Snee-oosh Creek and some assumptions about relations between runoff, ground-water recharge and discharge, precipitation, and evapotranspiration. Because the estimate of 3.3 in. of runoff includes many assumptions and is uncertain, this study used a range of plus and minus 50 percent, which is 1.6 to 5.0 in.

Another estimate of recharge was made using the estimates of ground-water age determined in this study. A full explanation of the age estimates is given in the section "Ground-Water Age, Flow, and Quality near the Landfill".

Age estimates for ground-water samples collected from two wells were suitable for the recharge analysis. Wells 34N/02E-26F05 and 34N/02E-35C02 are shallow and near a ground-water divide; therefore, ground-water flow is predominately downward at those sites. The estimates of recharge were made using an equation that assumes downward piston flow (Daniels and others, 1991; and Bauer and Mastin, 1997):

$$Q = \left(\frac{Z}{t}\right)n , \qquad (4)$$

where

Q is downward flow or recharge, in inches per year;

Z is depth to sampling point, in inches;

t is transit time or ground-water age, in years; and

n is porosity of hydrogeologic unit.

For well 34N/02E-26F05, Z is 30 ft or 360 in. (bottom of well); t is 15 to 43 years; and n is estimated to be 0.1 for the till unit. For well 34N/02E-35C02, Z is 48 ft or 576 in. (midpoint of a 10-ft screen); t is 15 to 43 years; and n is estimated to be 0.2 for the outwash aquifer. The resulting range of recharge was 0.8 to 2.4 in. for the till unit near well 34N/02E-26F05 and 2.7 to 7.7 in. for the outwash aquifer near well 34N/02E-35C02.

The 3 in. of recharge estimated for the study area using the chloride mass-balance method is near the upper limit of 2.4 in. of recharge estimated for the till unit near well 34N/02E-26F05 using the ground-water-age method. This approximate agreement between two independent estimates of recharge also fits the conceptual model of recharge; the till unit covers about 85 percent of the study area, and the overall recharge for the study area is controlled mostly by recharge through the till unit. The larger amount of recharge estimated for the outwash unit (2.7 to 7.7 in.) may be reasonable, but the outwash unit only crops out in about 5 percent of the study area, so its contribution to study-area recharge is minimal.

The annual recharge of about 3 in. or 12 percent of annual precipitation is much smaller than previous estimates of recharge for the study area; Drost (1979) estimated 11 in. and Embrey and Jones (1997) estimated a range of 7 to 12 in. However, this small value agrees better with recharge that was estimated in three till-covered watersheds in the Puget Sound area (Bauer and Mastin, 1997); the annual recharge for the three watersheds ranged from 1 to 7 in. or 4 to 17 percent of annual precipitation. An important finding of the Bauer and Mastin (1997) study was that interception of precipitation by forest canopies and subsequent evaporation accounted for 37 to 47 percent of the annual precipitation. This study area is mostly covered by conifer trees, and Drost (1979) and Embrey and Jones (1997) did not account for interception in their estimates of recharge.

Directions of Flow

Ground-water flow directions determined for the study area (fig. 9) are consistent with the conceptual model of the system (fig. 8). Water moves radially from the center of the study area, with downward movement in the center and upward movement at the edges. Water-table altitudes are above 200 ft in the south-central part of the study area and above 100 ft in most of the area.

The water-table contour map constructed for this study is a refinement of a map constructed by Drost (1979) using geophysical data. The refinement was made on the basis of water levels measured in 87 wells that are less than 100 ft deep (fig. 9). Deeper wells in most of the study area have lower water levels than nearby shallow wells, indicating a large downward component of flow between higher and lower hydrogeologic units. Examples of large downward gradients between the till confining bed and the outwash aquifer are the measured water levels in two pairs of wells near the center of the study area. Wells 34N/02E-23P01 (depth of 46 ft) and 34N/02E-23P02 (depth of 159 ft) (fig. 5) have similar land-surface altitudes and are about 300 ft apart, but there is a water-level difference of 97 ft. Wells 34N/02E-35G01 (depth of 23 ft) and 34N/02E-35G03 (depth of 138 ft) (fig. 5) have similar land-surface altitudes and are about 200 ft apart, but there is a water-level difference of 90 ft between them.

Discharge

Natural discharge from the ground-water system is by subsurface flow to saltwater bodies and flow to springs and streams. Assuming the system is in a steady-state or equilibrium condition, then total discharge equals the total recharge of about 3 in. or 1,700 acre-ft.

Withdrawals from the ground-water system were estimated by multiplying an average per capita water use of 70 gal/d (Drost, 1979; Kahle and Olsen, 1995) times the 3,100 people served by ground water. The resulting estimate is 217,000 gal/d or 243 acre-ft per year. This average annual withdrawal rate is 14 percent of the average annual recharge. However, about 70 percent of the water used in houses with septic systems is returned to the water table as recharge from percolation from the septic-system drain fields (M. van Heeswijk, U.S. Geological Survey, written commun., 1997). Considering the approximately 900 homes (2,250 people) on septic systems in the reservation, the estimated net withdrawal rate is therefore 120 acre-ft per year, or only 7 percent of the average annual recharge.

GROUND-WATER AGE, FLOW, AND QUALITY NEAR THE LANDFILL

Ground-water age, flow, and quality near the landfill in the south-central part of the reservation were evaluated using data collected during this study. Age-dating environmental tracers and general water chemistry were determined in water samples from nine wells near the landfill (fig. 7). Ground-water levels were measured in six of the nine wells and in other wells near the landfill. The analysis of these data did not fully meet the objectives of the study, but the analysis improves on the understanding of ground-water flow and quality near the landfill.

The landfill is a 17-acre site located in the south-central part of the reservation on the southwest side of a hill with upper land-surface altitudes of 300 to 330 ft (fig. 2). The history of the landfill is uncertain and not well documented. Prior to 1960, gravel mining at the site removed portions of the hill, and the altitude of the base of the landfill is now at about 260 ft. During the 1960's and 1970's, the site was open; disposal of domestic wastes was likely, and disposal of industrial wastes was possible. From 1980 to 1993, the site was used for disposal of wood wastes from logging operations. The wood wastes cover most of the landfill, ranging from about 5 to 10 ft thick. Since 1993, all disposal activities have ceased (Q. Brown, Bureau of Indian Affairs, Portland, Oreg., written commun., March 1996).

The land surrounding the landfill is covered with till deposits that are about 50 to 100 ft thick. The gravel mining prior to 1960 stripped away most of the till unit, and the outwash aquifer is now exposed at the base of the landfill. Depth to the water table ranges from about 20 to 35 ft in the outwash aquifer under the landfill and from about 10 to 20 ft in the till unit near the landfill. Depth to water in the outwash aquifer near the landfill ranges from about 70 to 130 ft. The landfill is in a recharge area for the ground-water system. Precipitation infiltrates land surface and recharges the till unit near the landfill and recharges the outwash aquifer under the landfill. In the till unit, ground water flows radially from the landfill in a horizontal direction (fig. 9). In the outwash aquifer, ground water flows downward from the landfill then radially outward in a horizontal direction.

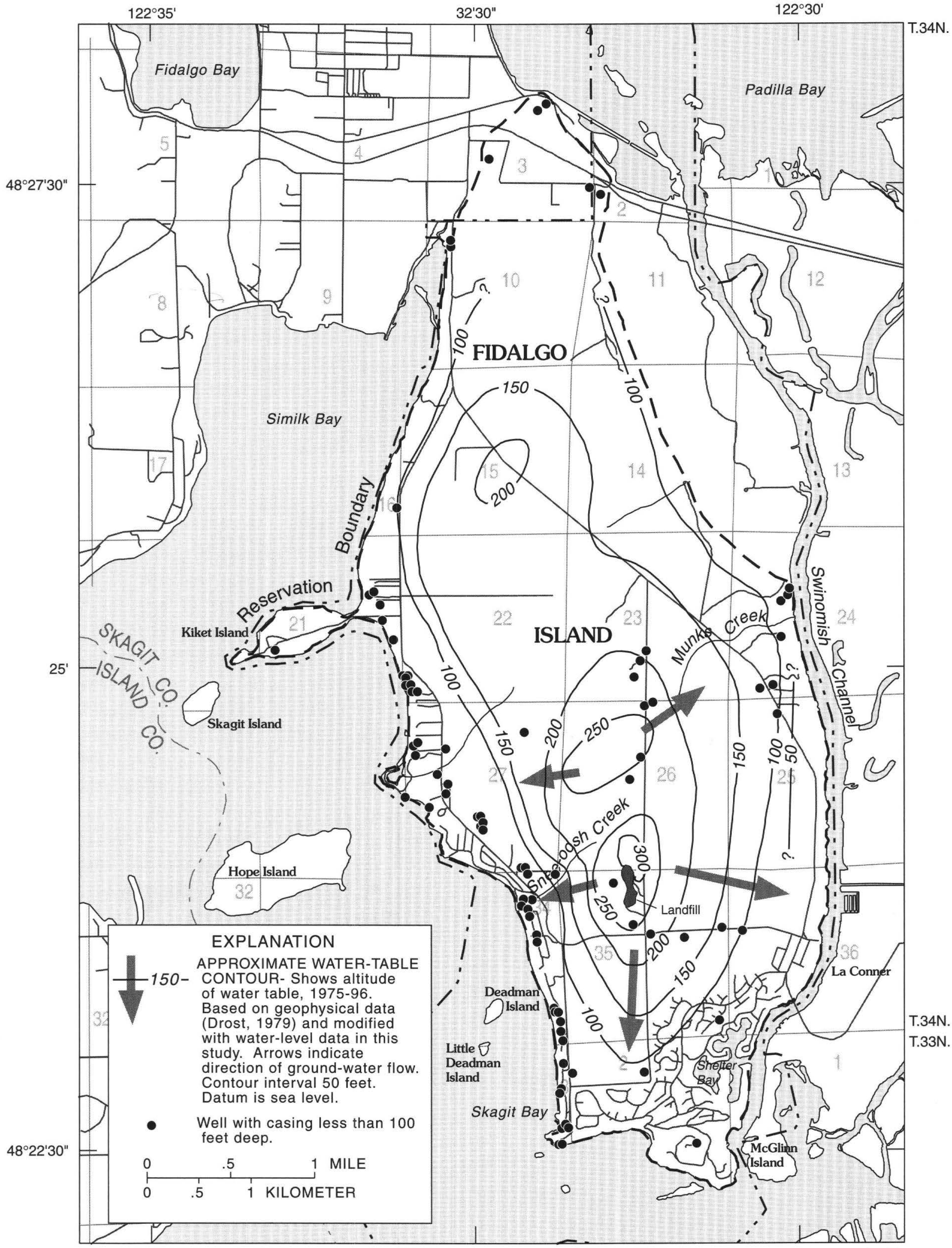


Figure 9. Approximate altitude of the water table, 1975-96.

Age-Dating Concepts

Tritium and chlorofluorocarbons (CFC's) are environmental tracers that were used in this study to estimate the age of ground water near the landfill. These chemical substances have been introduced into the atmosphere in large quantities by human activity during the last 40 to 60 years. Their concentrations can be used to estimate the age of ground water, which is then used to estimate sources of recharge and directions and rates of ground-water flow.

Tritium is an isotope of hydrogen with a half life of 12.43 years. The natural concentrations of tritium in precipitation in western Washington are low compared with the large influx of tritium to the atmosphere from above-ground testing of thermonuclear weapons. The large influx of tritium is commonly referred to as "bomb tritium," which entered the global water cycle primarily between 1953 and 1965. Thatcher (1962) estimated that the natural or "pre-bomb" concentration of tritium in precipitation in western Washington is on the order of 3-5 TU. The concentrations of tritium in ground water recharged from precipitation prior to 1953, which contained naturally generated tritium at 3-5 TU, would have decayed roughly 3.5 half-lives by 1996, resulting in a concentration of less than 1 TU. Thus, barring mixing of ground water from multiple sources, tritium concentrations higher than 1 TU in ground-water samples indicate that the ground water was recharged after 1953. Ground water estimated to have been recharged prior to 1953 is referred to as premodern; ground water recharged after 1953 is referred to as modern. The irregular historical pattern of the production of bomb tritium is such that tritium data can often only be used to determine whether the age of ground water is either modern or premodern; however, other than its radioactive decay, tritium is non-reactive within a ground-water system and thus is a very reliable tracer of ground water recharged after 1953 (Plummer and others, 1993; Mazor, 1991).

Chlorofluorocarbons (CFC's) are a class of synthetic compounds that are slightly soluble in water and chemically stable in many aerobic ground-water settings. There are no known natural sources for CFC's, which were first manufactured in the 1930's and were used primarily as refrigerants and for other industrial applications. Chlorofluorocarbons have been released to the atmosphere and hydrosphere where they can be detected in very small quantities in water (one part in 10^{15} by weight) and in air (one part in 10^{12} by volume). Atmospheric concentrations of CFC's have increased steadily from the time of their introduction to 1995 (E. Busenberg, written commun., 1996). Measurements of several individual CFC's in ground water (CFC-11, trichloroflourocarbon; CFC-12, dichlorodiflourocarbon; and CFC-113, trichlorotriflouroethane) can be used to date modern ground water (Dunkle and others, 1993; Plummer and others, 1993).

Chlorofluorocarbons are incorporated into ground-water recharge when atmospheric CFC's dissolve in rainwater; the resulting concentration in ground water is directly related to the atmospheric concentration of CFC's. With an established concentration history of CFC's in the atmosphere, concentrations of CFC's measured in ground water can be related to atmospheric concentrations to establish the time period when that ground water was in contact with the atmosphere. Examples of using the concentration of CFC's to age-date ground water include Busenberg and Plummer (1992), Busenberg and others (1993), Ekwurzel and others (1994), Hinkle and Snyder (1994) and Hinkle (1995).

Applying CFC's to estimate ground-water age is complicated; most notable is the difficulty in collecting and preserving uncontaminated samples at the parts per quadrillion level. In addition, microbial degradation of some CFC's under anaerobic conditions and sorption of some CFC's to particulate organic matter within the aquifer matrix affect the reliability of CFC's as environmental tracers. Recent improvement in sampling design by Busenberg and Plummer (1992) make possible the collection and preservation of uncontaminated samples, and reliable CFC age dates have been estimated under mildly anaerobic conditions (sulfate reducing) using CFC-12, which is the CFC compound most resistant to microbial degradation (Lovley and Woodward, 1992). Because CFC-113 and CFC-11 also can sorb to particulate organic matter, CFC-12 is typically the most reliable CFC age-dating tracer.

Age-Dating and Flow Analysis

Estimated ground-water ages near the landfill (fig. 7) ranged from less than 43 years, to between 15 and 43 years, to greater than 43 years. More precise estimates could not be made, given the limitations of the data. The age estimates of less than 43 years could be as recent as one to two years. The ground-water ages were estimated on the basis of concentrations of tritium and CFC's. The tritium data provided the more reliable ground-water age data because geochemical conditions within the ground water increased the uncertainty of the CFC data.

Tritium concentrations ranged from less than (<) 0.1 to 16 TU in water samples from nine wells (table 1). The nine samples were split into three age classes on the basis of tritium concentrations; concentrations lower than 1.0 TU indicate recharge prior to 1953 and an age of greater than 43 years; concentrations between 1.0 and 10 TU indicate an age of less than 43 years; and concentrations higher than 10 TU indicate an age of between 15 and 43 years.

The magnitude of tritium concentrations in ground water in 1996 is a result of the concentrations of tritium in recharge from infiltration and percolation of precipitation during the past 43 years. Measured tritium concentrations in precipitation samples collected in Portland, Oreg., were used to estimate the age of the ground-water samples collected in this study (fig. 10; Rodney Caldwell, U.S. Geological Survey, written commun., 1996).

The method for determining modern or premodern ground water (younger or older than 43 years) was explained in the preceding section, "Age Dating Concepts." Modern ground water can be classified into two age groups: less than 43 years old, or 15 to 43 years old. The broad estimate of less than 43 years old is made for water samples with low concentrations of tritium of between 1.0 and 10 TU. Assuming no dilution with premodern ground water, low concentrations of tritium in ground water are the result of low concentrations in precipitation and recharge either before or after the peak period of such concentrations (between the late 1950's and early 1980's) (fig. 10). After the peak period, tritium concentrations in precipitation slowly declined to low levels because of radioactive decay and the continued removal of atmospheric tritium that was dissolved in precipitation.

Table 1. Concentrations of tritium, chlorofluorocarbons, and dissolved gases in water samples from selected wells, and estimated ages of ground water, September 1996, Swinomish Indian Reservation, Washington

[T, till confining bed; O, outwash aquifer; C, clay confining bed; TU, tritium unit; pg/kg, picograms per kilogram; mg/L, milligrams per liter; µg/L, micrograms per liter; CFC-11, dichlorodifluoromethane; CFC-12, trichlorotriflouroethane; CH_4, methane; >, greater than; < less than; --, no data]

Local well number	Hydro-geologic unit	Well depth (feet)	Tritium concentration (TU)	Tritium age range (years)	CFC-11 concentration (pg/kg)	CFC-11 age (years)	CFC-12 concentration (pg/kg)	CFC-12 age (years)	Dissolved oxygen concentration (mg/L)	Dissolved CH_4 concentration (µg/L)	Dissolved argon concentration (mg/L)
Wells upgradient or across a ground-water divide from landfill											
34N/02E-23P03	O	170	2.8	<43	1.2	>50	0.0	>50	0.1	1.0	0.82
34N/02E-26F05	T	30	13	15-43	--	--	--	--	8.2	--	--
Well adjacent to landfill											
34N/02E-35C02	O	53	13	15-43	--	--	--	--	2.1	--	--
Wells downgradient from landfill											
34N/02E-27R01	C	72	0.3	>43	2.1	46	[1]con	--	0.2	2.0	.74
34N/02E-27R04	C	78	<.1	>43	--	--	--	--	<0.1	--	--
34N/02E-35G01	O	138	9.3	<43	19.4	39	15.4	39	<0.1	0.5	.85
34N/02E-35G03	T	23	4.0	<43	--	--	--	--	<0.1	--	--
34N/02E-35G04	O	89	0.5	>43	1.8	46	0.0	>50	0.2	10	.78
34N/02E-35H02	O	84	16	15-43	--	--	--	--	--	--	--

[1] con, sample was contaminated.

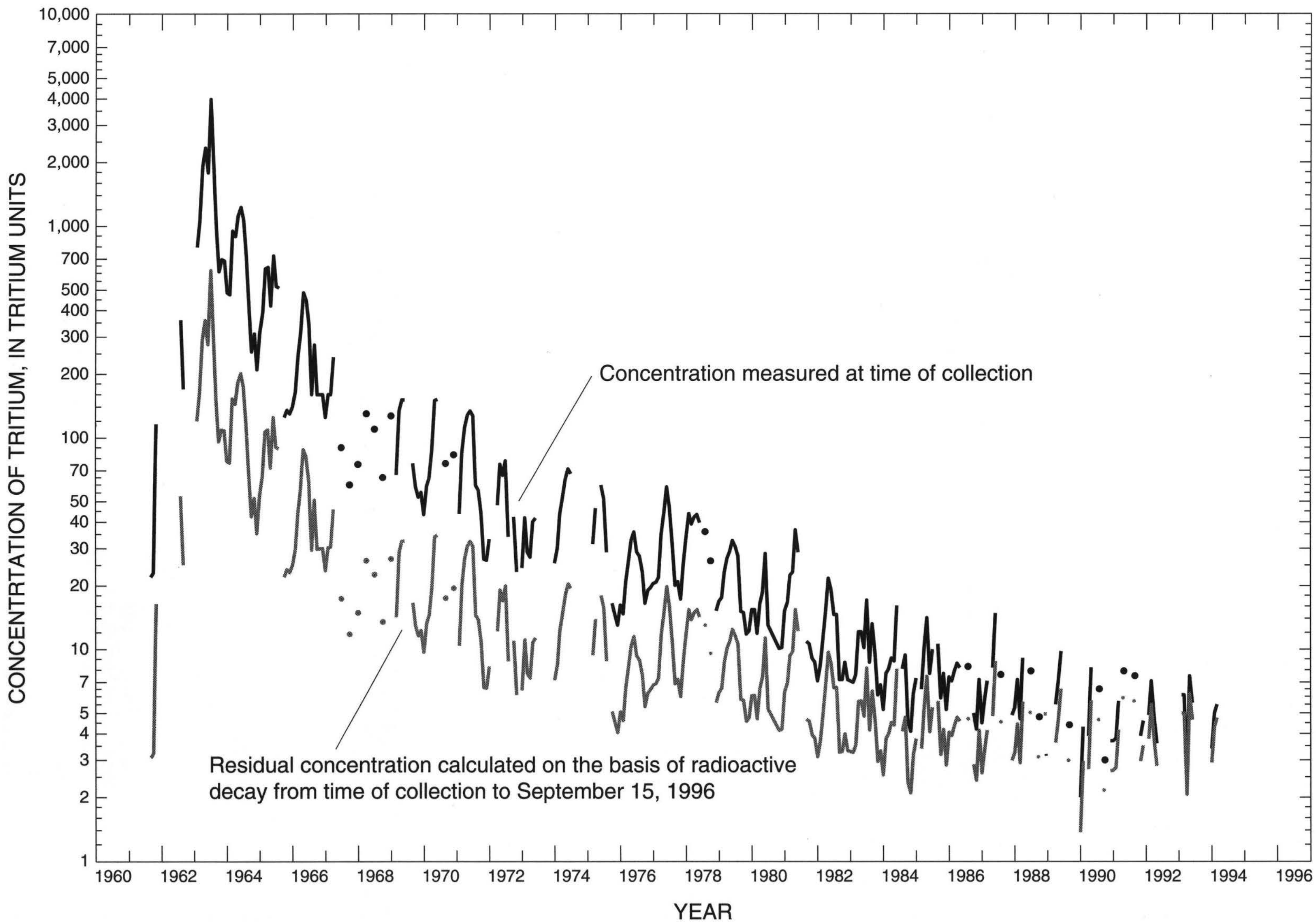


Figure 10. Concentration of tritium measured in monthly samples of rainfall collected in Portland, Oregon; and residual tritium concentration calculated on the basis of radioactive decay from time of collection to September 15, 1996.

Ground-water samples with tritium concentrations higher than 10 TU were estimated to be between 15 and 43 years old. A ground-water age of at least 10 years can be assumed by examining the measured concentration of tritium in precipitation (fig. 10). Ground water with tritium concentrations higher than 10 TU was recharged before 1986, because most precipitation samples had tritium concentrations lower than 10 TU since 1986. Considering radioactive decay, the age estimate of such ground water can be increased to at least 15 years old (recharge in 1981). Tritium decays at a radioactive half-life of 12.43 years. Tritium concentrations in precipitation and recharge were about 25 TU or higher in or before 1981 (fig. 10); therefore, ground water that was recharged in or before 1981 would have decayed tritium concentrations of 10 TU or higher.

An even older ground-water age might be estimated if the seasonal variation of tritium concentration is considered; during a typical year, most of the ground-water recharge is in the winter when tritium concentrations in precipitation are lowest in the seasonal cycle. This seasonal factor could push back the year of recharge and tritium input from 1981 to several years earlier. However, the conservative limit of 15 years is used in this report.

Well construction and plumbing conditions at four of the nine wells were suitable to collect water samples for CFC analysis. Prior to submitting the CFC samples for analysis, a volatile organic compound screening sample was collected from well 34N/02E-35G01 to determine if high CFC concentrations might be present as a result of buried refrigeration equipment in the landfill. None of the 60 VOC's included in the analysis (table 2), including the CFC's of interest, were detected above the analytical reporting level.

The concentrations of CFC-11 and CFC-12 in the samples from four wells were less than 20 pg/kg water (table 1). One sample for CFC-12 in well 34N/02E-27R01 was contaminated by an unknown source. These low CFC concentrations generally indicate that the ground water is from 30 to 60 years old. The CFC ages agreed with the tritium ages in three of the four wells. The CFC and tritium ages for wells 34N/02E-27R01 and 34N/02E-35G04 both indicate that the water is older than 43 years. Likewise, the CFC age of 39 years for well 34N/02E-35G01 agrees with a tritium age of less than 43 years.

At well 34N/02E-23P03, the ground-water ages estimated from CFC's indicate the water is greater than 50 years old, but the tritium concentration of 2.8 TU clearly shows the water from this well is less than 43 years old. This discrepancy is likely caused by anaerobic or methanogenic conditions, as indicated by the low dissolved oxygen concentrations and the presence of methane (table 1). All CFC's degrade under methanogenic conditions, so the low concentration of CFC's for well 34N/02E-23P03 may be the residual CFC's left from degradation, and the determined age is falsely high. In fact, because of the widespread anaerobic conditions in the ground water, it may be mere coincidence if the CFC ages agree with the tritium ages for all the water samples.

Ground-water ages were estimated for five samples from the outwash aquifer; four of the five ages were modern and one was premodern, and two of the modern ages were between 15 and 43 years (table 1). While not conclusive, these data indicate that the average ground-water travel time of recharge water through the surficial till unit to the underlying outwash aquifer is typically between 15 and 43 years. Two water samples from a recharge area of the surficial till unit were estimated to be modern, as expected for shallow wells of 23 ft (34N/02E-35G03) and 30 ft (34N/02E-26F05).

Premodern ages were estimated for two water samples from the clay confining bed (wells 34N/02E-27R01 and 34N/02E-27R04). This older water is expected because the water has to travel through the till confining bed and the outwash aquifer to reach the clay confining bed (fig. 8).

The ground-water age estimates generated from these samples could not be used for the intended purpose of estimating directions and rates of ground-water flow because flow paths are complex near the landfill; there was a limited distribution of available wells to sample; and the sampled wells were located on mostly different flow paths. Approximate directions of ground-water flow near the landfill can be discerned from the water-table map shown on figure 9. The landfill is just south of a mound of ground water, with the water table at an altitude of about 300 ft. Therefore, the landfill is in a recharge area, and ground water flows radially away in all directions except the north. Some ground water might flow from north to south into the north end of the landfill.

Table 2. Reported concentrations of volatile organic compounds in a water sample from well 34N/02E-35G01, September 19, 1996, and drinking water standards, Swinomish Indian Reservation, Washington

[µg/L, micrograms per liter; drinking water standards or guidelines are U.S. Environmental Protection Agency (USEPA) maximum contaminant levels for drinking water (USEPA, 1996); --, no standard or guideline]

Volatile organic compound	Common or alternate name	Chemical abstract services registry number	Reported concentration (µg/L)	Drinking water standard or guideline (µg/L)
2-chloro-1-methylbenzene	*o*-Chlorotoluene	95-49-8	<0.2	--
4-chloro-1-methyl benzene	*p*-Chlorotoluene	106-43-4	<0.2	--
1,1-Dichloroethane	Ethylidene chloride	75-34-3	<0.2	--
1,1-Dichloroethene	--	75-35-4	<0.2	7
1,1-Dichloropropene	--	563-58-6	<0.2	--
1,2-Dibromo-3-chloropropane	DBCP	96-12-8	<1.0	0.2
1,2-Dibromoethane	EDB	106-93-4	<0.2	0.05
1,2-Dichlorobenzene	*o*-Dichlorobenzene	95-50-1	<0.2	600
1,2-Dichloroethane	Ethylene dichloride	107-06-2	<0.2	5
cis-1,2-Dichloroethene	Acetylene dichloride	156-59-4	<0.2	70
trans-1,2-Dichloroethene	--	156-60-5	<0.2	100
1,2-Dichloropropane	Propylene, dichloride	78-87-5	<0.2	5
1,3-Dichlorobenzene	*m*-Dichlorobenzene	541-73-1	<0.2	600
1,3-Dichloropropane	--	142-28-9	<0.2	--
cis-1,3-Dichloropropene	--	100-61-015	<0.2	--
trans-1,3-Dichloropropene	--	100-61-026	<0.2	--
1,4-Dichlorobenzene	*p*-Dichlorobenzene	106-46-7	<0.2	75
2,2-Dichloropropane	--	594-20-7	<0.2	--
1,1,1-Trichloroethane	Methyl chloroform	71-55-6	<0.2	200
1,1,2-Trichloroethane	Vinyl trichloride	79-00-5	<0.2	5
1,1,2-Trichloro-1,2,2trifluoroethane	CFC-113	76-13-1	<0.2	--
1,2,3-Trichlorobenzene	--	87-61-6	<0.2	--
1,2,3-Trichloropropane	--	96-18-4	<0.2	--
1,2,4-Trichlorobenzene	--	120-82-1	<0.2	70
1,2,3-Trimethylbenzene	--	526-73-8	<0.2	--
1,2,4-Trimethylbenzene	Pseudocumene	95-63-6	<0.2	--
1,3,5-Trimethylbenzene	Mesitylene	108-67-8	<0.2	--
1,1,1,2-Tetrachloroethane	--	630-20-6	<0.2	--
1,1,2,2-Tetrachoroethane	--	79-34-5	<0.2	--
Benzene	--	71-43-2	<0.2	5
Bromobenzene	Phenyl bromide	108-86-1	<0.2	--
Bromochloromethane	Methylene chlorobromide	74-97-5	<0.2	--
Bromodichloromethane	Dichlorobromomethane	75-27-4	<0.2	--
Bromomethane	Methyl bromide	74-83-9	<0.2	--

Table 2. Reported concentrations of volatile organic compounds in a water sample from well 34N/02E-35G01, September 19, 1996, and drinking water standards, Swinomish Indian Reservation, Washington--Continued

Volatile organic compound	Common or alternate name	Chemical abstract services registry number	Reported concen-tration (µg/L)	Drinking water standard or guideline (µg/L)
n-Butylbenzene	1-phenylbutane	104-51-8	<0.2	--
sec-Butylbenzene	2-phenylbutane	135-98-8	<0.2	--
tert-Butylbenzene	2-methyl-2-phenylpropane	98-06-6	<0.2	--
Chlorobenzene	Phenyl chloride	108-90-7	<0.2	100
Chloroethane	Ethyl chloride	75-00-3	<0.2	--
Chloroethene	Vinyl chloride	75-01-4	<0.2	2
Chloromethane	Methyl chloride	74-87-3	<0.2	--
Dibromochloromethane	--	124-48-1	<0.2	100
Dibromomethane	Methylene bromide	74-95-3	<0.2	--
Dichlorodifluoromethane	CFC-12	75-71-8	<0.2	--
Dichloromethane	Methylene chloride	75-09-2	<0.2	5
Ethylbenzene	--	100-41-4	<0.2	700
Hexachlorobutadiene	HCBD	87-68-3	<0.2	--
Isopropyl benzene	Cumene	98-82-8	<0.2	--
p-Isopropyltoluene	*p*-Cymene	99-87-6	<0.2	--
Methyl *tert*-butyl ether	MTBE	163-40-44	<0.2	--
Methylbenzene	Toluene	108-88-3	<0.2	1000
n-Propylbenzene	1-Phenylpropane	105-65-1	<0.2	--
Styrene	Vinyl benzene	100-42-5	<0.2	100
Tetrachloroethene	Perchloroethylene, PCE	127-18-4	<0.2	5
Tetrachloromethane	Carbon tetrachloride	56-23-5	<0.2	5
Tribromomethane	Bromoform	75-25-2	<0.2	100
Trichloroethene	TCE	79-01-6	<0.2	5
Trichlorofluoromethane	CFC-11	75-69-4	<0.2	--
Trichloromethane	Chloroform	67-66-3	<0.2	100
Xylenes, total		108-38-3	<0.2	--

Water-Quality Analysis

Water-quality data collected for this study and review of existing data indicate that material in the landfill has had no appreciable impact on the quality of ground water outside of the landfill. The water quality of samples from the wells near the landfill (table 3) appears to be similar to the ground-water quality described for the study area by Drost (1979). The principal water-quality problem in the samples from wells near the landfill was high iron and manganese concentrations; 56 percent of the samples exceeded the secondary drinking water standard (SMCL) for iron (300 µg/L) and 78 percent of the samples exceeded the SMCL for manganese (50 µg/L) (U.S. Environmental Protection Agency, 1996). These high concentrations, however, are probably within the range of natural concentrations for the study area. Water samples analyzed during the Drost (1979) study also had high iron and manganese concentrations; 27 percent of the wells had water samples exceeding the SMCL for iron, and 50 percent of the wells had samples exceeding the SMCL for manganese. High concentrations of iron and manganese in ground water are also common throughout the glaciated parts of the Puget Sound Lowland (Turney, 1986).

Table 3. Field measurements and concentrations of inorganic and organic constituents in water samples from selected wells near the landfill, September 1996, Swinomish Indian Reservation, Washington

[Relation of well to landfill: up, ground-water levels are upgradient or across a ground-water divide from landfill; aj, adjacent to landfill; dn, ground-water levels are downgradient of landfill; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per ltier; --, no data; <, less than]

Local well number	Relation of well to landfill	Date	Time	Land-surface altitude (feet)	Depth of well (feet)	Specific conductance, field (µS/cm)	Specific conductance, laboratory (µS/cm)	pH, field (standard units)	pH, laboratory (standard units)
34N/02E-23P03	up	09-26-96	1620	270	170	402	394	8.0	7.4
34N/02E-26F05	up	09-20-96	1130	247	30	278	277	7.1	7.3
34N/02E-35C02	aj	09-26-96	1030	277	53	930	756	7.6	7.8
34N/02E-27R01	dn	09-26-96	1300	105	72	450	452	8.4	8.1
34N/02E-27R04	dn	09-20-96	1330	152	78	340	337	--	7.7
34N/02E-35G01	dn	09-19-96	1230	235	138	327	323	7.2	7.2
34N/02E-35G03	dn	09-20-96	0830	230	23	300	289	6.4	6.4
34N/02E-35G04	dn	09-25-96	1400	192	89	361	357	7.5	7.2
34N/02E-35H02	dn	09-26-96	1820	178	84	--	276	--	7.9

Local well number	Temperature, water (°C)	Oxygen, (milli-dissolved (mg/L)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, total field (mg/L as $CaCO_3$)	Alkalinity, total laboratory (mg/L as $CaCO_3$)
34N/02E-23P03	10.5	0.1	29	22	12	2.5	105	116
34N/02E-26F05	11.0	8.2	16	15	12	1.0	65	70
34N/02E-35C02	11.0	2.1	80	59	24	3.3	400	313
34N/02E-27R01	12.0	0.2	23	30	20	4.3	172	186
34N/02E-27R04	--	<0.1	22	18	15	2.5	--	144
34N/02E-35G01	11.0	<0.1	22	18	14	2.1	120	126
34N/02E-35G03	11.0	<0.1	25	6.3	13	7.0	91	86
34N/02E-35G04	11.0	0.2	27	19	12	2.2	104	120
34N/02E-35H02	--	--	18	14	12	1.6	--	92

Table 3. Field measurements and concentrations of inorganic and organic constituents in water samples from selected wells near the landfill, September 1996, Swinomish Indian Reservation, Washington--Continued

Local well number	Sulfate, dissolved (mg/L as SO4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO2)	Dissolved solids, residue at 180°C (mg/L)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)
34N/02E-23P03	64	14	0.3	0.07	22	235	<0.01	<0.05
34N/02E-26F05	19	11	<0.1	.07	32	179	<.01	5.3
34N/02E-35C02	43	28	<.1	.16	25	489	<.01	.91
34N/02E-27R01	12	29	.1	.11	22	235	<.01	<.05
34N/02E-27R04	2.5	17	.1	.07	36	210	.02	.10
34N/02E-35G01	18	16	<.1	.08	31	201	.01	.09
34N/02E-35G03	15	14	<.1	.09	16	196	.02	1.5
34N/02E-35G04	45	12	.2	.07	37	222	<.01	<.05
34N/02E-35H02	25	14	.1	.21	31	172	.02	<.05

Local well number	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Carbon, organic dissolved (mg/L as C)
34N/02E-23P03	0.09	<0.20	<0.01	<0.01	1,200	480	0.90
34N/02E-26F05	.02	<.20	.05	.07	28	<1.0	1.3
34N/02E-35C02	<.015	<.20	.06	.04	16	220	1.1
34N/02E-27R01	.06	<.20	.07	.09	7.0	7.0	1.3
34N/02E-27R04	.71	.70	.23	.29	97	250	2.4
34N/02E-35G01	.05	<.20	.02	.03	960	95	.70
34N/02E-35G03	1.9	2.1	.09	.14	4,400	720	12
34N/02E-35G04	<.015	<.20	.03	.02	550	120	1.7
34N/02E-35H02	.03	<.20	<.01	<.01	2,800	160	--

Iron and manganese concentrations are usually low in shallow ground water because shallow ground water typically contains substantial dissolved oxygen, which creates geochemical conditions in which iron remains insoluble. When oxygen is absent, however, iron and manganese are readily soluble, often leading to very high concentrations. A lack of oxygen in ground water can be created by natural organic materials such as peat that will consume oxygen while decaying. Wood or other debris buried in a landfill can have the same effect. The low dissolved oxygen concentrations (less than 0.5 mg/L) and the high dissolved organic carbon concentrations found in most of the samples (table 3) indicate that these conditions are common in the ground water near the landfill. Therefore, the high iron and manganese concentrations in these samples are likely caused by natural geochemical processes.

In addition to the high iron and manganese concentrations found in most of the samples near the landfill, human-related conditions appear to have resulted in high nutrient concentrations in two of the well samples. An elevated nitrate concentration of 5.3 mg/L was observed in the sample from well 34N/02E-26F05; this is a shallow well located in a pasture upgradient of the landfill. Elevated concentrations of ammonia (1.9 mg/L), nitrate (1.5 mg/L), and dissolved organic carbon (12 mg/L) at well 34N/02E-35G03 are likely related to its shallow depth (23 ft) and its proximity to a septic-system drain field.

A ground-water-quality study of the landfill was conducted in 1994 and 1995 for the Swinomish Indian Tribal Authority and the Bureau of Indian Affairs (BIA) (Q. Brown, Bureau of Indian Affairs, Portland, Oreg. written commun., March 1996). In September 1994, water samples were collected from two observation wells in the landfill (34N/02E-35C01, MW-1 and 34N/02E-35C03, MW-3) and from one observation well adjacent to the landfill (34N/02E-35C02, MW-2). These three wells are open to the outwash aquifer beneath any wood waste. Wells 34N/02E-35C01 and 34N/02E-35C03 had samples with high concentrations of chloride, total dissolved solids, iron, and manganese. Analyses of duplicate water samples collected from well 34N/02E-35C02 on the same day agreed poorly, so all analyses for well 34N/02E-35C02 are discounted. Analyses were made for about 100 organic compounds in samples from wells 34N/02E-35C01 and 34N/02E-35C03 and only one compound was detected. Bis (2-ethylhexyl) phthalate was detected at a concentration of 1 µg/L in the sample from well 34N/02E-35C01. Because that compound was also found in a blank sample, it is probably a laboratory contaminant.

The concentrations of chloride, total dissolved solids, iron, and manganese in water samples from the landfill monitoring wells 34N/02E-35C01 and 34N/02E-35C03 are much higher than the concentrations in any water samples analyzed in this study (table 3). Chloride concentrations were 520 mg/L for 34N/02E-35C01 and 110 mg/L for 34N/02E-35C03, and the concentrations ranged from 12 to 29 mg/L for the six wells downgradient of the landfill in this study. Total dissolved solids concentrations were 1,900 mg/L for 34N/02E-35C01 and 900 mg/L for 34N/02E-35C03, and the concentrations ranged from 172 to 235 mg/L for the six downgradient wells. Iron concentrations were 17,000 µg/L for 34N/02E-35C01 and 24,000 µg/L for 34N/02E-35C03, and the concentrations ranged from 7 to 4,400 µg/L for the six downgradient wells. Manganese concentrations also had similar differences in magnitude between the landfill wells and the other wells in this study. The high concentrations of iron, manganese, and total dissolved solids in the samples from the landfill wells are probably a result of the decomposition of woody debris. The cause of the high chloride concentrations in the samples from the landfill is unknown.

One sample was collected in this study from an observation well about 100 ft from the west edge of the landfill (well 34N/02E-35C02, well MW-2). The water-level gradient and flow direction between the well and the landfill is not known. The water from this well appears to be slightly affected by material in the landfill. The chloride, iron, and manganese concentrations are within natural ranges, but the total dissolved solids concentration of 489 mg/L is higher than expected for the study area (table 3).

In December 1995, a water sample was collected from well 34N/02E-35G01 as part of the BIA study. The sample had high concentrations of iron (2,400 µg/L) and manganese (110 µg/L) and a low concentration of chloromethane (1.4 µg/L). A sample from well 34N/02E-35G01 was also collected in this study; the water sample had a lower concentration of iron (960 µg/L) and a similar concentration of manganese (95 µg/L) (table 3), but no VOC's were detected, including chloromethane (table 2). It is possible that the chloromethane in the first sample was related to chlorination of the well.

Available water-quality data indicate that material in the landfill has had no appreciable impact on the quality of ground water outside of the landfill. The high concentrations of chloride, total dissolved solids, iron, and manganese in the samples of water from two wells in the landfill (34N/02E-35C01 and 34N/02E-35C03) are evidence of contamination of water under the landfill. It appears that the contamination has not spread from the landfill to ground water near the six downgradient wells in this study; the concentrations of chloride, total dissolved solids, iron, and manganese in water samples from the six downgradient wells are much lower than the concentrations in the samples from the landfill wells and appear to be within natural ranges. These data indicate no appreciable spread of contamination outside the landfill, but the data are not conclusive. The complex vertical and horizontal ground-water flow patterns, the limited number of wells and water samples, and potential geochemical reactions make it possible that some contamination has spread but was not detected in the six water samples.

CHANGES IN GROUND-WATER CONDITIONS FROM 1976 TO 1996

Changes in ground-water discharge, ground-water levels, and seawater intrusion into ground water between 1976 and 1996 were evaluated by comparing data collected during and between those two years. Because these ground-water conditions are influenced by precipitation, the precipitation before 1976 and between 1976 and 1996 needs to be considered. A Kendall-Theil statistical test (Helsel and Hirsch, 1992, p. 266-274) found no significant increasing or decreasing trend in annual precipitation from 1976 to 1996 at Anacortes, Wash. The precipitation during the time of data collection was 3.26 in. in July to September 1976 and 3.02 in. in July to September 1996 (table 4). Precipitation during the six-month period before data collection (January to June) was 13.18 in. in 1976 and 14.08 in. in 1996. Three-year precipitation was 74.41 in. for 1973-75 and 69.16 in. for 1993-95.

Table 4. Monthly precipitation for an average year, 1976, and 1996 at the National Weather Service station in Anacortes, Washington

Month	Precipitation, in inches		
	Average year	1976	1996
January-June	12.53	13.18	14.08
July	0.96	0.63	0.56
August	1.00	2.00	0.22
September	1.44	0.63	2.24

There were no large changes in ground-water discharge to streams, ground-water levels, and seawater intrusion from 1976 to 1996. Two principal factors in the study area can cause large changes in those ground-water conditions over time—precipitation and ground-water pumping. Precipitation was similar between 1976 and 1996; therefore, ground-water pumping had no appreciable effect on those ground-water conditions.

Ground-Water Discharge

Changes in ground-water discharge from 1976 to 1996 were evaluated by comparing summer flows in the two largest streams in the study area. During the summer, all of the flow in Munks Creek and Snee-oosh Creek is from ground-water discharge (Drost, 1979, p. 29). If ground-water pumping over the past 20 years had caused a decline in ground-water levels, a decrease in ground-water discharge would be expected.

The flows in Snee-oosh Creek and Munks Creek had mostly similar magnitudes in the summers of 1976 and 1996 (table 5), showing no evidence of an appreciable change in ground-water discharge. Therefore, ground-water pumping has not caused any large declines in ground-water discharge in the study area. Flows in Snee-oosh Creek ranged from 0.07 to 0.14 ft^3/s, and flows in Munks Creek ranged from 0.08 to 0.15 ft^3/s. Considering a streamflow measurement error of as much as 20 percent, the only flows that are appreciably different are the September flows in Snee-oosh Creek of 0.07 ft^3/s in 1976 and 0.14 ft^3/s in 1996. But the larger 1996 flows may be a result of greater precipitation in September 1996 than in September 1976 (table 4), and the September flows in Munks Creek have the opposite relation of smaller flows in 1996 than in 1976.

Ground-Water Levels

The rise or fall in ground-water levels over a period of time are an indication of changes in the available ground-water supply. If water levels decline, there is a loss of available water; if water levels rise, there is a gain. Usually a decline in water levels over a long period of time is a result of overpumping or mining of ground water. Decreasing recharge by paving over the land surface can also cause water-level declines, but that is not a factor in this study area. The most common natural factor that may cause long-term changes in ground-water levels is a decreasing or increasing trend in precipitation.

Table 5. Streamflow and chemical characteristics of Munks Creek and Snee-oosh Creek, 1976 and 1996, Swinomish Indian Reservation, Washington

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, no data]

Stream	Date	Discharge (cubic feet per second)	Specific conductance (µs/cm)	pH (standard units)	Temperature, water (degrees Celsius)	Oxygen, dissolved (mg/L)
Munks Creek	05-21-76	0.16	--	8.5	9.0	11.8
	08-26-76	0.12	--	--	10.6	11.1
	09-24-76	0.13	--	--	10.8	10.5
	07-26-96	0.15	303	8.2	13.0	10.0
	08-27-96	0.11	303	7.8	11.8	10.8
	09-25-96	0.08	301	8.3	10.3	11.0
Snee-oosh Creek	05-21-76	0.17	--	7.6	8.6	11.9
	08-26-76	0.09	--	--	11.4	10.4
	09-24-76	0.07	--	--	11.5	10.2
	07-26-96	0.13	503	7.9	13.9	9.1
	08-27-96	0.11	489	7.9	12.9	7.7
	09-25-96	0.14	490	--	10.6	10.0

Ground-water levels have not declined appreciably between 1976 and 1996, so it appears that overpumping has not been a problem during that time period. The changes in water levels at 20 wells with measurements made more than 10 years apart were evaluated (table 6). There is no apparent areal pattern to those water-level changes (fig. 11). The average water-level change for the 20 wells was -0.7 ft, and only two of those wells had greater than a 5 ft change. The water level in well 34N/02E-23P02 declined by 9 ft from 1977 to 1990, and the water level in well 34N/02E-35L01 declined by 6 ft from 1976 to 1996. These two water-level declines are not large enough to indicate a regional decline in water levels. The dates of measurements indicate that seasonal water-level variations, which average 3.4 ft in the study area, could be a factor.

Seawater Intrusion into Ground Water

Seawater intrusion is the migration of seawater into a freshwater aquifer. It is generally caused by pumping water from an aquifer that is hydraulically connected to the sea. Heavy pumping in coastal areas can cause a hydraulic gradient in the aquifer, such that seawater will flow from the sea toward the well. Usually, the first indication of seawater intrusion is an increase in chloride concentrations above normal levels. Chloride is a principal component of seawater, it is chemically stable, and it moves through an aquifer at about the same rate as the intruding seawater. Chloride concentrations, therefore, were used in this study to assess the extent of seawater intrusion in 1996 and to evaluate possible increases in seawater intrusion between 1976 and 1996. A threshold concentration of 50 mg/L was used as a conservative indicator of seawater intrusion (Walters, 1971).

No appreciable seawater intrusion was found in the ground water in 1996, and there was no significant increase in the extent of seawater intrusion from 1976 to 1996. There was only a minor amount of intrusion in 1976 and 1996; in both years more than 90 percent of the water samples from wells had chloride concentrations lower than 50 mg/L. Seawater intrusion is a continuing concern, however, because seawater is a boundary for most of the ground-water system (fig. 8), and any large decrease in recharge or increase in pumping could upset the balance between freshwater and seawater.

Table 6. Historical changes in water levels in wells with more than 10 years between measurements, Swinomish Indian Reservation, Washington

[GS, U.S. Geological Survey, RP, reported by driller or other source]

Local well number	Water level (feet below land surface)	Date	Source	Water level (feet below land surface)	Date	Source	Change in water levels (feet)
33N/02E-03H08	22	03-29-79	RP	18.4	08-27-90	GS	3.6
34N/02E-10D02	5.0	07-23-75	GS	1.2	08-14-96	GS	3.8
34N/02E-15L02	221	07-13-78	RP	219	08-14-96	GS	2
34N/02E-21H08	36.5	08-27-75	GS	37.4	08-13-96	GS	-0.9
34N/02E-22E01	83.0	03-09-76	GS	86.1	08-23-96	GS	-3.1
34N/02E-22E02	74.1	07-21-76	GS	75.8	08-14-96	GS	-1.7
34N/02E-23C02	100	12-13-78	RP	98.5	08-22-96	GS	1.5
34N/02E-23P02	130	11-08-77	RP	139	08-28-90	GS	-9
34N/02E-23P03	150	01-30-81	RP	154	08-13-96	GS	-4
34N/02E-27D11	6.7	03-09-76	GS	9.4	08-27-96	GS	-2.7
34N/02E-27R01	22	10-09-72	RP	26.7	08-28-90	GS	-4.7
34N/02E-27R03	40	11-25-74	RP	36.3	08-28-90	GS	3.7
34N/02E-27R04	48	07-18-80	RP	48.4	08-15-96	GS	-0.4
34N/02E-34A06	15	12-12-75	RP	15.4	08-13-96	GS	-0.4
34N/02E-34A07	53	11-04-81	RP	50.3	08-22-96	GS	2.7
34N/02E-34J01	55.8	07-30-75	GS	54.6	08-12-96	GS	1.2
34N/02E-34R06	44.0	04-20-76	GS	43.9	08-21-96	GS	0.1
34N/02E-35G01	110	07-23-75	GS	110	08-14-96	GS	0
34N/02E-35G03	15.4	08-26-76	GS	14.7	08-14-96	GS	0.7
34N/02E-35L01	109	03-09-76	GS	115	08-21-96	GS	-6

The median chloride concentration of 35 water samples collected in 1996 was 18 mg/L, and only three samples had concentrations higher than 50 mg/L (tables 7 and 8). The median concentration of 18 mg/L is somewhat higher than is typical for Washington ground-water systems, but it is within normal ranges for typical island ground-water systems in Puget Sound (Kahle and Olsen, 1995; Dion and Sumioka, 1984; and Turney, 1986). The three samples with chloride concentrations of higher than 50 mg/L are all from wells that are within 300 ft of the shoreline, have screens that are lower than sea level, and have water levels that are less than 10 ft above sea level (wells 33N/02E-03J04, 34N/02E-27D02, and 34N/03E-34A02) (table 7).

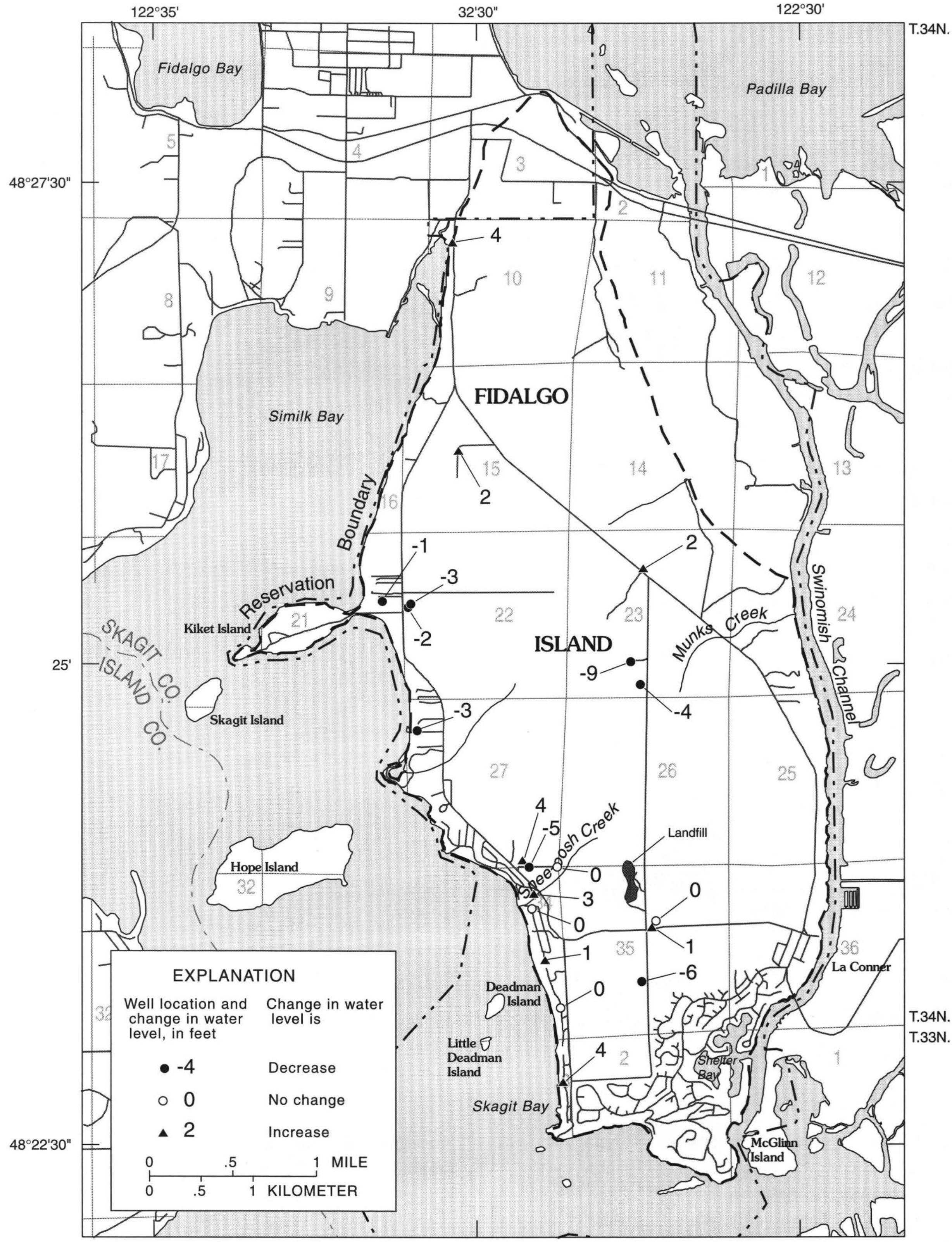


Figure 11. Changes in water levels in wells with more than 10 years between measurements, 1975-96.

Table 7. Water levels, field measurements of specific conductance, and concentrations of chloride in water samples from selected wells, 1953 to 1996, Swinomish Indian Reservation, Washington

[Water level; F, flowing; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/l, milligrams per liter; --, no data]

Local well number	Land-surface altitude (feet)	Depth of well (feet)	Date	Water level (feet below land surface)	Specific conductance, field (µS/cm)	Chloride, dissolved (mg/L as Cl)
33N/02E-03J04	43	67	11-16-76	--	770	140
			08-15-96	--	1,110	160
34N/02E-02N01	86	90	08-12-76	--	430	16
34N/02E-03G01	15	18	04-06-61	--	--	16
34N/02E-03K01	144	200	11-19-62	--	270	12
34N/02E-03L01	90	108	06-13-78	--	261	16
34N/02E-10D02	15	6	08-28-96	--	307	11
34N/02E-10D03	10	77	08-14-96	5.7	341	14
34N/02E-15C01	193	150	03-11-76	108	345	11
34N/02E-15L02	286	280	05-20-91	--	381	13
			08-14-96	219	392	15
34N/02E-15L03	280	272	05-20-91	--	390	18
34N/02E-15R01	234	143	08-17-76	--	400	14
34N/02E-15R02	240	273	05-20-91	--	359	18
34N/02E-15R03	240	261	05-20-91	--	344	19
34N/02E-21H01	32	65	05-03-67	--	578	55
			11-30-76	--	625	48
34N/02E-21H08	43	80	11-30-76	--	520	34
			08-13-96	37.4	551	28
34N/02E-22E01	98	107	03-09-76	83.0	715	45
			08-28-96	--	702	49
34N/02E-22E02	95	108	03-11-76	73.9	665	37

Table 7. Water levels, field measurements of specific conductance, and concentrations of chloride in water samples from selected wells, 1953 to 1996, Swinomish Indian Reservation, Washington--Continued

Local well number	Land-surface altitude (feet)	Depth of well (feet)	Date	Water level (feet below land surface)	Specific conductance, field (µS/cm)	Chloride, dissolved (mg/L as Cl)
34N/02E-25C02	145	60	08-13-96	26.8	264	12
34N/02E-25C03	75	123	08-13-96	--	710	18
34N/02E-26A01	250	169	08-15-96	--	239	10
34N/02E-26F01	281	40	03-11-76	--	195	14
34N/02E-26F05	247	30	08-13-96	12.1	287	12
			09-20-96	--	278	11
34N/02E-27D01	21	108	05-03-67	--	486	31
34N/02E-27D02	16	72	05-03-67	8.7	536	44
			11-16-76	--	600	46
			06-12-78	--	570	47
			08-15-96	--	635	53
34N/02E-27D03	25	112	11-16-76	--	550	33
34N/02E-27D06	68	177	10-22-75	--	--	22
			11-16-76	--	450	22
34N/02E-27D10	29	75	05-12-53	--	--	26
			05-03-67		558	30
34N/02E-27D11	20	141	03-09-76	6.7	500	22
			11-16-76	--	480	22
			08-27-96	9.4	497	22
34N/02E-27E01	23	56	11-16-76	--	550	42
34N/02E-27E03	30	53	08-14-96	--	501	24

Table 7. Water levels, field measurements of specific conductance, and concentrations of chloride in water samples from selected wells, 1953 to 1996, Swinomish Indian Reservation, Washington--Continued

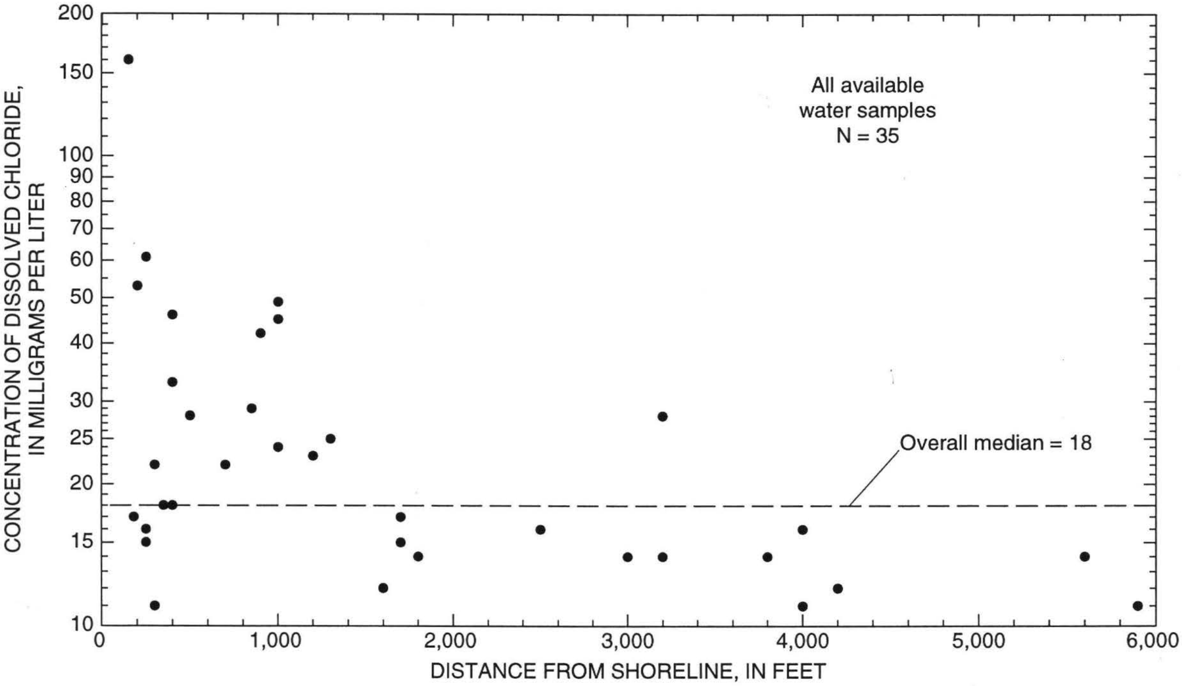
Local well number	Land-surface altitude (feet)	Depth of well (feet)	Date	Water level (feet below land surface)	Specific conductance, field (µS/cm)	Chloride, dissolved (mg/L as Cl)
34N/02E-27R01	105	72	08-15-96	--	465	28
			09-26-96	--	450	29
34N/02E-27R04	152	78	08-15-96	48.4	349	17
			09-20-96	--	340	17
34N/02E-34A02	38	99	10-22-75	--	280	20
			08-27-96	--	665	61
34N/02E-34A06	35	58	08-13-96	15.4	373	16
34N/02E-34A07	58	85	08-22-96	50.3	--	46
34N/02E-34B01	13	112	05-02-67	F	366	24
			10-22-75	-2.9	300	23
			01-26-76	-11	370	22
			11-16-76	-12	364	21
34N/02E-34H01	35	53	05-03-67	--	355	20
			03-09-76	--	375	16
34N/02E-34J01	105	160	03-09-76	54.8	388	15
			06-09-78	66.9	348	17
			08-12-96	54.6	365	15
34N/02E-34R02	43	95	11-16-76	--	373	25
34N/02E-34R06	40	200	01-26-76	50.1	2,450	410
			07-23-76	50.7	2,580	440
			11-16-76	--	2,420	420
			06-09-78	--	2,620	400
34N/02E-34R07	50	75	10-22-75	48.0	340	43

Table 7. Water levels, field measurements of specific conductance, and concentrations of chloride in water samples from selected wells, 1953 to 1996, Swinomish Indian Reservation, Washington--Continued

Local well number	Land-surface altitude (feet)	Depth of well (feet)	Date	Water level (feet below land surface)	Specific conductance, field (µS/cm)	Chloride, dissolved (mg/L as Cl)
34N/02E-35H01	178	21	05-13-53	14.1	--	28
			03-09-76	--	297	15
34N/02E-35H02	178	84	05-02-67	--	286	19
			03-09-76	--	297	15
			06-09-78	--	272	17
			08-14-96	--	288	14
			09-26-96	--	--	14
34N/02E-35H03	153	180	05-02-67	138	402	16
34N/02E-35L01	232	130	03-09-76	109	360	14
			08-21-96	115	363	14

The chloride concentrations in 1996 were related to distance from the shoreline and to altitude of the well bottom (fig. 12). Chloride concentrations are strongly related to distance from the shoreline; 93 percent of the samples from wells that are more than 1,500 ft from the shoreline have concentrations below the overall median of 18 mg/L. The chloride concentrations are generally higher within 1,500 ft of the shoreline; 71 percent of the sample concentrations are above the overall median, but there is considerable spread in the concentrations of samples from these wells. In an attempt to determine a possible reason for the large spread in chloride concentrations for wells near the shoreline, the concentrations were compared to altitude of the well bottom (fig. 12). One would expect the chloride concentration to increase as the bottom of a well declines further below sea level and the bottom approaches the freshwater-saltwater boundary (fig. 8). There is a slight trend of increasing concentrations with lower well bottoms, but still a large spread in the data. Apparently, none of the well bottoms are deep enough to be strongly influenced by the freshwater-saltwater boundary. The spread in data is probably a result of different lithologies, ground-water levels, and pumping rates at each well site.

Nonparametric statistical tests were made to determine if chloride concentrations in ground-water samples had significantly increased from 1976 to 1996. Four tests were performed on different groups of samples collected from wells in 1976 and in 1996; (1) a rank-sum test on all available samples, (2) a rank-sum test on samples from wells within 1,500 ft of the shoreline, (3) a Wilcoxon signed-rank test on all paired samples, and (4) a Wilcoxon signed-rank test on paired samples from wells within 1,500 ft of the shoreline (Helsel and Hirsch, 1992). Using the groups of wells within 1,500 ft of the shoreline results in a more controlled test than that from using all available wells; some of the influence of other environmental factors is removed, so the test is a more accurate indication of differences in chloride concentration as a result of time. Similarly, using the paired samples gives an even more controlled test because the influence of most other environmental factors is removed.



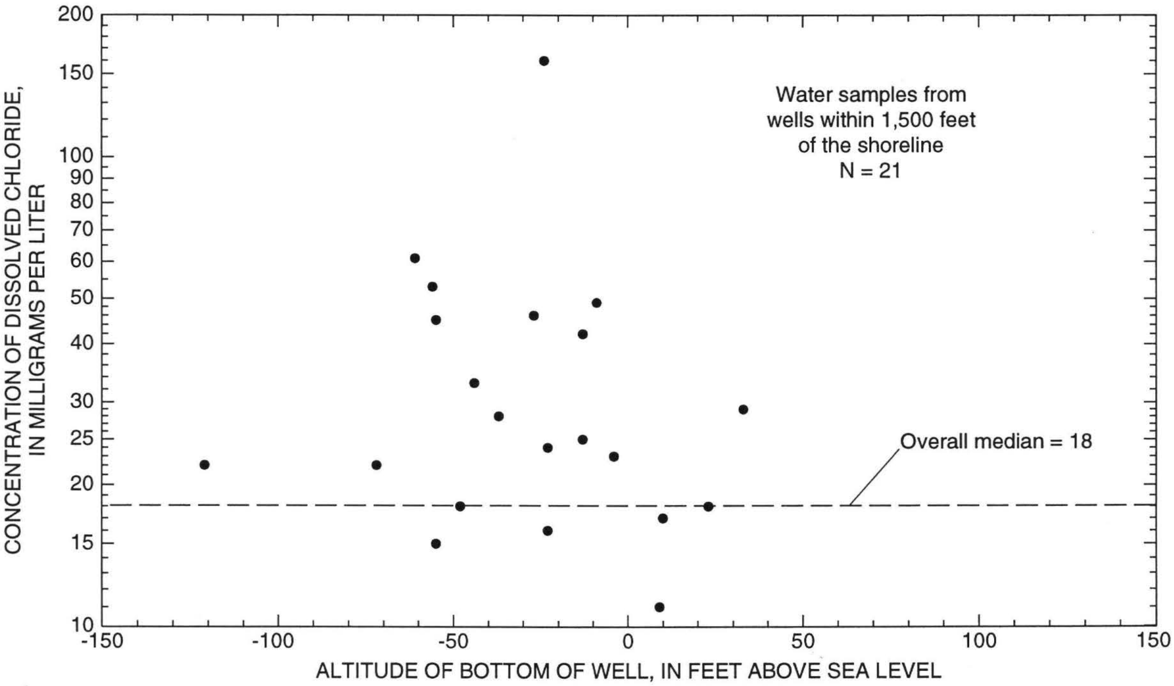


Figure 12. Relation between chloride concentration in ground water in 1996, distance from shoreline, and altitude of bottom of well, Swinomish Indian Reservation, Washington.

Chloride concentrations in ground water did not significantly increase from 1976 to 1996 (table 8). All four statistical tests found no significant increase in chloride concentrations (at $\alpha = 0.05$). Median concentrations for all available ground-water samples were 22 mg/L in 1976 and 18 mg/L in 1996. Concentrations were higher in the samples from wells within 1,500 ft of the shoreline; the medians were 25 mg/L in 1976 and in 1996. The statistical tests performed on paired samples showed much stronger evidence of a possible increase in chloride concentrations than the tests on all samples. The p-values for the paired tests were barely greater than 0.05; p-values of less than or equal to 0.05 are commonly used to demonstrate statistically significant differences. The results of the paired tests are not given much weight in this study because the sample sizes are small (9 and 13 samples) and the magnitude of increase in chloride concentrations is very small.

There does not appear to be a change in the areal distributions of chloride concentrations from 1976 (fig. 13) to 1996 (fig. 14). Both distributions have a similar pattern of the lowest concentrations near the center of the study area and the highest concentrations near the shoreline. The areal distribution of changes in chloride concentrations also has no apparent pattern (fig. 15).

Table 8. Chloride concentrations in ground-water samples collected in July to September 1976 and in August to September 1996, Swinomish Indian Reservation, Washington

			Chloride concentration, in milligrams per liter			
Group of samples	Year	Number of samples	25th percentile	Median	75th percentile	P-value
All	1976	30	15	22	43	[1]0.248
	1996	35	14	18	29	
All, within 1,500 feet of shoreline	1976	23	16	25	46	[1]0.477
	1996	21	18	25	46	
Paired, all	1976	13	15	21	42	[2]0.051
	1996	13	14	22	46	
Paired, within 1,500 feet of shoreline	1976	9	18	34	46	[2]0.053
	1996	9	20	28	51	

[1]A rank-sum nonparametric test (one-sided) was used to test the hypothesis that the chloride concentrations in 1976 are the same as the chloride concentrations in 1996. P-values greater than 0.05 indicate no significant increase in chloride concentrations from 1976 to 1996.

[2]A Wilcoxon signed-ranks nonparametric test (one-sided) was used to test the hypothesis that the chloride concentrations in 1976 are the same as the chloride concentrations in 1996. It is a test on paired samples; samples collected in 1976 and in 1996 from the same well. P-values greater than 0.05 indicate no significant increase in chloride concentrations from 1976 to 1996.

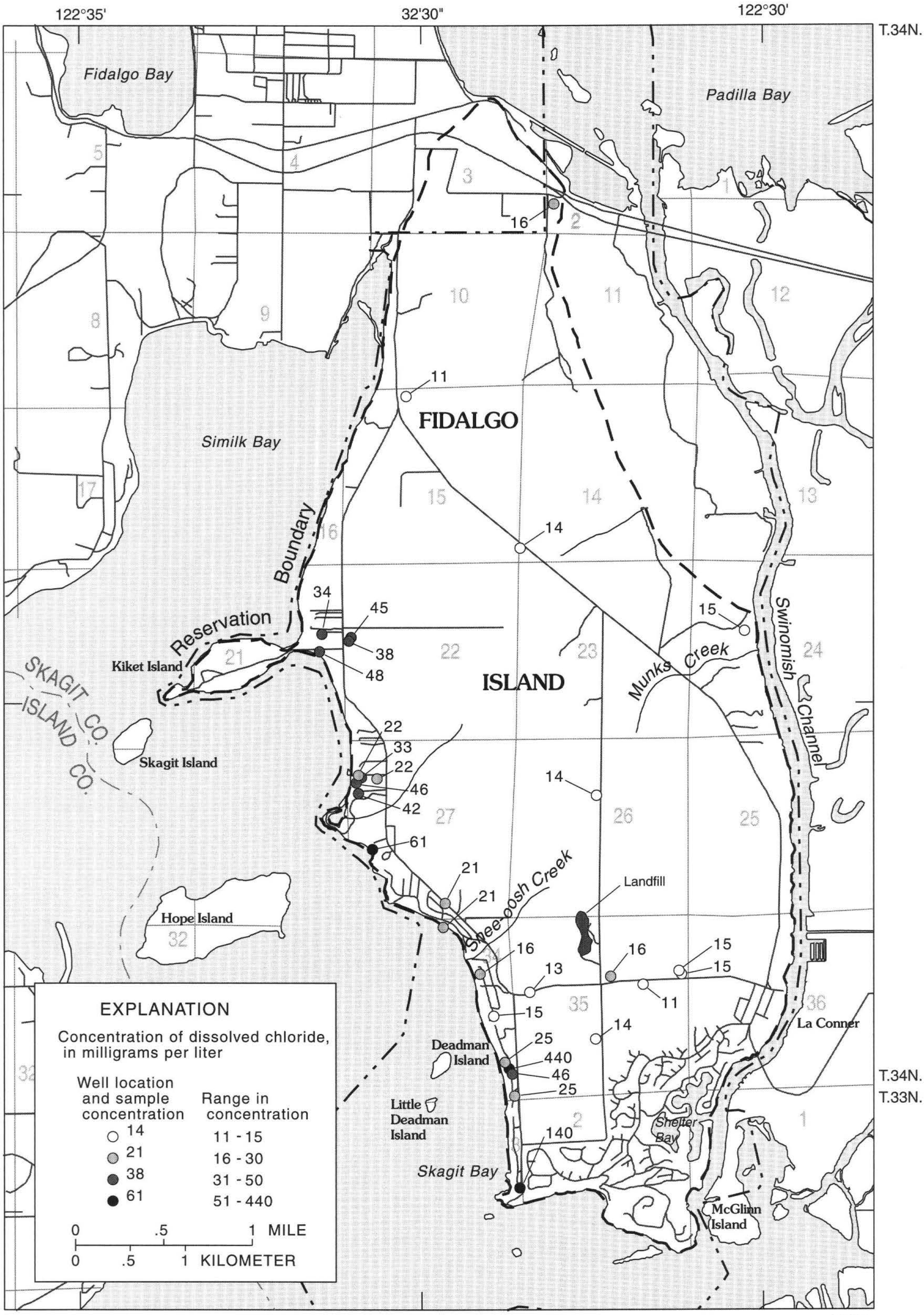


Figure 13. Concentrations of dissolved chloride in ground water, 1976.

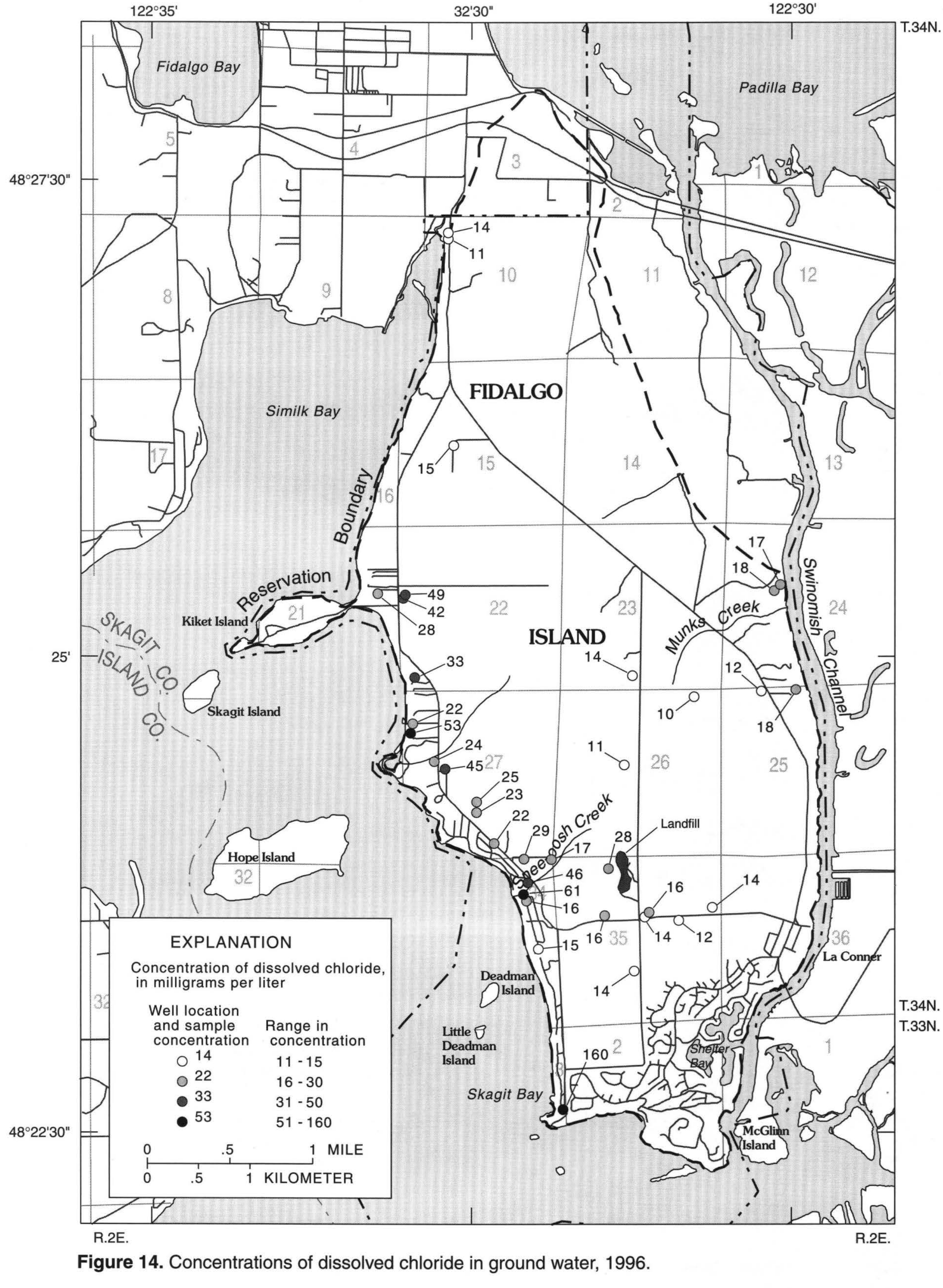


Figure 14. Concentrations of dissolved chloride in ground water, 1996.

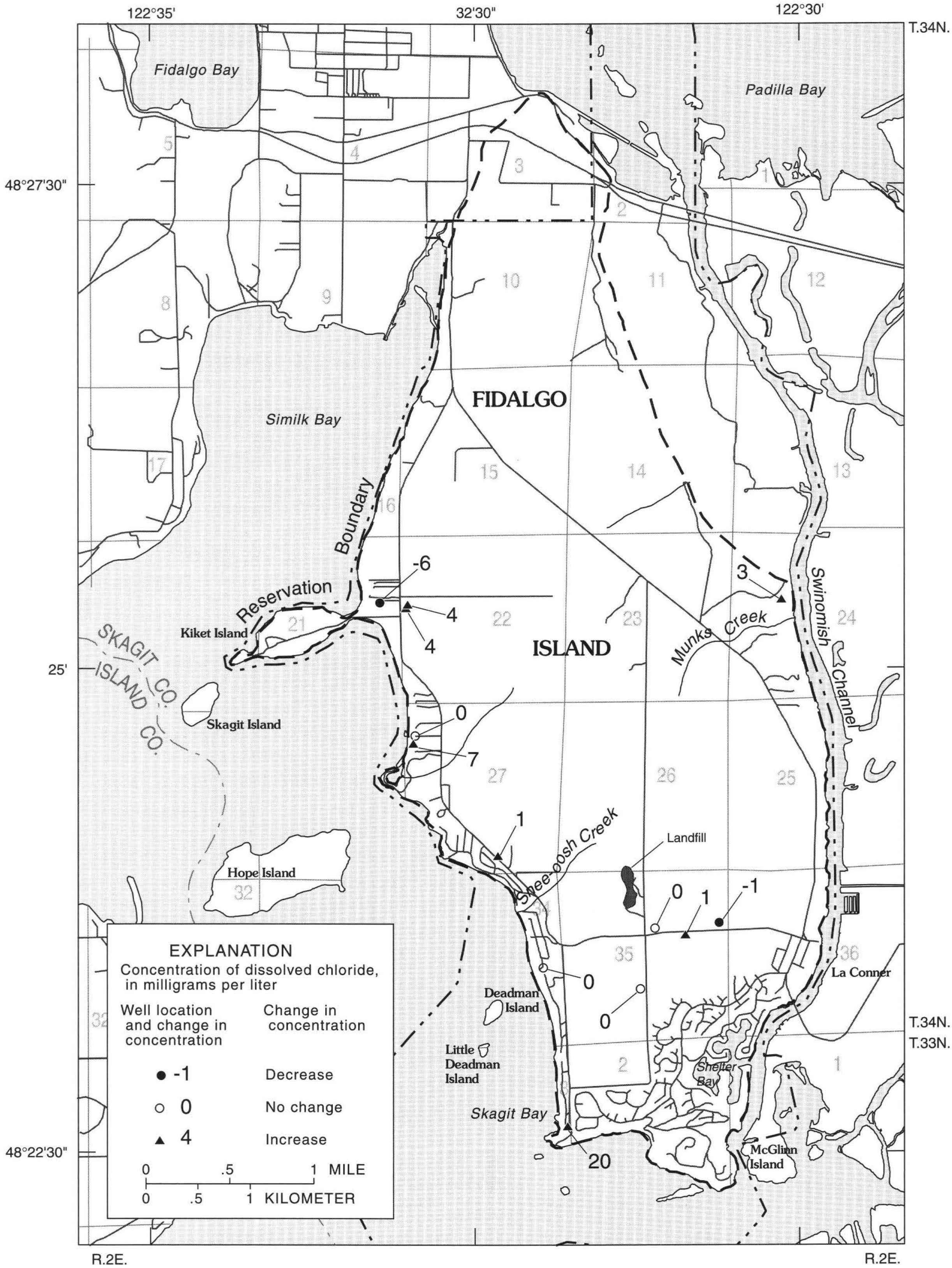


Figure 15. Changes in dissolved chloride concentrations in ground water, 1976-96.

NEED FOR ADDITIONAL STUDIES AND MONITORING

Additional studies and monitoring would provide a better understanding of the ground-water system and ground-water quality of the Swinomish Indian Reservation. Components of the ground-water system that are not well defined are the boundaries of the lower hydrogeologic units, hydraulic and storage properties of the hydrogeologic units, magnitude and temporal variability of ground-water recharge, ground-water movement in the outwash and sea-level aquifers, and magnitude and areal distribution of ground-water discharge. The response of the ground-water system to a stress such as heavy pumping is an important characteristic that is not known. The general chemical characteristics of the ground water are adequately described; however, some constituents may need periodic monitoring in the future because their concentrations can change over time as a result of human activity. Nitrate, chloride, trace elements, and synthetic organic compounds are examples of such constituents.

The boundaries of hydrogeologic units are the areal extents and top and bottom surfaces. The boundaries of the till confining bed and outwash aquifer are roughly described by Drost (1979), and a minimal amount of work with existing geophysical data and lithologic logs of wells could produce an adequate definition of those boundaries. The boundaries of the sea-level aquifer and boundaries within the lower undifferentiated unit are not well defined. Lithologic logs from new deeper wells or new geophysical studies could provide the information needed to define these boundaries. A productive aquifer in the undifferentiated unit might be found with such information.

The hydraulic and storage properties of the hydrogeologic units have been estimated using normalized specific capacities of wells completed in each unit. These estimates are adequate for relative comparisons, but the absolute magnitudes and areal distributions of these properties are not well defined. Transmissivity, hydraulic conductivity, and storage coefficients are needed to define the amount of ground water available for development and to determine ground-water velocities. In addition, they are helpful in estimating recharge and discharge. Aquifer tests are reliable methods for estimating these properties, and slug tests are useful for estimating hydraulic conductivity in shallow hydrogeologic units.

Average annual ground-water recharge has been estimated using a water-budget approach (Drost, 1979), empirical regression relations (Embrey and Jones, 1997), a chloride mass-balance method, and a flow equation using ground-water ages as input. These estimates of recharge for the upper boundary of the system (water table) are uncertain, as indicated by a large range of 3 to 12 in. In addition, the short- and long-term temporal variability of recharge to the water table is not well defined, and the amount of recharge to the lower hydrogeologic units is unknown. If a large amount of ground-water development is anticipated in the future, detailed studies of recharge would be needed.

Ground-water movement is not well defined in the study area. Ground-water flow directions have been described for flow in the upper 100 ft of the unconsolidated deposits. These flow directions are only approximate because they are based on water levels deduced from geophysical data and water levels in an uneven areal distribution of shallow wells. Flow directions in the middle and lower parts of the system (the outwash and sea-level aquifers) are not well defined. The directions probably follow the directions for the shallow system, but water-level gradients are not known. Measurements of water levels in the middle and lower parts of the system are needed to determine flow directions and water-level gradients. New wells would need to be drilled in the parts of the study area where there are no existing wells.

Ground-water discharge in the study area is not well defined. Most discharge is by flow to springs and streams and by subsurface flow to saltwater bodies. Periodic measurements of spring flow and summer streamflow could help define the magnitude and variability of this discharge with the added benefit of monitoring for possible human-caused changes to the hydrologic system. Subsurface flow to saltwater bodies is difficult to estimate, but a better understanding of hydrogeologic boundaries, hydraulic properties, and water-level gradients could be used to estimate this discharge using Darcy's Law.

The response of the ground-water system to a stress such as heavy ground-water pumping is not known. If a large population growth and associated increase in ground-water pumping is anticipated, a digital three-dimensional ground-water model could be constructed to estimate the response of the system to such a stress. A model needs comprehensive information on hydrogeologic boundaries, recharge, discharge, water levels, and hydraulic and storage properties.

The long-term effects of ground-water development and of changing land-use conditions in the study area could be monitored by the establishment of a water-level measurement and water-quality sampling network. Water-level declines beyond those expected for seasonal or climatic reasons could provide an early warning of ground-water mining; water-quality degradation could indicate the need to revise land-use controls.

As a long-term, minimum level of effort to monitor water quantity, water levels could be measured twice annually in selected wells in spring (when water levels are highest) and in autumn (when water levels are lowest). Observation wells could be selected to provide broad areal coverage and coverage of the areas of greatest ground-water withdrawals.

A minimum water-quality monitoring program would be the periodic collection of samples for the analysis of nitrate and chloride. Monitoring of these constituents would detect contamination from the most common sources in the study area—septic systems, animal wastes, and fertilizers. If other sources of contamination became a concern, such as industrial, commercial, or agricultural activity, an expanded program could be established. This expanded program could include analyses for common ions, trace elements, and synthetic organic compounds (including pesticides). For either program, the collection of water samples would be targeted to areas of potential contamination. If elevated concentrations of a constituent were found, samples could then be collected from areas where no contamination is expected (control samples) to determine natural levels of the constituent.

Although no appreciable seawater intrusion was found in the ground water, a periodic monitoring program of the collection of samples and analyses for chloride could detect early seawater intrusion problems. The samples would be collected from wells throughout the reservation, with particular emphasis on wells that are open near or below sea level.

The evaluation of ground-water age, flow, and quality near the landfill in the south-central part of the reservation improved the understanding of the ground water in that area. However, the specific objective of determining directions and rates of ground-water flow could not be achieved. The principal method used for evaluating the age and flow of ground water was to determine concentrations of the environmental tracers, tritium and CFC's. The location, depths, and plumbing characteristics of the wells available for sampling were not suitable for using the environmental tracers. The water-chemistry data that were determined, however, appear to show that the landfill has not caused any contamination of nearby domestic wells, and therefore, knowing directions and rates of flow is not a high priority. Periodic monitoring of ground-water quality near the landfill, as part of an overall monitoring network, could detect any problems not found in this study and would detect contamination from any future human activities.

Additional age-dating of deep ground water and ground water in discharge areas near the shoreline using carbon-14 methods would provide estimates of the time required for ground water to move completely through the ground-water flow system.

SUMMARY AND CONCLUSIONS

This report describes the results of two related studies: a study of ground-water age, flow, and quality near a landfill in the south-central part of the Swinomish Indian Reservation; and a study of changes in ground-water conditions for the entire reservation from 1976 to 1996. The Swinomish Indian Reservation is a 17 mi^2 part of Fidalgo Island in northwestern Washington. The ground-water flow system in the reservation is probably independent of other flow systems in the area because it is almost completely surrounded by salt water.

Stress on the ground-water resources of the reservation has increased because the population has almost tripled during the past 20 years and 65 percent of the population obtain their domestic water supply from the local ground-water system. The Swinomish Tribe is concerned that increased pumping of ground water might have caused decreased ground-water discharge into streams, declines in ground-water levels, and seawater intrusion into the ground-water system. There is also concern that leachate from an inactive landfill containing household and wood-processing wastes may be contaminating the ground water.

Hydrogeologic data were collected in the summer of 1996 to provide some of the information needed to address the concerns about the ground-water resources. Water-level, chloride-concentration, and specific-conductance data were collected during an inventory of 58 wells, and streamflows were measured in Snee-oosh Creek and Munks Creek once each month in July, August, and September. Water samples were collected from nine wells near the landfill, and analyses were made for general chemical characteristics and ground-water age data.

The study area is underlain by unconsolidated glacial and interglacial deposits of Quaternary age that range from about 300 to 900 ft thick. The ground-water system in the unconsolidated deposits contains two aquifers, two confining beds, and an undifferentiated hydrogeologic unit. An outwash aquifer lies between a till confining bed at the surface and an underlying clay confining bed. Most of the productive wells in the reservation obtain their water from this outwash aquifer. A sea-level aquifer lies beneath the clay confining bed and above an undifferentiated unit. Five wells are completed in this aquifer, including two public-supply wells owned by the SwinomiahTribe that supply water to about 1,000 people. Little is known about the undifferentiated unit, but it could contain a productive aquifer.

The ground-water flow system in the reservation is similar to other island-type flow systems. Water enters the system through the water table as infiltration and percolation of precipitation (recharge), then the water flows downward and radially outward from the center of the island. At the outside edges of the system, ground water flows upward to discharge into the surrounding saltwater bodies. Average annual recharge is estimated to be about 3 in., or 12 percent of the average annual precipitation.

Ground water in the outwash aquifer near the landfill is estimated to be between 15 and 43 years old. This age range represents the time since water from precipitation first infiltrated land surface and then flowed to the well sampling sites. Some deeper ground waters and ground water near the discharge areas close to the shoreline are older than 43 years.

Analysis of water-quality data collected for this study and review of existing data indicate that material in the landfill has had no appreciable impact on the current quality of ground water outside of the landfill. The water quality of samples from seven wells near and downgradient of the landfill appears to be similar to the ground-water quality throughout the entire study area. The high iron and manganese concentrations found in most of the samples from wells near the landfill are probably within the range of natural concentrations for the study area. Elevated nitrate and ammonia concentrations in two samples appear to be related to local sources, such as septic systems and animal wastes from pastures.

Ground-water pumping during the past 20 years has not caused any large decreases in ground-water discharge to streams, declines in ground-water levels, or increases in seawater intrusion into the ground-water system. Data collected during and between 1976 and 1996 showed no appreciable changes in those ground-water conditions. In addition, there were no large trends in precipitation during that time period that might have caused changes in ground-water conditions.

Ground-water discharges into Snee-oosh Creek and Munks Creek were similar in the summers of 1976 and 1996. Flows in Snee-oosh Creek ranged from 0.07 to 0.14 ft^3/s, and flows in Munks Creek ranged from 0.08 to 0.15 ft^3/s.

Ground-water levels changed minimally between 1976 and 1996. The average water-level change for 20 wells with more than 10 years between measurements was -0.7 ft. Only two wells had greater than a 5 ft change; one well had a 6-ft water-level decline, and one well had a 9 ft decline. The average seasonal change for water levels in the reservation is about 3.4 ft.

No appreciable seawater intrusion was found in the ground water in 1996, and there was no significant increase in the extent of seawater intrusion from 1976 to 1996. Median chloride concentrations of water samples collected from wells were 22 mg/L in 1976 and 18 mg/L in 1996. Seawater intrusion is a continuing concern, however, because seawater is a boundary of most of the ground-water system, and any large decrease in recharge or increase in pumping (discharge) could upset the balance between freshwater and seawater.

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Appendix A. Physical and hydrologic data for the study wells

EXPLANATION

Location reliability:	C, field checked; U, unchecked;
Date inventoried:	--, not inventoried;
Land-surface altitude:	Feet above sea level; --, unknown;
Well depth:	Depth of casing and screen, in feet below land surface; --, unknown;
Casing diameter:	--, unknown;
Water use:	C, commercial; H, domestic; I, irrigation; P, public supply; U, unused; --, unknown;
Construction method:	A, air rotary; B, bored or augured; C, cable tool; D, dug; H, hydraulic rotary; --, unknown;
Water-level data:	Feet below land surface; date, 00 indicates month or day unknown; source, GS, U.S. Geological Survey; RP, reported by driller, geologist, other government agency, or owner; --, not determined;
Well-discharge data:	gal/min/ft, gallons per minute per foot of drawdown; date, 00 indicates month or day unknown; --, not determined;
1996 Water-quality sample:	C, chloride analysis; G, general chemistry and age-dating analyses; --, no sample.

Appendix A. Physical and hydrologic data for the study wells

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
33N/02E-02D01	C	11-19-75	85	3	39	H	D	--	--	--	--	--	--	--
33N/02E-02D02	U	--	90	99	6	H	C	79	07-29-77	RP	8	1.1	07-29-77	--
33N/02E-02D03	C	09-07-90	120	179	6	U	A	73.8	09-07-90	GS	5	0.1	01-27-81	--
33N/02E-02D04	C	09-07-90	120	59	6	H	A	30.2	09-07-90	GS	8	.4	03-18-81	--
33N/02E-02K01	C	04-20-76	169	18.7	--	H	--	12.4	04-20-76	GS	--	--	--	--
33N/02E-03A01	C	07-29-75	28	25	36	H	D	--	--	--	--	--	--	--
33N/02E-03A04	C	08-26-75	45	28	6	H	C	6.6	08-26-76	GS	16	3.2	12-12-63	--
33N/02E-03H01	C	07-29-75	41	113	6	H	C	27.5	07-25-75	RP	2	.04	07-25-75	--
33N/02E-03H02	C	08-25-75	38	92	6	H	C	25.3	08-26-76	GS	8	.2	06-30-73	--
33N/02E-03H03	C	07-29-75	32	15	38	H	D	4.7	07-29-75	GS	--	--	--	--
33N/02E-03H04	U	--	36	80	--	H	--	--	--	--	--	--	--	--
33N/02E-03H05	U	--	30	--	--	H	--	--	--	--	--	--	--	--
33N/02E-03H06	U	--	25	12	--	H	D	9	07-29-75	RP	--	--	--	--
33N/02E-03H07	U	--	30	12	--	H	D	9	07-29-75	RP	--	--	--	--
33N/02E-03H08	C	08-27-90	40	45	6	H	C	18.4	08-27-90	GS	16	5.3	03-29-79	--
33N/02E-03J01	C	07-29-75	35	43	6	U	C	22.6	07-29-75	GS	--	--	--	--
33N/02E-03J02	U	--	45	--	6	U	C	--	--	--	--	--	--	--
33N/02E-03J03	C	07-29-75	37	77	5	H	C	35.3	07-29-75	GS	0.3	--	06-00-49	--
33N/02E-03J04	C	08-15-96	43	67	6	I	C	43.2	08-25-75	GS	--	--	--	C
34N/02E-02N01	C	08-26-76	86	90	6	U	C	68.7	08-26-76	GS	18	4.5	08-11-76	--
34N/02E-02P01	U	--	2	--	--	U	--	2	06-20-68	RP	--	--	--	--
34N/02E-02Q01	U	--	10	--	--	U	--	10	06-13-68	RP	--	--	--	--
34N/02E-03G01	C	03-11-76	15	18.5	8	P	C	1.2	08-26-76	GS	75	8.9	02-27-61	--
34N/02E-03G02	U	--	117	106	--	--	--	100	01-00-53	RP	--	--	--	--
34N/02E-03G03	U	--	16	10.8	--	--	--	5.5	11-15-63	RP	--	--	--	--
34N/02E-03K01	C	03-11-76	144	200	8	P	C	129	07-28-76	GS	142	20	11-15-55	--

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-03K02	U	--	135	170	8	U	--	--	--	--	--	--	--	--
34N/02E-03K03	U	--	140	132	--	--	--	--	--	--	--	--	--	--
34N/02E-03L01	C	07-23-75	90	108	10	H	--	73.7	07-23-75	GS	2.5	12	10-25-55	--
34N/02E-03L02	C	07-23-75	32	44	--	H	--	--	--	--	--	--	--	--
34N/02E-03L03	C	07-23-75	46	24	40	H	D	13.1	07-23-75	GS	--	--	--	--
34N/02E-03P01	C	07-23-75	55	15	--	H	D	--	--	--	--	--	--	--
34N/02E-03Q01	U	--	149	--	--	U	--	25	01-00-61	RP	3	--	01-00-61	--
34N/02E-03R01	U	--	76	72	--	H	C	57	07-23-75	RP	--	--	--	--
34N/02E-10D01	U	--	35	--	--	H	--	--	--	--	--	--	--	--
34N/02E-10D02	C	08-14-96	15	6	36	U	D	1.2	08-14-96	GS	--	--	--	C
34N/02E-10D03	C	08-14-96	10	77	6	H	H	4	07-27-95	RP	5	--	07-27-95	C
34N/02E-11A01	U	--	3	--	--	U	--	3	06-07-68	RP	--	--	--	--
34N/02E-11A02	U	--	4	--	--	U	--	4	06-12-68	RP	--	--	--	--
34N/02E-11A03	U	--	--	--	--	U	--	--	--	--	--	--	--	--
34N/02E-11B01	U	--	--	--	--	U	--	--	--	--	--	--	--	--
34N/02E-14Q01	C	08-29-90	220	118	6	U	A	--	--	--	--	--	--	--
34N/02E-15C01	C	09-03-96	193	150	6	U	C	104	09-24-76	GS	20	.6	08-31-72	--
34N/02E-15D01	C	09-05-96	80	--	--	U	D	--	--	--	--	--	--	--
34N/02E-15L01	C	08-27-90	240	200	6	H	C	181	09-24-76	GS	12	12	06-12-74	--
34N/02E-15L02	C	08-14-96	286	280	6	H	A	219	08-14-96	GS	28	2.6	07-13-78	C
34N/02E-15L03	C	08-28-90	280	272	6	H	C	215	08-28-90	GS	15	3.0	11-19-86	--
34N/02E-15R01	C	09-03-96	234	143	6	U	C	110	08-05-76	GS	53	10	08-17-76	--
34N/02E-15R02	C	08-27-90	240	273	8	P	C	178	08-27-90	GS	125	22	01-23-87	--
34N/02E-15R03	C	08-27-90	240	261	8	P	A	175	08-27-90	GS	151	2.9	01-12-89	--
34N/02E-16R01	C	09-06-90	165	90	6	H	A	63.6	09-06-90	GS	15	1.5	09-30-86	--

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-21H01	C	05-03-67	32	65	6	H	C	--	--	--	10	--	00-00-61	--
34N/02E-21H02	U	--	58	125	6	H	--	--	--	--	--	--	--	--
34N/02E-21H03	C	08-26-75	26	--	42	H	D	23.1	08-26-75	GS	--	--	--	--
34N/02E-21H04	C	07-23-75	23	30	30	H	D	6	07-23-75	RP	--	--	--	--
34N/02E-21H07	C	08-27-75	33	40	6	H	--	--	--	--	--	--	--	--
34N/02E-21H08	C	08-13-96	43	80	6	H	--	37.4	08-13-96	GS	--	--	--	C
34N/02E-21H09	U	--	62	125	--	H	--	--	--	--	--	--	--	--
34N/02E-21H10	U	--	45	76	6	H	A	34	12-12-77	RP	7	.2	12-12-77	--
34N/02E-21J01	C	07-23-75	25	60	6	H	--	22.1	07-23-75	GS	--	--	--	--
34N/02E-21J02	U	--	30	--	--	H	--	--	--	--	--	--	--	--
34N/02E-21J03	C	07-23-75	21	48	6	H	C	--	--	--	10	--	00-00-45	--
34N/02E-21J06	U	--	38	--	--	H	--	--	--	--	--	--	--	--
34N/02E-21J08	C	07-23-75	28	40	--	H	D	--	--	--	--	--	--	--
34N/02E-21J09	U	--	25	93	6	H	C	17	08-08-77	RP	24	.4	08-08-77	--
34N/02E-21M01	C	07-24-75	41	10	60	H	D	0	07-24-75	RP	--	--	--	--
34N/02E-22E01	C	08-26-96	98	107	6	U	C	86.1	08-23-96	GS	7	1.0	12-06-63	C
34N/02E-22E02	C	08-14-96	95	108	6	H	C	75.8	08-14-96	GS	--	--	--	C
34N/02E-22E03	U	--	120	132	6	H	A	107	09-16-77	RP	5	.2	09-21-77	--
34N/02E-22E04	C	08-29-90	140	179	6	H	A	77.5	08-29-90	GS	10	1.7	12-21-87	--
34N/02E-22F01	C	08-31-90	240	125	6	H	A	110	08-31-90	GS	15	1.5	01-22-81	--
34N/02E-22F02	C	08-28-90	220	137	6	H	A	111	08-20-90	GS	4	--	05-10-90	--
34N/02E-22F03	C	08-29-90	280	198	6	H	--	178	08-29-90	GS	5	.3	04-23-82	--
34N/02E-22F04	C	08-31-90	260	150	6	H	A	140	08-31-90	GS	6	1.0	09-10-90	--
34N/02E-22H01	C	09-06-90	280	263	6	H	A	239	09-06-90	GS	10	2.0	03-31-87	--
34N/02E-22N01	C	05-12-53	34	52	4	H	C	8.7	05-12-53	GS	6.7	.4	01-08-48	--

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-22N02	U	--	36	64	6.2	--	C	12	01-00-48	RP	20	.8	01-00-48	--
34N/02E-22N03	C	07-23-75	32	42	5.8	H	C	8	02-00-48	RP	6.7	.3	02-00-48	--
34N/02E-22N05	C	07-00-75	34	47	6	H	C	9	02-00-48	RP	6.7	.3	02-00-48	--
34N/02E-22N06	U	--	40	77	6	H	C	20	09-23-77	RP	8	.2	09-23-77	--
34N/02E-22N08	C	08-21-96	27	71	6	H	A	17.5	08-30-90	GS	4	.2	03-23-87	C
34N/02E-22N09	C	08-31-90	30	85	6	H	A	12.9	08-31-90	GS	8	--	09-30-81	--
34N/02E-23A01	C	08-29-90	195	160	6	U	A	--	--	--	--	--	--	--
34N/02E-23A02	C	08-29-90	175	180	6	U	A	--	--	--	--	--	--	--
34N/02E-23C01	C	08-16-96	239	105	6	U	C	89.8	07-21-75	GS	--	--	--	--
34N/02E-23C02	C	08-16-96	245	160	6	H	A	98.5	08-22-96	GS	60	1.5	12-13-78	--
34N/02E-23F01	C	08-26-76	245	135	6	U	C	108	08-26-76	GS	9	3.0	12-20-63	--
34N/02E-23L01	C	07-21-75	254	93	6	H	C	68	11-18-63	RP	10	2.0	11-18-63	--
34N/02E-23L02	U	--	250	49	6	H	--	37	10-28-77	RP	25	2.1	--	--
34N/02E-23P01	C	08-13-96	262	46	6	U	C	38.7	07-22-75	GS	10	10	11-23-63	--
34N/02E-23P02	C	08-13-96	265	159	6	U	A	139	08-28-90	GS	7	--	11-08-77	--
34N/02E-23P03	C	08-13-96	270	170	6	H	--	154	08-13-96	GS	15	1.5	01-30-81	C,G
34N/02E-24F01	C	07-22-75	25	21.5	36	H	D	11.1	10-23-75	GS	--	--	--	--
34N/02E-24F02	C	08-22-96	35	25	36	H	D	15	07-22-75	RP	--	--	--	C
34N/02E-24F04	C	07-23-75	20	32	36	H	D	--	--	--	--	--	--	--
34N/02E-24F06	U	--	70	--	--	U	C	--	--	--	--	--	--	--
34N/02E-24F07	C	08-22-96	58	35	42	H	D	19.5	09-29-72	RP	--	--	--	C
34N/02E-24F08	C	08-29-90	80	140	6	U	A	--	--	--	--	--	--	--
34N/02E-24M01	C	08-26-76	175	99	6	U	C	84.9	08-26-76	GS	--	--	--	--
34N/02E-24N01	C	07-21-75	182	25	40	H	D	10	07-21-75	RP	--	--	--	--
34N/02E-24P01	C	08-30-90	140	70	6	P	A	40	05-10-79	RP	30	1.5	05-10-79	--

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-25C01	C	09-06-90	125	30	6	U	C	14.2	07-21-75	GS	10	5.0	12-13-63	--
34N/02E-25C02	C	08-13-96	145	60	6	H	A	--	--	--	12	2.7	09-27-85	C
34N/02E-25C03	C	08-13-96	75	123	6	H	A	68	07-10-85	RP	15	.5	07-10-85	C
34N/02E-25D01	U	--	150	65	6	H	C	--	--	--	12	--	--	--
34N/02E-26A01	C	08-15-96	250	169	6	H	A	139	08-30-90	GS	20	2.0	06-26-85	C
34N/02E-26B01	C	09-06-90	270	48	6	H	A	38	09-06-90	GS	12	2.0	06-15-84	--
34N/02E-26C01	C	08-13-96	273	46	6	U	C	32.4	07-29-76	GS	10	10	11-22-63	--
34N/02E-26F01	C	07-21-75	281	40.2	6	H	C	25	08-31-72	RP	10	10	11-25-63	--
34N/02E-26F02	U	--	265	161	6	H	--	135	03-29-77	RP	10	5.0	03-29-77	--
34N/02E-26F03	U	--	320	280	--	U	--	--	--	--	--	--	--	--
34N/02E-26F04	C	08-13-96	260	200	6	U	A	--	--	--	--	--	--	--
34N/02E-26F05	C	08-13-96	247	30	6	H	--	12.1	08-13-96	GS	--	--	--	C,G
34N/02E-27C01	C	08-29-90	140	160	6	H	A	--	--	--	20	.4	08-28-78	--
34N/02E-27C02	C	08-27-90	100	66	6	H	A	53.5	08-27-90	GS	9	.9	04-23-85	--
34N/02E-27C03	C	08-30-90	85	125	6	H	A	56.5	08-30-90	GS	5	.2	01-30-90	--
34N/02E-27D01	C	05-12-53	21	108	8	H	C	4	03-01-67	RP	30	.6	00-00-46	--
34N/02E-27D02	C	08-15-96	16	72	6.2	H	C	9.5	07-31-75	GS	.5	--	12-00-47	C
34N/02E-27D03	C	05-12-53	25	112	4	H	C	11.5	07-31-75	GS	10	.3	--	--
34N/02E-27D05	C	07-31-75	66	--	4	H	--	--	--	--	--	--	--	--
34N/02E-27D06	C	07-31-75	68	177	6	H	C	31.1	07-31-75	GS	9	.1	03-03-75	--
34N/02E-27D07	C	07-31-75	20	50	6	H	--	10.3	07-31-75	GS	--	--	--	--
34N/02E-27D10	U	--	29	75	6	H	C	--	--	--	15	1.5	04-00-49	--
34N/02E-27D11	C	08-27-96	20	141	6	H	C	9.4	08-27-96	GS	30	.5	09-30-75	C
34N/02E-27E01	C	09-09-96	23	56	6	U	--	13.4	07-31-75	GS	--	--	--	--
34N/02E-27E02	C	08-30-90	20	160	6	U	A	--	--	--	--	--	--	--
34N/02E-27E03	C	08-14-96	30	53	6	P	A	7	02-14-78	RP	23	3.3	02-14-78	C

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-27F01	C	05-03-67	80	42	6	C	C	37.9	06-12-78	GS	--	--	--	--
34N/02E-27F02	C	09-10-96	43	98	6	P	--	18	04-20-64	RP	7	.1	04-20-64	C
34N/02E-27F03	C	09-05-90	65	150	6	H	C	41.9	09-05-90	GS	10	.2	07-25-84	--
34N/02E-27K01	C	08-30-90	48	89	6	P	--	22.0	09-04-75	GS	14	.7	00-00-28	--
34N/02E-27K02	C	08-30-90	50	70	8	U	--	24.0	09-04-75	GS	--	--	--	--
34N/02E-27K03	C	08-27-96	44	48	8	P	--	17.2	08-27-96	GS	6	.5	11-05-57	C
34N/02E-27K04	C	05-02-67	44	54	6	P	--	17.4	05-02-67	GS	10	.8	11-05-57	--
34N/02E-27K05	C	05-02-67	51	48	8	P	C	--	--	--	--	--	--	--
34N/02E-27K06	C	08-30-90	60	36	--	U	A	--	--	--	--	--	--	--
34N/02E-27K07	C	08-30-90	60	74	6	P	A	32.1	08-30-90	GS	7	.2	05-28-87	--
34N/02E-27K08	C	08-16-96	52	65	6	P	A	21	08-30-90	GS	6	.2	07-12-89	C
34N/02E-27L01	C	09-10-96	40	99	6	U	--	6	04-20-64	RP	7	.1	04-20-64	--
34N/02E-27L02	U	--	50	112	6	H	A	12	07-06-77	RP	15	.2	--	--
34N/02E-27L03	C	09-06-90	45	73	6	H	A	27.2	09-06-90	GS	4	.2	02-07-84	--
34N/02E-27M01	U	--	35	--	--	U	--	--	--	--	--	--	--	--
34N/02E-27M02	U	--	20	--	--	U	--	--	--	--	--	--	--	--
34N/02E-27M03	C	08-21-96	14	28	6	U	--	10.3	07-21-76	GS	--	--	--	--
34N/02E-27P01	U	--	20	--	--	U	C	--	--	--	--	--	--	--
34N/02E-27P02	U	--	35	--	--	U	C	--	--	--	--	--	--	--
34N/02E-27Q01	U	--	40	--	--	U	C	--	--	--	--	--	--	--
34N/02E-27Q02	C	08-16-96	45	117	6	U	--	-0.1	07-30-75	GS	12	.1	09-22-75	C
34N/02E-27Q03	C	08-16-96	47	--	8	U	--	--	--	--	3.5	--	00-00-75	--
34N/02E-27R01	C	08-15-96	105	72	6	H	C	26.7	08-28-90	GS	5	.1	10-13-72	C,G
34N/02E-27R02	C	08-28-90	113	85	6	P	C	33	04-12-65	RP	9	.3	--	--
34N/02E-27R03	C	08-28-90	111	72	6	P	C	36.3	08-28-90	GS	4	.2	11-25-74	--

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-27R04	C	08-15-96	152	78	6	P	A	48.4	08-15-96	GS	11	.6	07-18-80	C,G
34N/02E-34A01	C	07-30-75	36	89	6	H	C	30	07-30-75	GS	5	.1	04-23-74	--
34N/02E-34A02	C	08-26-96	38	99	6	H	C	29.5	07-30-75	GS	2.5	.04	04-23-74	C
34N/02E-34A03	C	07-31-75	23	100	6	H	C	--	--	--	--	--	--	--
34N/02E-34A04	U	--	37	95	6	H	C	30	04-01-77	RP	6	.1	04-01-77	--
34N/02E-34A05	U	--	50	128	6	H	C	38	10-29-76	RP	3	.04	--	--
34N/02E-34A06	C	08-13-96	35	58	6	H	A	15.4	08-13-96	GS	10	--	12-12-75	C
34N/02E-34A07	C	08-22-96	58	85	6	H	A	50.3	08-22-96	GS	15	.8	11-04-81	C
34N/02E-34B01	C	08-15-96	13	112	6	U	C	-2.6	09-22-75	GS	6	.2	05-02-67	--
34N/02E-34H01	C	05-12-53	35	53	8	P	C	--	--	--	50	2.8	05-12-53	--
34N/02E-34H02	C	08-30-90	90	97	6	H	A	53.5	08-30-90	GS	15	.8	05-24-83	--
34N/02E-34H03	C	08-31-90	80	67	6	H	A	42	08-31-90	GS	12	.6	12-29-81	--
34N/02E-34J01	C	08-12-96	105	160	6	P	--	54.6	08-12-96	GS	15	--	00-00-72	C
34N/02E-34R01	C	08-25-75	32	35	6	H	C	1.3	08-26-76	GS	14	1.4	07-00-73	--
34N/02E-34R02	C	07-29-75	43	95	6	H	C	38	01-00-70	RP	3.3	.1	00-00-70	--
34N/02E-34R03	C	09-05-96	50	87	6	U	C	--	--	--	--	--	--	--
34N/02E-34R04	C	07-30-75	33	16	36	U	D	--	--	--	--	--	--	--
34N/02E-34R05	C	09-09-96	50	25	36	U	D	5	07-30-75	GS	--	--	--	--
34N/02E-34R06	C	08-20-96	40	200	6	U	C	43.9	08-21-96	GS	--	--	--	--
34N/02E-34R07	C	08-14-96	50	75	6	U	--	48.6	08-26-76	GS	--	--	--	--
34N/02E-34R08	C	08-25-75	36	--	6	H	--	1.7	08-25-75	GS	--	--	--	--
34N/02E-34R09	C	09-04-75	50	80	6	H	C	48.9	09-22-75	GS	15	1.7	09-00-75	--
34N/02E-34R10	U	--	65	125	6	H	A	60	01-03-77	RP	15	.4	01-03-77	--
34N/02E-34R11	C	09-07-90	45	60	6	H	A	30.4	09-07-90	GS	15	1.0	01-29-85	--

Appendix A. Physical and hydrologic data for the study wells--Continued

Local well number	Location reliability	Date inventoried	Land-surface altitude (feet)	Well depth (feet)	Casing diameter (inches)	Water use	Construction method	Water-level data (feet)	Water-level data Date	Water-level data Source	Well-discharge data Yield (gallons per minute)	Well-discharge data Specific capacity (gal/min/ft)	Well-discharge data Date	1996 Water-quality sample
34N/02E-35C01	C	09-06-96	260	49	2	U	B	34	09-17-93	RP	--	--	--	--
34N/02E-35C02	C	09-06-96	277	53	2	U	B	35.8	09-26-96	GS	--	--	--	C,G
34N/02E-35C03	C	09-06-96	270	28	2	U	B	17	09-17-93	RP	--	--	--	--
34N/02E-35E01	C	08-14-96	205	108	6	U	--	82.7	08-26-76	GS	15	4.8	05-20-76	--
34N/02E-35F01	C	07-22-75	256	20	30	H	D	5	07-22-75	RP	--	--	--	--
34N/02E-35F02	C	07-22-75	232	124	6	H	--	103	08-26-76	GS	--	--	--	--
34N/02E-35F03	C	08-21-96	238	149	6	H	C	118	08-27-90	GS	15	15	08-03-79	C
34N/02E-35F04	C	08-29-90	250	304	6	U	A	--	--	--	--	--	--	--
34N/02E-35G01	C	08-14-96	235	138	6	U	C	110	08-14-96	GS	--	--	--	C,G
34N/02E-35G02	C	07-23-75	226	120	6	H	C	--	--	--	--	--	--	--
34N/02E-35G03	C	08-14-96	230	23	24	U	--	14.7	08-14-96	GS	--	--	--	C,G
34N/02E-35G04	C	08-15-96	192	89	6	H	--	71.9	07-22-76	GS	--	--	--	C,G
34N/02E-35H01	C	08-14-96	178	21	48	U	D	14.1	05-13-53	GS	--	--	--	--
34N/02E-35H02	C	08-14-96	178	84	6	H	C	--	--	--	--	--	--	C,G
34N/02E-35H03	C	05-02-67	153	180	6	H	C	138	05-02-67	GS	10	--	10-00-56	--
34N/02E-35H04	U	--	170	110	6	H	A	64	09-09-77	RP	4	.1	--	--
34N/02E-35L01	C	08-21-96	232	130	6	H	--	115	08-21-96	GS	4	.7	09-14-72	C
34N/02E-35L02	C	08-28-90	220	120	6	H	A	100	12-14-87	RP	12	1.0	12-14-87	--
34N/02E-35R01	C	08-26-75	80	91	6	U	C	45.9	08-26-76	GS	7	.4	12-11-63	--
34N/02E-36B01	C	09-09-96	8	20	36	U	--	--	--	--	--	--	--	--
34N/02E-36E01	U	--	142	47	--	U	D	43	05-13-53	RP	--	--	--	--

Appendix B. Latitude and longitude for the study wells

Local well number	Latitude	Longitude	Local well number	Latitude	Longitude
la33N/02E-02D01	48°22'52"	122°31'48"	34N/02E-11B01	48°27'17"	122°30'49"
33N/02E-02D02	48°22'54"	122°31'48"	34N/02E-14Q01	48°25'47"	122°31'10"
33N/02E-02D03	48°22'53"	122°31'14"	34N/02E-15C01	48°26'30"	122°32'38"
33N/02E-02D04	48°22'54"	122°31'14"	34N/02E-15D01	48°26'23"	122°32'54"
33N/02E-02K01	48°22'32"	122°30'50"	34N/02E-15L01	48°26'02"	122°32'36"
33N/02E-03A01	48°22'52"	122°31'54"	34N/02E-15L02	48°26'06"	122°32'40"
33N/02E-03A04	48°22'57"	122°31'52"	34N/02E-15L03	48°26'01"	122°32'41"
33N/02E-03H01	48°22'39"	122°31'51"	34N/02E-15R01	48°25'45"	122°31'48"
33N/02E-03H02	48°22'38"	122°31'51"	34N/02E-15R02	48°25'49"	122°31'57"
33N/02E-03H03	48°22'37"	122°31'53"	34N/02E-15R03	48°25'49"	122°32'02"
33N/02E-03H04	48°22'36"	122°31'51"	34N/02E-16R01	48°25'50"	122°33'08"
33N/02E-03H05	48°22'35"	122°31'52"	34N/02E-21H01	48°25'15"	122°33'17"
33N/02E-03H06	48°22'48"	122°31'54"	34N/02E-21H02	48°25'27"	122°33'21"
33N/02E-03H07	48°22'48"	122°31'54"	34N/02E-21H03	48°25'24"	122°33'20"
33N/02E-03H08	48°22'49"	122°31'53"	34N/02E-21H04	48°25'23"	122°33'21"
33N/02E-03J01	48°22'32"	122°31'53"	34N/02E-21H07	48°25'21"	122°33'18"
33N/02E-03J02	48°22'32"	122°31'52"	34N/02E-21H08	48°25'20"	122°33'16"
33N/02E-03J03	48°22'32"	122°31'54"	34N/02E-21H09	48°25'28"	122°33'20"
33N/02E-03J04	48°22'37"	122°31'50"	34N/02E-21H10	48°25'24"	122°33'19"
34N/02E-02N01	48°27'27"	122°31'32"	34N/02E-21J01	48°25'15"	122°33'15"
34N/02E-02P01	48°27'18"	122°30'56"	34N/02E-21J02	48°25'14"	122°33'13"
34N/02E-02Q01	48°27'18"	122°30'53"	34N/02E-21J03	48°25'14"	122°33'13"
34N/02E-03G01	48°27'55"	122°31'57"	34N/02E-21J06	48°25'12"	122°33'10"
34N/02E-03G02	48°27'45"	122°31'56"	34N/02E-21J08	48°25'08"	122°33'10"
34N/02E-03G03	48°27'53"	122°32'01"	34N/02E-21J09	48°25'09"	122°33'10"
34N/02E-03K01	48°27'35"	122°32'12"	34N/02E-21M01	48°25'06"	122°34'05"
34N/02E-03K02	48°27'40"	122°32'02"	34N/02E-22E01	48°25'19"	122°33'03"
34N/02E-03K03	48°27'43"	122°32'04"	34N/02E-22E02	48°25'18"	122°33'04"
34N/02E-03L01	48°27'40"	122°32'14"	34N/02E-22E03	48°°25'22"	122°33'04"
34N/02E-03L02	48°27'41"	122°32'24"	34N/02E-22E04	48°25'22"	122°32'57"
34N/02E-03L03	48°27'38"	122°32'24"	34N/02E-22F01	48°25'21"	122°32'36"
34N/02E-03P01	48°27'26"	122°32'31"	34N/02E-22F02	48°25'20"	122°32'41"
34N/02E-03Q01	48°27'22"	122°32'12"	34N/02E-22F03	48°25'21"	122°32'29"
34N/02E-03R01	48°27'29"	122°31'37"	34N/02E-22F04	48°25'20"	122°32'33"
34N/02E-10D01	48°27'16"	122°32'36"	34N/02E-22H01	48°25'21"	122°32'04"
34N/02E-10D02	48°27'11"	122°32'42"	34N/02E-22N01	48°24'57"	122°33'04"
34N/02E-10D03	48°27'13"	122°32'42"	34N/02E-22N02	48°24'58"	122°33'05"
34N/02E-11A01	48°27'16"	122°30'39"	34N/02E-22N03	48°24'58"	122°33'03"
34N/02E-11A02	48°27'16"	122°30'42"	34N/02E-22N05	48°24'53"	122°33'01"
34N/02E-11A03	48°27'17"	122°30'45"	34N/02E-22N06	48°24'55"	122°33'02"

Appendix B. Latitude and longitude for the study wells--Continued

Local well number	Latitude	Longitude	Local well number	Latitude	Longitude
34N/02E-22N08	48°24'53"	122°32'59"	34N/02E-27D06	48°24'38"	122°32'52"
34N/02E-22N09	48°24'55"	122°33'04"	34N/02E-27D07	48°24'37"	122°32'59"
34N/02E-23A01	48°25'37"	122°30'52"	34N/02E-27D10	48°24'47"	122°33'00"
34N/02E-23A02	48°25'37"	122°30'48"	34N/02E-27D11	48°24'39"	122°33'00"
34N/02E-23C01	48°25'33"	122°31'17"	34N/02E-27E01	48°24'33"	122°33'00"
34N/02E-23C02	48°25'29"	122°31'14"	34N/02E-27E02	48°24'29"	122°32'58"
34N/02E-23F01	48°25'27"	122°31'14"	34N/02E-27E03	48°24'27"	122°32'50"
34N/02E-23L01	48°25'05"	122°31'12"	34N/02E-27F01	48°24'35"	122°32'46"
34N/02E-23L02	48°25'02"	122°31'15"	34N/02E-27F02	48°24'24"	122°32'45"
34N/02E-23P01	48°24'57"	122°31'18"	34N/02E-27F03	48°24'33"	122°32'46"
34N/02E-23P02	48°25'00"	122°31'20"	34N/02E-27K01	48°24'10"	122°32'29"
34N/02E-23P03	48°24'53"	122°31'16"	34N/02E-27K02	48°24'12"	122°32'29"
34N/02E-24F01	48°25'24"	122°30'05"	34N/02E-27K03	48°24'11"	122°32'30"
34N/02E-24F02	48°25'22"	122°30'06"	34N/02E-27K04	48°24'11"	122°32'30"
34N/02E-24F04	48°25'26"	122°30'09"	34N/02E-27K05	48°24'14"	122°32'30"
34N/02E-24F06	48°25'21"	122°30'09"	34N/02E-27K06	48°24'12"	122°32'29"
34N/02E-24F07	48°25'20"	122°30'09"	34N/02E-27K07	48°24'14"	122°32'31"
34N/02E-24F08	48°25'23"	122°30'12"	34N/02E-27K08	48°24'14"	122°32'30"
34N/02E-24M01	48°25'09"	122°30'09"	34N/02E-27L01	48°24'20"	122°33'05"
34N/02E-24N01	48°24'53"	122°30'19"	34N/02E-27L02	48°24'21"	122°32'41"
34N/02E-24P01	48°24'54"	122°30'13"	34N/02E-27L03	48°24'21"	122°32'46"
34N/02E-25C01	48°24'45"	122°30'11"	34N/02E-27M01	48°24'12"	122°32'50"
34N/02E-25C02	48°24'48"	122°30'15"	34N/02E-27M02	48°24'15"	122°32'52"
34N/02E-25C03	48°24'49"	122°29'59"	34N/02E-27M03	48°24'17"	122°32'54"
34N/02E-25D01	48°24'44"	122°30'12"	34N/02E-27P01	48°24'06"	122°32'36"
34N/02E-26A01	48°24'46"	122°30'46"	34N/02E-27P02	48°24'07"	122°32'36"
34N/02E-26B01	48°24'49"	122°31'09"	34N/02E-27Q01	48°24'07"	122°32'29"
34N/02E-26C01	48°24'48"	122°31'13"	34N/02E-27Q02	48°24'01"	122°32'22"
34N/02E-26F01	48°24'32"	122°31'15"	34N/02E-27Q03	48°24'02"	122°32'20"
34N/02E-26F02	48°24'28"	122°31'15"	34N/02E-27R01	48°23'56"	122°32'08"
34N/02E-26F03	48°24'30"	122°31'30"	34N/02E-27R02	48°23'58"	122°32'09"
34N/02E-26F04	48°24'27"	122°31'16"	34N/02E-27R03	48°23'58"	122°32'11"
34N/02E-26F05	48°24'25"	122°31'20"	34N/02E-27R04	48°23'56"	122°31'55"
34N/02E-27C01	48°24'46"	122°32'32"	34N/02E-34A01	48°23'46"	122°32'11"
34N/02E-27C02	48°24'40"	122°32'09"	34N/02E-34A02	48°23'45"	122°32'08"
34N/02E-27C03	48°24'38"	122°32'46"	34N/02E-34A03	48°23'44"	122°32'11"
34N/02E-27D01	48°24'40"	122°33'01"	34N/02E-34A04	48°23'48"	122°32'10"
34N/02E-27D02	48°24'36"	122°33'01"	34N/02E-34A05	48°23'48"	122°32'05"
34N/02E-27D03	48°24'38"	122°33'00"	34N/02E-34A06	48°23'43"	122°32'07"
34N/02E-27D05	48°24'37"	122°32'53"	34N/02E-34A07	48°23'48"	122°32'06"

Appendix B.--*Latitude and longitude for the study wells--Continued*

Local well number	Latitude (degrees)	Longitude (degrees)	Local well number	Latitude (degrees)	Longitude (degrees)
34N/02E-34B01	48°23'54"	122°32'23"	34N/02E-35F01	48°23'40"	122°31'19"
34N/02E-34H01	48°23'40"	122°32'07"	34N/02E-35F02	48°23'32"	122°31'28"
34N/02E-34H02	48°23'35"	122°32'04"	34N/02E-35F03	48°23'38"	122°31'30"
34N/02E-34H03	48°23'37"	122°32'04"	34N/02E-35F04	48°23'42"	122°31'16"
34N/02E-34J01	48°23'27"	122°32'01"	34N/02E-35G01	48°23'39"	122°31'09"
34N/02E-34R01	48°23'07"	122°31'53"	34N/02E-35G02	48°23'37"	122°31'08"
34N/02E-34R02	48°23'04"	122°31'52"	34N/02E-35G03	48°23'37"	122°31'11"
34N/02E-34R03	48°23'15"	122°31'56"	34N/02E-35G04	48°23'36"	122°30'55"
34N/02E-34R04	48°23'12"	122°31'54"	34N/02E-35H01	48°23'39"	122°30'38"
34N/02E-34R05	48°23'13"	122°31'54"	34N/02E-35H02	48°23'40"	122°30'39"
34N/02E-34R06	48°23'12"	122°31'54"	34N/02E-35H03	48°23'34"	122°30'36"
34N/02E-34R07	48°23'10"	122°31'53"	34N/02E-35H04	48°23'38"	122°30'39"
34N/02E-34R08	48°23'06"	122°31'52"	34N/02E-35L01	48°23'20"	122°31'16"
34N/02E-34R09	48°23'14"	122°31'56"	34N/02E-35L02	48°23'25"	122°31'16"
34N/02E-34R10	48°23'02"	122°31'50"	34N/02E-35R01	48°23'10"	122°30'39"
34N/02E-34R11	48°23'13"	122°31'55"	34N/02E-36B01	48°23'47"	122°29'52"
34N/02E-35C01	48°23'57"	122°31'24"	34N/02E-36E01	48°23'38"	122°30'28"
34N/02E-35C02	48°23'53"	122°31'28"			
34N/02E-35C03	48°23'50"	122°31'23"			
34N/02E-35E01	48°23'34"	122°31'45"			

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