Occurrence and Quality of Ground Water in Southwestern King County, Washington

By D. G. Woodward, F. A. Packard, N. P. Dion, and S. S. Sumioka

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	0.003785	cubic meter
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
degree Fahrenheit (°F)	°C=5/9(°F-32)	degree Celsius (°C)

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.

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ABSTRACT

Southwestern King County, Washington, is undergoing rapid growth in population and urban development, creating increased demands for municipal and domestic water supplies. Because most surface waters are already appropriated, ground-water resources are anticipated to meet the new demands. This report describes the ground-water system in the Quaternary sediments of southwestern King County.

The 250-square-mile study area is underlain by sediments as much as 2,200 feet thick, deposited during at least four continental glacial/interglacial periods. Subsurface stratigraphy was delineated by extrapolating information from published surficial geologic maps and from drillers' lithologic logs for about 700 wells field-located in the area. The preparation of 28 cross sections aided in defining 9 hydrogeologic units--5 aquifers, 3 confining beds, and 1 basal undifferentiated unit. Maps depicting the configuration of the tops of the three buried aquifers (Qva, Q(A)c, and Q(B)c) show the extent and the geometry of those aquifers. Maps showing the thickness of the Qva and Q(A)c aquifers also were prepared.

Water-level and potentiometric-surface maps for the major aquifers--the Qal, Qva, and Q(A)c--are based on water levels measured in about 400 wells during April 1987. Hydraulic characteristics of the major aquifers are mapped and show the results of more than 1,100 specific-capacity calculations and about 240 hydraulic-conductivity determinations for selected wells in the study area.

Estimates of the average annual recharge to the ground-water system from precipitation for the entire study area were based on relations determined from modeling selected basins. Discharges from the ground-water system were based on estimates of springflow and diffuse seepage from the bluffs surrounding the uplands, and the quantity of ground water withdrawn from high-capacity wells. In addition, water-budget calculations for the Big Soos Creek Basin indicate that about 80 percent of the recharge to the shallow ground-water system eventually is returned to the streams within the basin as baseflow.

A total of 242 water samples from 223 wells was collected during two mass samplings and analyzed for the presence of common constituents. In addition, samples also were collected for heavy metals, boron, detergents, and volatile organic compounds. An analysis of the water-quality data indicates that there is no widespread degradation of ground-water quality in southwestern King County.

INTRODUCTION

Southwestern King County (plate 1A) is one of several areas in the Puget Sound region of western Washington that is experiencing rapid growth in population and urban development and therefore has increasing demands for water for public supply, domestic, commercial, and industrial uses. Historically, the area has relied heavily on ground water to meet increased water demands. However, in recent years conflicts have arisen between surface- and ground-water interests. For example, the initiation of pumping from a high-capacity well decreased the discharge from a nearby spring, which was an important source of public-water supply. Several municipalities in southwestern King County have recently drilled additional public-supply wells to satisfy both normal and peaking water demands.

Concerns about the availability of ground water and the effects of withdrawals from wells on lakes, springs, wetlands, and instream flows are becoming important issues to be reconciled. The State of Washington Department of Ecology (Ecology), which manages the State's water resources and issues water rights for both ground- and surface-water withdrawals, has closed many streams in the area to further appropriation. Another concern relates to the possible reduction in ground-water recharge caused by current land-development practices, whereby large areas are being paved or developed in ways that impede the percolation of precipitation downward toward the ground-water system.

In addition to concerns about the availability of ground water and the effects of ground-water development on surface-water features, ground-water quality is also of great concern. Several serious water-quality problems related to industrial and waste-disposal practices have been recognized at sites in southwestern King County (Sherrie Hanson, Washington Department of Ecology, written commun., 1992). The large number of septic systems in the area, the potential for seawater intrusion along the coast, and the naturally large iron and manganese concentrations in water from some wells are also of concern.

In order to plan for the development, use, and management of the water resources of the area, a better understanding of the entire natural hydrologic system is needed, including the regional geometry of the aquifers and confining beds, the ground-water flow system, the relation between ground water and surface water, natural ground-water-quality characteristics, and spatial and temporal trends in water levels and water quality.

Concerns about how to effectively plan and provide for the increased water demand for rapidly increasing industrial and residential growth in southwestern King County are not new. In 1961, the U.S. Geological Survey (USGS), in cooperation with the Washington Department of Water Resources (the former State agency whose responsibilities were transferred to Ecology), began a study to determine the extent of ground-water development in southwestern King County and to describe the geology in sufficient detail to explain the occurrence of ground water. Additionally, the study was to provide a framework for future quantitative investigations (Luzier, 1969, p. 2). The framework for future investigations included the presentation of a surficial-geology map of the area; the beginning of a differentiation of the glacial drift sequence into aquifer and confining units; and a compilation of well logs, springs, water chemistry, and water-pumpage data.

Since the initial framework study, State and local agencies responsible for managing the water resources in the area have voiced their concern about ground-water quantity and quality problems. Thus, in 1986, the USGS began a cooperative study to define more precisely the ground-water flow regime of the Quaternary deposits that underlie southwestern King County. Agencies cooperating with the USGS in this study were Ecology, the Regional Water Association of South King County, and the Seattle-King County Department of Public Health. The objectives of the study were to:

1. Describe and quantify the ground-water system, to the extent that available or readily collectible data allow;

2. Determine the general water chemistry of the major aquifers; and

3. Determine what additional data and analyses, if any, are required to characterize the ground-water system sufficiently in order to aid in management decisions for developing additional water supplies.

Purpose and Scope

This report describes and quantifies the ground-water system in the Quaternary sediments in southwestern King County by

*Segregating the sediments into hydrogeologic units--five aquifers and three confining beds--and describing each unit;

*Delineating on maps the areal extent and structural configuration of the tops and thicknesses of the major aquifers;

*Delineating on generalized hydrogeologic sections the subsurface geometry of the aquifers and confining beds;

*Depicting the ground-water flow system on maps that show the configuration of the water table or potentiometric surface and, where practical, the implied vertical and horizontal directions of water movement in each aquifer;

*Depicting the geographic distribution of specific-capacity and hydraulic-conductivity data for the major aquifers;

*Delineating on a map the volume of ground-water recharge derived from precipitation for the surficial aquifers in the study area;

*Characterizing the principal ground-water discharge relations in the study area and determining the location, average annual withdrawal, and use of the withdrawn water for domestic, public supply, irrigation, and industrial/commercial purposes in the study area; and

*Calculating a comprehensive water-budget analysis for the Big Soos Creek Basin.

The general water chemistry of each major aquifer is described in the text, documented in a series of tables that present the chemical data, and delineated on a map showing locations of sampling sites.

Two main premises guided the data-collection stage of this study: (1) Only data either already available or readily collectible would be used--that is, no test drilling, river-seepage determinations, or borehole geophysical logging was envisioned for this study; and (2) because of the size of the study area (about 250 mi^2) and the complexity and heterogeneity of the subsurface deposits, a regional perspective would be used in characterizing and describing the individual hydrogeologic units and the movement and quality of water in each aquifer.

Methods

The methods used to fulfill the objectives of this study involved not only the collection, compilation, analysis, and interpretation of data (both old and new) that provide point-source information, but also the extrapolation of those data to "fill in the gaps" and produce regional relations. The following discussion explains the approach and methods used to complete the various study components.

The bulk of the data used to describe and quantify the ground-water system in the Quaternary sediments came from records of approximately 790 wells that were inventoried during the initial phase of the study (see plate 1A). The inventory process included field-locating the well; determining the latitude, longitude, and land-surface altitude of the top of the well; measuring the water level in the well, where practical; compiling, analyzing, and interpreting the information incorporated on the driller's log, such as earth materials penetrated, hydraulic testing (pump test, bail test, aquifer test), and water use; and then coding the information and entering it into a computerized data base.

The primary source of data used to interpret the subsurface stratigraphy in most of the study area was lithologic information from drillers' logs for about 700 wells in the data base. The areal distribution and range in depths of these wells in the study area are adequate for this purpose except in the northern Des Moines Plain (plate 1A), where the wells are sparse and are completed only in the shallower units. Surficial geologic maps prepared by a variety of researchers also were used to interpret the subsurface stratigraphy in the study area. Field observations by project personnel and by Derek Booth (King County Planning, written commun., 1986-87) provided additional information about geologic outcrops along cliff faces and at other locales. In the northern Des Moines Plain, lithologic information for the shallow deposits also was obtained from surface geologic and geophysical investigations conducted by Yount (1983) and by Liesch and others (1963); lithologic information for the deeper deposits there could not be obtained.

Marine seismic surveys originally were scheduled in order to collect subsurface stratigraphic information along the Puget Sound coast, the Duwamish Waterway/River, and the Green River. During March 1987, marine seismic surveys were attempted on the Duwamish Waterway/River downstream of Tukwila and on two reaches of the Green River near Kent. Two sources were used to generate the seismic energy, a fixed-gain air gun and a fixed-gain pulser. A variety of source frequencies and recording parameters were tried, but credible subsurface information could not be obtained in these areas with the equipment available (Mark Holmes, U.S. Geological Survey, oral commun., 1987), and plans for additional surveys were abandoned.

Twenty-eight generalized stratigraphic sections were constructed across the study area; four representative sections are presented later in the report. Interpretation and correlation of these 28 sections allowed the delineation of 9 major hydrogeologic units--5 aquifers, 3 intervening confining beds, and a basal, undifferentiated unit. These units correspond with the large-scale geologic events during and after the glacial Pleistocene Epoch. The final step after the correlation of sections was to construct maps showing the extent and thickness of the major aquifers and the structural configurations of their tops.

The ground-water flow systems are depicted, in part, on maps showing the water table or potentiometric surface for each of the major aquifers. These were determined largely from elevations of the water levels measured in about 400 wells during April 1987 (see plate 1A). The distribution of water-level measurements in the major aquifers was sufficient to allow construction of contour maps. Vertical flow directions generally were determined in areas where closely spaced wells were completed in different aquifers; no nested piezometers were available.

Describing and delineating the distribution of hydraulic characteristics within the aquifers were complex tasks. The commonly used procedures available for determining permeability are rigorous and exacting; they include the hydraulic testing of preserved core samples and the completion of specially designed aquifer tests. These procedures must be conducted with the end result in mind; the information required cannot be extracted from data collected for other purposes. Laboratory permeability determinations for aquifers in the study area are rare, and data from rigorous aquifer tests are available, but they are not sufficient to infer regional characteristics. Therefore, permeability relations had to be inferred from readily obtainable information. Specific-capacity values of wells commonly are available and can be used to derive hydraulic-conductivity values in an aquifer, although the method required is less precise and factors other than aquifer permeability can influence the specific-capacity value of a well (Walton, 1967, p. 12). For this study, hydraulic characteristics of the aquifers were determined by calculating the hydraulic-conductivity values of the shallowest aquifers.

Estimates of the horizontal hydraulic conductivity for each aquifer were computed from test transmissivity values that were based on specific-capacity information compiled for approximately 1,175 wells in the study area. The information was derived from a variety of sources--reported results of bailer tests, air tests, pump tests, and aquifer tests. Many of the wells used for this purpose (see plates 3C and 3D) were not inventoried in the field and therefore are not included in the project data base (see plate 1A). Estimates of aquifer transmissivity were made for those wells that had the most complete and reliable set of specific-capacity information (constant discharge rate, a longer-duration test, well-construction data, geologic log); about 240 of the 1,175 wells met these criteria. In the procedure used for calculating hydraulic conductivity, the modified Theis equation (Theis, 1963) for nonleaky artesian aquifers (Ferris and others, 1962, p. 99) first was used to estimate test transmissivity values. To estimate an average hydraulic-conductivity value from the test transmissivity value, the aquifer thickness or open interval of the well is needed. In this study, thickness was used and was estimated from the aquifer-thickness maps developed during this study and presented in this report. The modified Theis equation requires an assumed value for the storage coefficient. Ferris (Ferris and others, 1962, p. 88) used a calculated value of 0.0015 for confined aquifers, and this value correlated with modeled storage-coefficient values used for similar glacial aquifers in Island County, Washington (Sapik, 1989). Thus, the value of 0.0015 was used for the confined aquifers in this study. This method assumes that well entrance losses are negligible, that the well is screened across the full thickness of the aquifer, and that flow into a well is sustained by withdrawal from storage within the saturated interval penetrated by the well.

Water-use data generated for this study were derived primarily from an inventory of ground-water withdrawals in 1986 done by a private consulting firm, Economic and Engineering Services, Inc. Questionnaires were sent to all managers of public supplies with five or more connections, and follow-up phone calls were made for public-supply, as well as for irrigation, commercial, institutional, and industrial well systems. Where contacts failed or data were unavailable, withdrawals were estimated on the basis of data obtained from Ecology water-management records or from Washington Department of Social and Health Services (WDSHS) water-facilities inventories. This inventory was supplemented by data collected by USGS personnel during field visits to well sites. Because of the method of compilation, many of the ground-water withdrawal sites shown on plate 4C are not included in the project data base (see plate 1A).

Public water systems in Washington at the time of this study were divided into four classes:

1. Class 1 systems had 100 or more services (a physical connection designed to serve a single family or equivalent use, based on 3 people per connection) or served a transitory population of 1,000 or more people on any one day.

2. Class 2 systems had 10 to 99 permanent services or served a transitory population of 300 to 999 people on any one day.

3. Class 3 systems served a transitory population of 25 to 299 people on any one day.

4. Class 4 systems had 2 to 9 permanent services or served a transitory population of less than 25 people per day.

Data for Class 1 systems (large municipal systems) consisted of metered volumes of total withdrawals, and generally the volumes were not reported for individual wells in the system; the total system withdrawals were distributed to individual wells on the basis of well-capacity determinations. Withdrawals by most Class 2, 3, and 4 systems were not metered; therefore, estimates of well withdrawals for these systems were based on the following formula:

Well withdrawal = number of connections x three people per connection x 100 gallons per day per person.

Ground-water withdrawals from individual wells for domestic use were calculated by determining the population of southwestern King County that is supplied water by a public water system and subtracting that number from the total population of the area, then applying a per-capita rate of 100 gallons per day to the population not supplied by a public water system.

Annual ground-water withdrawals for irrigation were calculated by either of two methods: (1) by applying a uniform application rate of 433,382 gallons of water (about 1.33 acre-feet) per acre per year for an assumed 150-day irrigation season, based on an assessment of irrigation requirements for Washington State by James and others (1988); or (2) by using the pumping capacity of the irrigation well multiplied by the duration of pumping during 1986. Information about irrigated acreage, pumping capacity of an irrigation well, and duration of pumping was obtained primarily by telephoning irrigators identified either in Ecology and USGS files or in the well-inventory process.

Ground-water withdrawals from private wells for commercial, industrial, and institutional purposes were estimated, based on a telephone canvass of identified well owners. It is unlikely, however, that all commercial, industrial, and institutional wells in southwestern King County were identified and inventoried during this study.

Ground-water-quality samples were collected in 1987 and 1988. Considerable effort was made to obtain water from a tap close to the wellhead; that is, before the water entered a pressure tank or treatment process. Water from the well was diverted through a stainless-steel manifold mounted in a mobile water-quality laboratory and into a transparent flow chamber where temperature, specific conductance, pH, and dissolved-oxygen concentration were monitored. Sampling began after these constituents had been stable for about 5 minutes. This procedure ensured that all supply lines had been flushed and that the water being sampled was representative of the aquifer. Aliquots of water then were processed for various analyses, the appropriate sample bottles were labeled and filled, and one aliquot was titrated with dilute acid to determine alkalinity.

Water samples for analyses of fecal-coliform and fecal-streptococci bacteria, however, were collected directly from the water tap and were not filtered or treated. All bacteria analyses were completed at the USGS laboratory in Tacoma, Wash., within 6 hours of collection. All other samples were submitted to the U.S. Geological Survey Central Laboratory in Arvada, Colo., to be analyzed for concentrations of calcium, magnesium, sodium, potassium, chloride, sulfate, nitrite plus nitrate, fluoride, silica, iron, manganese, and dissolved solids. In addition, approximately 25 percent of all samples were analyzed for concentration of dissolved organic carbon.

In the 1988 sampling effort, 23 water samples were analyzed for concentrations of the heavy metals--arsenic, barium, cadmium, chromium, copper, lead, mercury, selenium, silver, and zinc. Most of these samples were from wells located in areas of commercial or industrial activty. A set of 25 samples, also from wells in commercial/industrial areas, was analyzed for the presence of 36 purgeable organic compounds. In addition, a set of 24 samples, chiefly from wells in unsewered areas or near landfills, was analyzed for the presence of boron and detergents (methylene blue active substances, MBAS).

As part of the quality-assurance program for this study, field instruments for the measurement of specific conductance, pH, and dissolved-oxygen concentration were calibrated at the beginning of each workday and at midday. All sampling and preservation methodologies followed standard USGS procedures (Greeson and others, 1977; U.S. Geological Survey, 1977; Skougstad and others, 1979). Approximately 7 percent of the samples submitted to the Central Laboratory for inorganic analysis were duplicate samples and another 7 percent were blanks (deionized water). Of the samples submitted for analysis of heavy metals, volatile organic compounds, boron, and MBAS, approximately 16 percent were duplicates and another 16 percent were blanks. All wells that tested positive for the presence of significant amounts of bacteria, either fecal coliform or fecal streptococci, were resampled.

Wells that tested positive the second time were sampled a third time by personnel of both the USGS and the WDSHS; testing for bacteria was carried out by both agencies on split samples.

Description of Study Area

The study area consists of approximately 250 mi^2 in southwestern King County (plate 1A). The area is bounded on the north by the Duwamish Waterway/River system, the Cedar River, and the arbitrary boundary coincident with the north side of sections 24 (T.23 N., R.4 E.) and 19 (T.23 N., R.5 E.) and the west side of section 17 (T.23 N., R.5 E.) to where it intersects the Cedar River; on the east by the Cedar River and the eastern limit of the sediments that make up the Quaternary aquifer system; on the south by the Green River, the White River, the arbitrary boundary between the two rivers, which is coincident with the north side of sections 27 and 28 (T.21 N., R.5 E.), and the arbitrary boundary coincident with the King County boundary; and on the west by the Puget Sound. All boundaries of the study area except the arbitrary boundaries also function as hydrologic boundaries of the ground-water system. The hydrologic significance of all the boundaries is discussed later in this report.

Physiographically, the study area lies in the southeastern part of the Puget Sound Lowland, which is a topographically low region between the Olympic Mountains and the Cascade Range (inset, plate 1A) that has been subjected to several episodes of advancing and retreating continental glaciation. The configuration of the land surface of the study area is largely a result of erosion and deposition during and since the advent of the last glaciation (about 15,000 years ago). Generally, the land surface is a relatively featureless plain, composed largely of glacial drift, that is generally at an altitude of 400 to 600 feet above sea level. The effects of continental glaciation on the drift plain are evident in the alignment of lakes, ridges, and major stream valleys that reflects the general direction of ice movement, generally north-south and in places northwest-southeast. The drift plain is dissected by a network of incised major drainageways, the most prominent of which is the Duwamish Valley at an altitude of about 10 to 75 feet. Thus, the study area can be characterized by three dominant physiographic subdivisions described by Luzier (1969)--the Des Moines Plain to the west, the Duwamish Valley in the center, and the Covington Plain to the east (plate 1A). The plains exhibit low relief with poorly drained stream courses and local closed depressions occupied by lakes, wetlands, and peat bogs. The plains are separated from the major river valleys and from Puget Sound by steep bluffs.

The study area is drained by four prominent rivers--the Green, Cedar, Duwamish, and White Rivers--and by a number of creeks. The largest creek is Big Soos Creek, which drains most of the Covington Plain and flows into the Green River. The most prominent drainageway, the Duwamish Valley, actually is a former marine embayment that has been filled with sediment supplied by the ancestral Green River system. The Duwamish Valley, which is drained by the Green River, is relatively flat, with a downstream slope of about 4.5 ft/mi. The valley ranges from 8,500 to 15,500 feet wide and is incised 240 to 400 feet below the drift plains. The flood plain of the Green River upstream of the Duwamish Valley and downstream of the Green River Gorge ranges from 1,850 to 5,000 feet wide and is incised 150 to 375 feet below the drift plain. The valley walls bordering the incised drainages are rather steep-sided bluffs composed of glacial drift from a variety of glacial episodes.

The soils in the study area were derived primarily from deposits of glacial drift deposited during the last glaciation. Fieldwork and mapping for a soil survey of King County was completed in 1969 (Snyder and others, 1973); the soil associations defined and delineated in that survey are the basis for the following brief description of soils in southwestern King County. The general soil map (fig. 1) shows the four major soil associations in the study area--the Alderwood, Oridia-Seattle-Woodinville, Everett, and Beausite-Alderwood.

Soils in the Alderwood association formed on dense glacial till located on moderately well-drained, hilly to undulating slopes on the upland parts of the area--the Des Moines Plain and the northwestern part of the Covington Plain. The soils are gravelly, sandy loams that are well suited to pasture and timber production, but are poorly suited to cultivated crops (Snyder and others, 1973, p. 4).

Soils in the Oridia-Seattle-Woodinville association occur in the major stream valleys and drainageways--the Duwamish Valley and Green River Valley. The soils are generally poorly drained silt loams that are best suited for farming.

Soils in the Everett association formed on glacial outwash located on excessively drained, gently undulating terraces in the southeastern part of the Covington Plain. The soils are predominantly gravelly, sandy loams that are

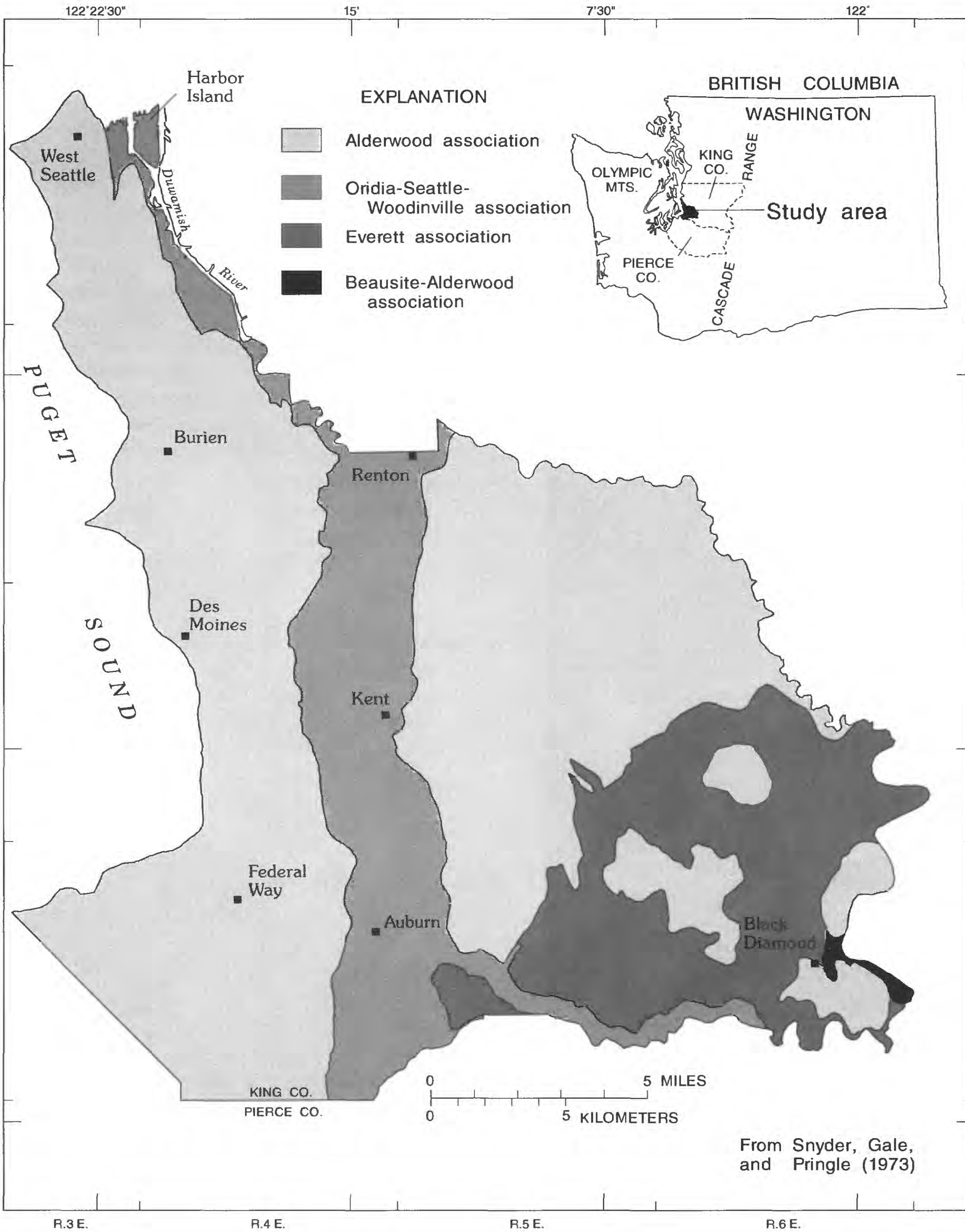


Figure 1.--Generalized distribution of soil associations.

poorly suited to farming, but have the fewest limitations to residential and industrial development of any soil in the study area (Snyder and others, 1973, p. 6).

Soils in the Beausite-Alderwood association formed on weathered sandstone or shale or from dense glacial till located on moderately well-drained, rolling to steep slopes on the uplands in the southeastern part of the study area. The soils generally are gravelly, sandy loams that are poorly suited for farming and severely limited for septic-tank filter fields.

The climate of the study area is influenced by maritime air masses originating over the Pacific Ocean throughout the year. Annual precipitation ranges from about 39 inches near Puget Sound to about 50 inches near Black Diamond. Figure 2 shows a well-defined rainy season in winter (75 percent of the annual precipitation falls from October through March) when the prevailing wind is from the southwest. During winter, rainfall is generally light to moderate in intensity and is virtually continuous.

A well-defined dry season generally occurs in summer (less than 5 percent of the annual precipitation falls in July and August) when the prevailing wind is from the northwest. Afternoon temperatures in the summer are commonly between 70 and 80^{o}F (degrees Fahrenheit), and can reach the low 90's on occasion.

The major rivers generally exhibit periods of high streamflow during the fall and winter that coincide with the rainy season, and during late spring that coincide with the snowpack melt in the mountains. Streams may rise above flood stage several times each rainy season.

Four-fifths of the approximately 450,000 people (Puget Sound Council of Governments, 1987) residing in southwestern King County live in the area's major cities, which include south Seattle, Renton, Kent, Auburn, Des Moines, and Federal Way. As in most of the nation's large metropolitan areas, suburban communities and surrounding rural areas have grown faster than the densely populated cities. This has been especially true on the Covington Plain, where development is proceeding at a faster rate than in most of the rest of the study area. The economy consists mainly of manufacturing, retail, government employment, and service-related industries.

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 02N/03E-07G01 (see fig. 3), the part preceding the hyphen indicates the township and range (T.02 N., R.03 E.) north and east of the Willamette base line and meridian, respectively. The first number following the hyphen (07) indicates the section, and the letter (G) gives the 40-acre tract within that section. The last number (01) is the serial number of the well in that 40-acre tract. If a well has been deepened, the serial number is followed by the letter "D" and a number indicating the sequence of the deepening. For example, if 02N/03E-07G01 were deepened twice, it would then be numbered 02N/03E-07G01D2. In some of the tables the well number has been abbreviated for purposes of convenience.

Acknowledgments

The authors wish to express their appreciation to four consultant firms who have shared data and expertise throughout the life of this project--Economic and Engineering Services, Inc.; The Hydrogroup; Hart Crowser and Associates; and Robinson and Noble. In addition, the cooperation of numerous residents of southwestern King County who permitted the USGS to measure water levels and collect water samples from their wells is appreciated.

The project team that completed this report gratefully acknowledges the contributions of other USGS personnel involved in the earlier portions of the study--thanks to Kristi Whiteman, the original Project Chief, for organizing and designing much of the initial data collection and compilation; Paul Haase, who did a commendable job of interpreting the drillers' logs, compiling the initial set of hydrogeologic control, and preparing the preliminary hydrogeologic maps; and Susan Ristuben and Myrtle Jones, who assisted in compiling the final set of hydrogeologic control data used in preparing the final sections and maps.

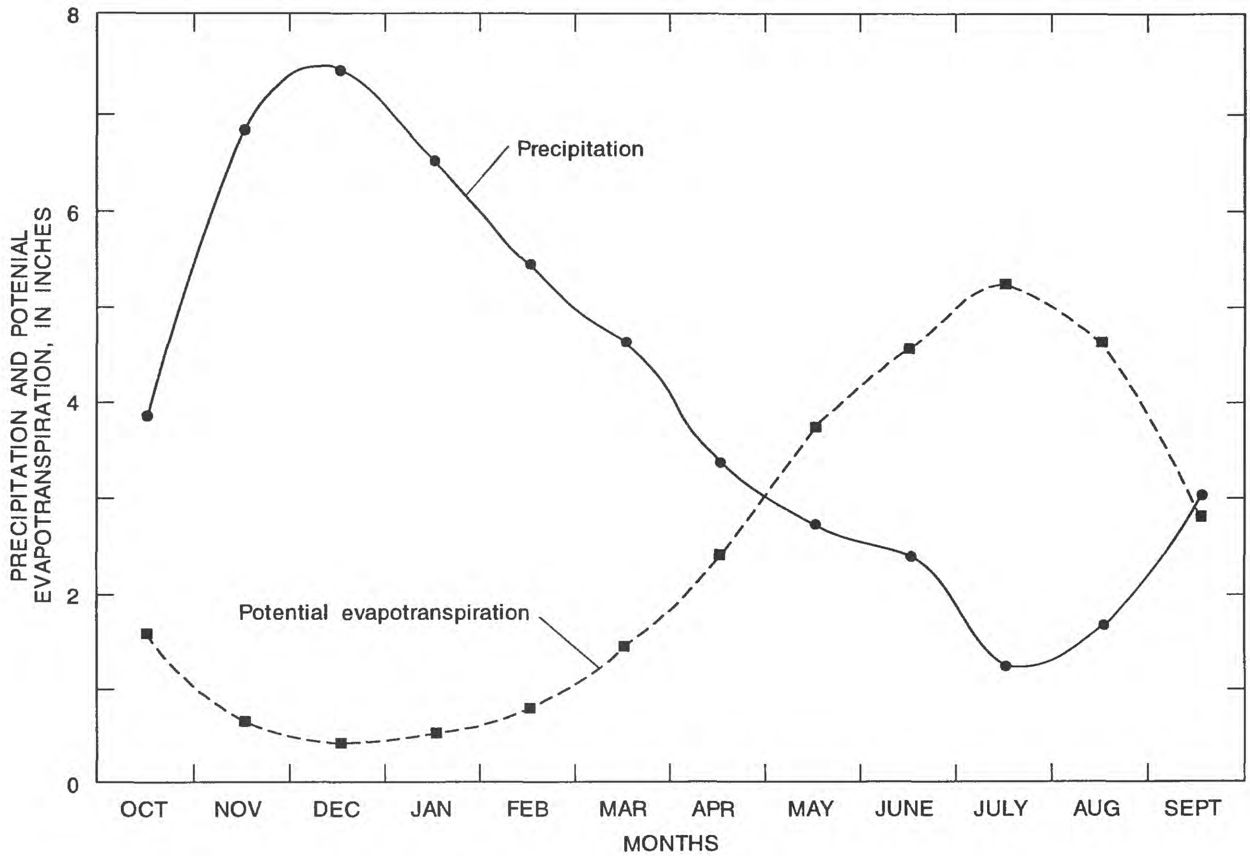


Figure 2.--Mean monthly precipitation and potential evapotranspiration for the Big Soos Creek Basin, King County, 1967-87.

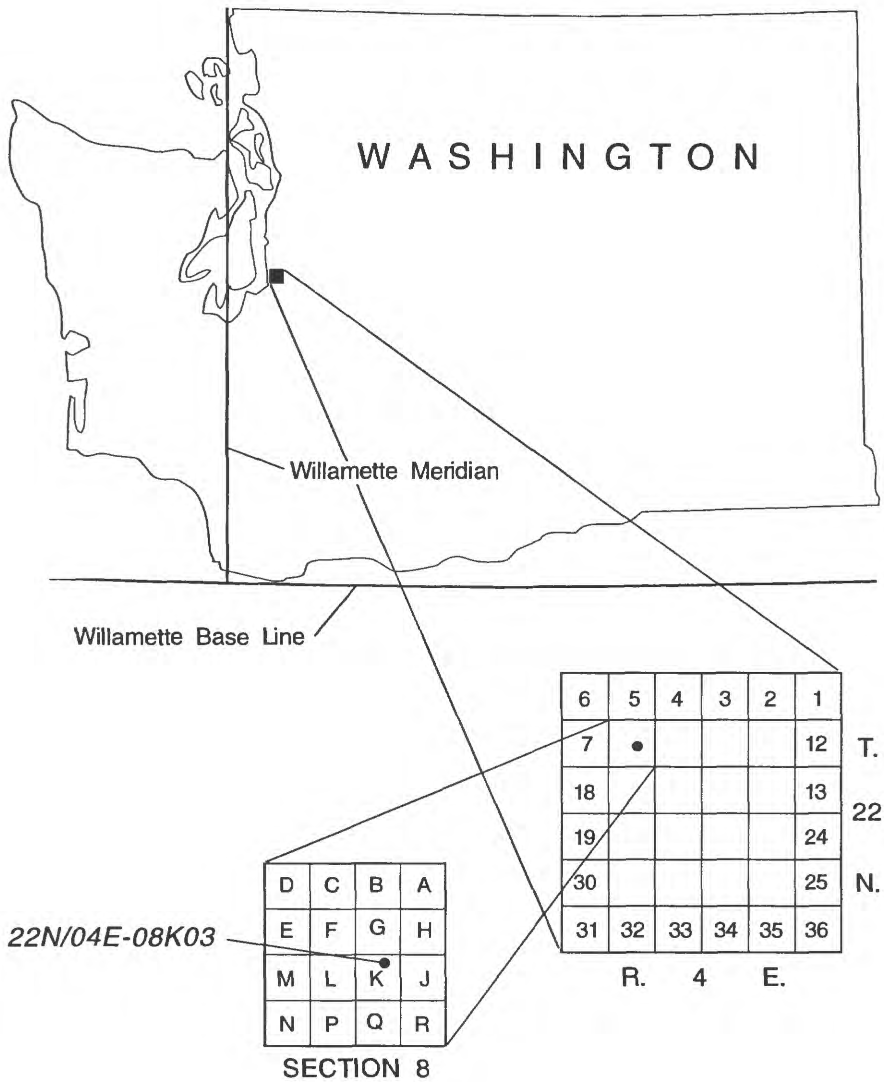


Figure 3.--Well numbering system used in Washington.

HYDROGEOLOGIC FRAMEWORK

The extent of the regional ground-water system that contributes flow to the Quaternary aquifers in the study area is unknown, but the system may reach to the crest of the Cascade Range. However, most of the water in the aquifers in the study area probably is derived from natural and man-induced recharge within the boundaries of the study area. The discussion that follows includes a detailed description of the geology, hydrogeology, ground-water flow system, and hydraulic characteristics of the major aquifers.

Geologic Structure and Setting

The tectonic framework of the Puget Sound region was described by Gower and others (1985). The structural features shown in figure 4, taken partly from that report, help provide a structural setting for the southwestern King County area. Most of the Quaternary deposits in the project area lie on a southwestward-dipping block located between two inferred northwest-oriented faults. A third fault, which cuts through Bainbridge Island and above the northern boundary of the study area, is inferred from the bedrock outcrops on that island to the immediate south, and from a thick sequence of Quaternary sediment to the north of the fault. It has been estimated that the Tertiary bedrock north of this third fault is overlain by more than 3,000 feet of deposits (Yount and others, 1985). The contours of the bedrock surface in the study area were modified from work by Hall and Othberg (1974) and by Yount and others (1985), on the basis of data collected during this study.

The hills just east of Black Diamond are composed of faulted and folded consolidated Tertiary rocks of sedimentary, volcanic, and intrusive igneous origin. These same rocks crop out along the upper Green River Valley, along the bluffs near Renton, in scattered places along the Cedar River, and in the eastern parts of the Covington Plain (fig. 4). This bedrock sequence also underlies the rest of the area at depths as much as 2,200 feet.

Younger Pleistocene till and outwash deposits mantle the Des Moines and Covington Plains (plate 1B), which slope gently westward from altitudes of 600 to about 400 feet; older Pleistocene drift and interglacial deposits crop out along the bluffs that border these upland plains. The incised major valleys of the Cedar, Green, Duwamish, and White Rivers are underlain by Holocene alluvium.

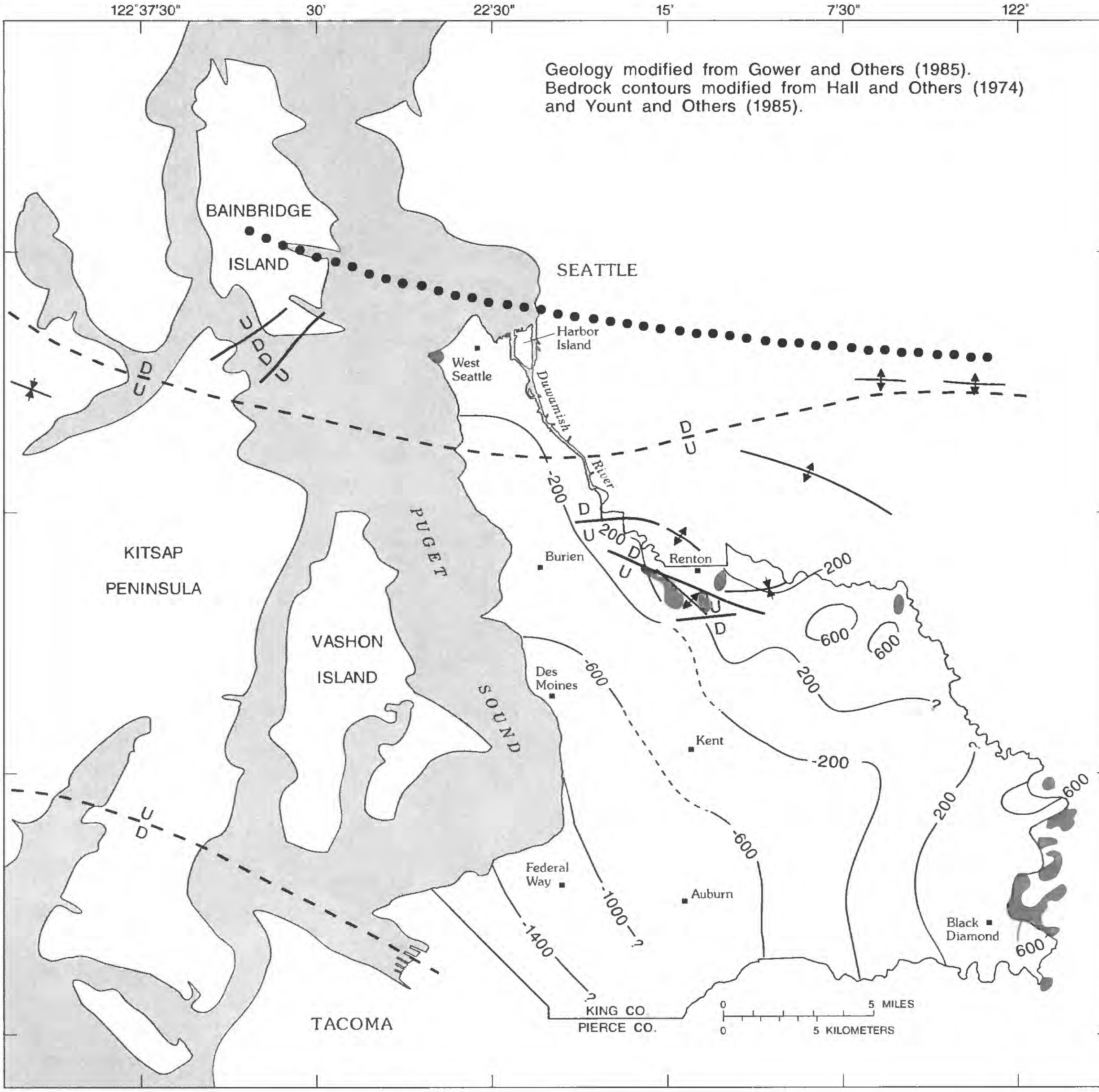
During the Pleistocene Epoch, the Puget Sound Lowland (which includes the study area) was a broad structural basin where as much as 3,600 feet of sediment was deposited. The lowland was glaciated at least four times (Mullineaux, 1970) by the Puget Lobe of the Cordilleran ice sheet that advanced southward from British Columbia, Canada. Each period of glaciation is represented in the sediment record by glacial drift deposits composed of generally coarse fluvial outwash and a compact mixture of unsorted coarse and fine sediments referred to as till or "hardpan." Interglacial periods, when the climate was warmer, are represented by predominantly fine silt and clay deposits, with some coarser sediments associated with streams issuing forth from bordering mountain valleys.

The correlation chart in figure 5 summarizes several recent naming conventions for the upper three glacial and two interglacial episodes of the late Quaternary in various parts of the Puget Sound Lowland. The differences in nomenclature largely reflect differences in opinion about the lateral continuity and age of various sedimentary units. The nomenclature used by Youngmann (1978), Easterbrook (1968), and Haase (1987) in the northern and central parts of the lowland has become accepted widely in the northern lowland in recent years. These names have not been accepted widely in the southern part of the lowland, however, because the stratigraphy cannot be correlated well near Seattle and thus cannot be extended easily southward. In part, the difference may be due to the second-most-recent glacial advance of the Puget Lobe, called the Possession Glaciation by researchers in the north. It appears that the Puget Lobe of the Possession Glaciation did not advance as far south as those that preceded or followed it. Recent evidence supports the inference that during its advance, the Possession Puget Lobe terminated its southward journey somewhere in the vicinity of south Seattle (Haase, 1987).

During the Holocene Epoch, erosion and deposition have occurred primarily along major river valleys and marine embayments. Holocene deposits include peat, mass-wasting debris, mudflow sediments generated on the volcanic peaks of the Cascade Range, and fluvial and deltaic sediments.

Description of Hydrogeologic Units

Previously published stratigraphic correlations of the Quaternary sediments were based almost solely on surface mapping, with the exception of a few subsurface studies in



EXPLANATION

BEDROCK OUTCROPS

FAULT - Dashed where covered or inferred. U, upthrown side; D, downthrown side

ANTICLINE

SYNCLINE

POSSIBLE QUATERNARY FAULT ZONE - Inferred from the presence of steeply dipping bedrock strata south of this zone and a thick section of Quaternary deposits to the north

200 CONTOUR - Dashed where inferred. Shows approximate top elevation of Tertiary bedrock below Quaternary deposits. Contour Interval is 400 feet. Datum is sea level

Figure 4.--Major structural features in the vicinity of southwestern King County

	Climate units & approximate Age[1]	Island County (Easterbrook, 1968)	Snohomish County (Newcomb, 1952)	N.W. King County (Liesch and Others 1963)	S.W. King County (Luizer, 1969)	Pierce County Walters and Krimmel, 1968)	Kitsap Peninsula (Garling, Molenaar and others, 1965)	Mason County (Molenaar and Noble, 1970)	Thurston County (Wallace and Molenaar, 1961)	Jefferson County (Griamstad and Carson, 1981)	Seattle (Stark and Mullineaux, 1950)
	HOLOCENE		Younger and Older Alluviums	Sedimaentary Depoist, Peat	Peat, Alluvium	Alluvium Peat	Alluvium	Alluvium	Alluvium		
PLEISTOCENE	10,000 FRASER GLACIATION 23,000	Glacial-marine Drift, Recessional Outwash Till Advance Outwash [2] Esperance Sand	Marysville Sand; Arlington Gravel; Stillaquamish Sand Members of the Vashon Drift Till Advance & Esperance Sand	Recessional and Delta Outwash Till Advance Outwash ?	Recessional Outwash Till Ice-marginal Deposits Advance Outwash	All phases of Vashon Drift (Recessional & Advance Outwash, till)	Recessional Outwash Till [2] Esperance Sand Advance Outwash	Recessional Outwash Till Advance Outwash	Recessional Outwash 1,2 Till Advance Outwash	Recessional Outwash Till Advance Outwash	Till Advance Outwash
PLEISTOCENE	OLYMPIA INTER-GLACIATION 60,000	Quada Formation	Pilchuck Clay Member	Unnamed sand ↑ Upper Clay	Salmon Springs Drift		Colvos Sand	Kitsap Formation	Kitsap Formation	↑ Undiffer-entiated ↓	Lawton Formation
PLEISTOCENE	POSSESSION GLACIATION 80,000	Possession Drift	Undiffer-entiated Till	Unnamed Gravel		Colvos Sand Salomon Springs Drift					Klinker Till, Beacon Till, Duwamish Formation
PLEISTOCENE	WHIDBEY INTER-GLACIATION >100,000	Whidbey Formation	Admiralty Clay ↓	Lower Clay ↓	Puyallup Formation	Kitsap Formation Puyallup Formation	Kitsap Formation		.		
PLEISTOCENE	DOUBLE BLUFFS GLACIATION	Double Bluffs Drift			Inter-mediate Drift	Stuck ? Drift	Salmon Springs Drift	Salmon Springs Drift	Salmon Springs Drift 1,2		

[1] Based on Marine Isotope Curve of Martinson and Others (1987) and dating work of Esterbrook (1982)
[2] Esperance Sand - Member

Figure 5.--Correlation of late Quaternary stratigraphy of Puget Sound Lowland, Washington.

well fields done by privately funded consultants. No regional net of subsurface correlations existed that carried units identified along bluffs at one side of the drift plains to the numerous wells beneath those plains and to outcrops along bluffs at the other side of the plains. As a result, no regional structure or thickness maps existed of individual aquifer units beneath the drift plains. The work described below was completed in order to produce the sections and maps required for a three-dimensional, regional characterization of the aquifer and nonaquifer units. This characterization, in turn, allowed the definition of a three-dimensional ground-water flow system.

The subsurface stratigraphy of the study area was delineated using lithologic information from surficial geologic mapping by various researchers (Waldron, 1961, 1962; Mullineaux, 1961, 1965a, 1965b, 1970; Vine, 1962; Luzier, 1969; and Booth, 1990a, 1990b) and from approximately 700 drillers' logs. This information first was used to construct 28 generalized hydrogeologic sections oriented east-west, north-south, and diagonally across the study area. The descriptions of sediments encountered by drillers were used to define three periods of glaciation with two intervening interglacial periods. At a greater depth, a fourth set of glacial and interglacial deposits has been defined tentatively from logs for the few deep wells in the area, but no regional correlation was attempted because of the sparse control.

Ideally, the undisturbed sequence of regional sediments associated with a single, complete cycle of continental glaciation would be a basal layer of coarse-grained, poorly to moderately sorted deposits of sand and gravel (representing advance outwash); an intermediate layer of compact, unsorted, unstratified boulder- to silt-sized sediments in a fine-grained matrix (representing glacial till); and an upper layer of moderately sorted, coarse-grained deposits of sand and gravel (representing recessional outwash). Deposits from the most recent continental glaciation--the Vashon Drift--have been studied more carefully than other drift deposits in the study area because these sediments are at or near the land surface and they are relatively undisturbed. The idealized, undisturbed sequence of three drift lithologies (basal, intermediate, and upper) for the Vashon Drift was delineated from surface and subsurface data, and each lithology was mapped as a separate hydrogeologic unit for this study. Previously accepted and published nomenclature associated with the Vashon Drift of the Fraser Glaciation (fig. 5) was used for the three hydrogeologic units--the Vashon advance outwash (Qva), Vashon till (Qvt), and Vashon recessional outwash (Qvr).

Older sediments, deposited during the two interglacial and glacial periods prior to the Vashon Drift of the Fraser Glaciation, crop out mostly along the bluffs adjoining the Covington and Des Moines Plains (plate 1B), and elsewhere these sediments are found in the subsurface beneath the Vashon deposits. With the sparse outcrop control and drillers' logs, it was not always feasible to distinguish glacial till from the outwash in these pre-Vashon deposits; in addition, coarser fractions of the interglacial deposits locally merge with the glacial outwash. Thus, the deeper, pre-Vashon deposits were defined as hydrogeologic units of a more general nature than the Vashon deposits and were distinguished on the basis of broad lateral continuity of a predominant grain size. The predominantly fine-grained, low-permeability units consist mostly of interglacial silt and clay with some glacial till, and the predominantly coarse-grained units of higher permeability consist mostly of outwash deposited during periods of glacial advance or recession. From a hydrogeologic perspective, the low-permeability units are considered to be confining beds and the high-permeability units, where saturated, to be aquifers.

Because of the difficulties mentioned previously in correlating units between northern and southern parts of the Puget Sound Lowland, the convention used in this report to designate the various hydrogeologic units older than Vashon is generic, and an identifying label was assigned on the basis of overall sediment size, degree of sorting, and relative age. Units beneath the Vashon Drift are identified with a "Q" representing the geologic age as Quaternary; this is followed by a sequence capital letter in parentheses indicating the unit's relative position below the Vashon (A is the unit just beneath the Vashon), and this is followed by either a lower case "c," "f," or "u" to indicate dominantly coarse-grained (mostly glacial), fine-grained (mostly interglacial), or undifferentiated materials, respectively. Interpretation and correlation of the 28 hydrogeologic sections led to the delineation of nine major hydrogeologic units (table 1) that correspond with the large-scale geologic events during and after the Pleistocene Epoch. Data from the few wells drilled into sediments below the Q(B)c unit indicate that still more aquifer units may exist at depth. Post-Pleistocene fluvial and deltaic sediments in valley floors account for the youngest of the hydrogeologic units, the Qal. The final step after the correlation of hydrogeologic sections was the construction of maps showing the extent, thickness, and top elevation of the aquifer units, based on interpretation of geologic maps and sections.

Table 1.--*Hydrogeologic units of Quaternary age in southwestern King County*

Hydro-geologic unit	Predominant geologic significance (see fig. 5)	Predominant hydrologic significance
Qal	Holocene alluvium	Aquifer[1] and confining bed
Qvr	Vashon recessional outwash	Aquifer[1]
Qvt	Vashon till	Confining bed
Qva	Vashon advance outwash	Aquifer[1]
Q(A)f	Mostly fine-grained interglacial sediments	Confining bed
Q(A)c	Outwash deposits of drift sediments	Aquifer[1]
Q(B)f	Mostly fine-grained interglacial sediments	Confining bed
Q(B)c	Outwash deposits of drift sediments	Aquifer[1]
Q(C)u	Undifferentiated, unconsolidated sediments	Unknown

[1] Where unit consists of coarse, saturated sediments.

Geologic mapping and making stratigraphic correlations proved difficult in the Cedar River Valley. The geologic processes and sediment records in this area are complicated by the presence at or near land surface of numerous bedrock knobs that affected glacial processes. In addition, evidence suggests that during the Pleistocene Epoch, the Cedar River Valley was periodically the site of an ice-dammed lake in which fine-grained sediments were deposited. Consequently, hydrogeologic units are difficult to correlate along the northern and northeastern edges of the Covington Plain, and confidence in the maps of this area is low. A more complete description of the bedrock and each hydrogeologic unit and their extent and lithologic character follows.

Bedrock is at or near land surface along the upper Green River, in the hills northeast of Black Diamond, near Renton, and along the northern part of the Covington Plain (plate 1C); the bedrock surface slopes downward to the west-southwest beneath unconsolidated sediments toward the center of the Puget Sound Lowland (fig. 4). The bedrock surface is important to the ground-water study in that it is assumed to represent the relatively impermeable basement of the glacial aquifer system. Where it has been observed, the bedrock is composed principally of cemented sandstone with interbedded shale and coal, with a few volcanic and intrusive igneous rocks. The bedrock has been described in more detail by Mullineaux (1970) and will not be discussed further herein.

As previously mentioned, unconsolidated sediments as much as 2,200 feet thick directly overlie the bedrock in the study area. Regional stratigraphic and hydrogeologic information, derived from outcrops and well control, is generally available for only the upper 600 feet of those sediments. A few well logs provide information about sediments deeper than 600 feet, but regional hydrogeologic correlation and extrapolation of those deeper sediments are not practical. For the purposes of this study, the deepest sediments are grouped into an undifferentiated hydrogeologic unit designated as Q(C)u (table 1); because of the sparse data, no regional geologic or hydrogeologic properties were assigned to this unit.

Outwash deposits of an old glacial drift overlie the Q(C)u unit. The coarse outwash deposits are designated as Q(B)c, and this unit is considered to be an aquifer. Q(B)c underlies each drift plain (plate 1C), except for the extreme northern part of the Des Moines Plain and the northern and eastern parts of the Covington Plain, where the unit pinches out against bedrock knobs. The Q(B)c aquifer is overlain throughout most of its extent by a confining bed (the Q(B)f unit). Few wells in the study area penetrate the Q(B)c unit because sufficient ground water usually can be found at shallower depths, and thus, this unit has the smallest data base from which to infer regional hydrogeologic properties and characteristics. However, both the King County Water District (KCWD) 75 and the city of Federal Way have public-supply wells that tap this aquifer.

The configuration of the top of the Q(B)c unit is somewhat irregular, but it generally slopes westward toward Puget Sound from an altitude of about 250 ft above to 150 ft below sea level in the Covington Plain, and from about 50 ft above to 450 ft below sea level in the Des Moines Plain (plate 2A). A rather deep, north-south-trending channel is apparent southwest of Federal Way; this feature commonly has been referred to as the Milton-Redondo channel. Available data indicate that this hydrogeologic unit averages about 50 ft in thickness, but the data are too sparse to present in a meaningful map.

Deposits composed primarily of clay, with some silt and fine sand, overlie the Q(B)c aquifer. These fine-grained deposits are designated as Q(B)f, and this hydrogeologic unit is considered to be a confining bed between aquifers in the overlying and underlying glacial drift. The Q(B)f confining bed was deposited during an interglacial period; in places, it also includes adjacent drift deposits. Where sandy lenses are extensive, the Q(B)f unit can yield small supplies of water to wells.

The more permeable, coarse deposits found within the second glacial drift sequence below land surface are designated as Q(A)c, and this unit is considered to be an aquifer where the deposits are saturated. Q(A)c sediments in both drift plains become more coarse toward the north, although few data are available for this unit in the northern part of the Des Moines Plain. Till lenses, as well as clay and silt lenses, are present irregularly throughout the Q(A)c unit. The heterogeneous character of the Q(A)c sediments may reflect the complexity of glacial processes near the terminal zone of this particular ice lobe. The Q(A)c unit underlies most of the drift plains except near the highest bedrock knobs and near the mouth of the Big Soos Creek Basin (plate 1C). The Q(A)c unit generally is overlain by the Q(A)f confining bed, but that confining bed is not present in the northwestern and southwestern parts of the Covington Plain and in the northeastern and southwestern parts of the Des Moines Plain. In these areas, the Q(A)c unit is in direct hydraulic connection with another, shallower aquifer (the Qva unit), forming a combined aquifer unit--the Qva/Q(A)c unit. The Q(A)c hydrogeologic unit is presently (1989) the third most extensively used aquifer in southwestern King County. The cities of Federal Way and Kent, and KCWDs 54 and 111 have public-supply wells that tap the Q(A)c aquifer, and the city of Federal Way has public-supply wells that tap the combined Qva/Q(A)c aquifer.

The top of the Q(A)c aquifer (plate 2B) is irregular; it ranges in altitude from about 500 ft above sea level, bordering the bedrock knobs in the northern Covington Plain, to about 200 ft below sea level, in the southern Des Moines Plain. The thickness of the Q(A)c unit (plate 2C) ranges from 0 to about 200 ft and averages about 85 ft. Regionally, the Q(A)c unit tends to be thicker in structurally low areas, which is reasonable given the glaciofluvial origin of this unit.

Deposits of clay, silt, and fine sand generally overlie the Q(A)c aquifer. These fine-grained deposits are designated as Q(A)f, and the unit is considered to be a confining bed. Some of these fine-grained sediments were deposited during an interglacial period, and in places they include overlying and underlying drift deposits. The Q(A)f locally contains sand and gravel lenses that supply small quantities of water to a few wells in the study area. As previously mentioned, the Q(A)f unit has been eroded away in the northwestern and southwestern parts of the Covington Plain and in the northeastern and southwestern parts of the Des Moines Plain (plate 1C). The unit is also thin in the northern Covington Plain where bedrock is at or near the land surface. The thickness of the unit ranges from 0 to more than 200 ft; the interglacial sediments are generally less than 50 ft in thickness and, consequently, the greater thickness of the Q(A)f unit occurs in areas where till and unsorted glacial drift are present within the unit. The Q(A)f unit is generally thicker on the Des Moines Plain than on the Covington Plain (plate 1C).

The Qva unit consists of moderately well-sorted sand and gravel and represents the advance outwash deposits of the Fraser Glaciation; it is an important aquifer in the study area where the deposits are saturated. The cities of Federal Way and Kent, and KCWDs 94, 105, and 111 have public-supply wells withdrawing water from this aquifer. The Qva unit has less lateral continuity than most of the other hydrogeologic units (plate 1C) due to the irregular nature of its deposition by streams issuing forth from the advancing Puget Lobe. It is absent in major river and stream valleys, having been eroded away, and is thin or absent over large areas where bedrock is at or near the land surface. The Qva unit generally is overlain by the Qvt confining bed. As previously discussed, there are places in the study area where the Qva and the underlying Q(A)c aquifer units merge into a combined Qva/Q(A)c aquifer unit.

The top of the Qva unit is generally within 100 feet of land surface and ranges in altitude from about 650 to less than 100 ft above sea level (plate 2D). The unit generally slopes downward from east to west. Thicknesses range from 0 to about 200 ft, with the thicker deposits generally in the northern half of the area (plate 2E).

The Qvt unit represents the till deposited by the Fraser Glaciation. Till has been described by Garling and others (1965) as "a gray to bluish-gray compact and unsorted mixture of cobbles and pebbles in a binder of silt and clay. This material was 'smeared' along the ground by the tremendous pressure produced by the weight of the ice. This basal deposit of the ice characteristically forms a capping on the topography over which the ice sheet advanced.... It is commonly so hard that blasting is required during the construction of dug wells, although in some places where the ice rode over sandy materials...the till may be sandy and relatively friable." Although this unit principally functions as a confining bed in the study area, numerous shallow dug wells produce domestic supplies of ground water from sand and gravel lenses within the upper less-compact part of the till.

The Qvt unit occurs at land surface throughout most of the study area except along major valleys, where it has been eroded away (plate 1B). It is within 50 ft of land surface where it underlies the Qvr unit. The unit is commonly thin and discontinuous or absent along steep coastal and valley bluffs.

The thickness of the Qvt unit ranges from 0 to less than 200 ft, and it averages about 60 ft. This unit generally thickens toward the Puget Sound. On the Des Moines Plain, it is absent in the extreme north and thickens toward the south; on the Covington Plain, the unit thins toward the south and east and is often less than 25 feet thick beneath the recessional outwash plain. Locally, the unit is thickest in topographically high areas and thins in the adjacent lowland areas. This pattern has been observed by other researchers, including Brown and others (1987) and Haase (1987).

The Qvr unit represents the recessional outwash deposits of the Fraser Glaciation and is considered to be an aquifer where the deposits are saturated. The unit consists primarily of sand, with lesser amounts of gravel and some clay. Except for an extensive kame terrace on the west side of the Duwamish Valley, these sediments were deposited in the topographic "lows" of the irregular surface of the Qvt till plain. In many places, the Qvr unit is not continuous or thick enough to map; in addition, the coarse, poorly sorted recessional outwash sands are difficult in many places to distinguish from the underlying sand-rich till. For these reasons, the Qvr is considered to be a minor aquifer in the study area. The most prominent feature within the Qvr unit is the large recessional outwash plain that occupies the southeastern part of the Covington Plain (plate 1B). Here, the Qvr deposits are almost everywhere underlain by till (Qvt unit). Hydrogeologic data for this unit generally are lacking on the northern Des Moines Plain. The unit thickness averages about 30 ft.

Alluvium found in the valleys of the Green, Cedar, Duwamish, and White Rivers (plate 1B) is designated as Qal, and this unit is considered to be an important aquifer. Few wells fully penetrate the Qal unit in the study area, so the thickness of the unit generally is not known. The alluvium in the Green River Valley east of Auburn and in the Cedar River Valley consists mainly of pebble-to-cobble gravel and sand, and is generally less than 30 feet thick along the Green and less than 60 feet thick along the Cedar. However, locally in the Green River Valley the alluvium exceeds 400 ft in thickness. Near the steep sides of each valley, Qal is interbedded with and sometimes overlain by mass-wasting debris. The alluvium in much of the lower Duwamish Valley is characterized by medium- to fine-grained sand and silt that was deposited in a delta complex when the valley was a submerged marine embayment; these sediments generally do not yield appreciable volumes of water to wells. Two large alluvial fan deposits are present in the study area, one in the northern part of the Cedar River Valley near Renton and the other in the southern part of the Green-Duwamish Valley near Auburn. Both fans are composed of thick sequences of coarse sand and gravel that are highly permeable and capable of yielding large quantities of water to wells. The older parts of the Auburn fan deposits (possibly the Green River fan described by Mullineaux, 1970) probably correlate with Vashon recessional deposits exposed at the surface just east of Auburn, but Vashon-age deposits have been included in the Qal hydrogeologic unit (aquifer) in this report. Mullineaux (1970) identified younger Holocene deposits above and down valley from the Qvr buried beneath Auburn as being part of the White River fan deposits. The cities of Renton, Auburn, Kent, Algona, and Pacific have municipal public-supply wells that produce water from these fan deposits. Much less is known about the lithology, thickness, or water-yielding capacity of the Qal deposits in the central and lower parts of the Duwamish Valley than about those near Auburn.

Ground-Water Flow System

In previous attempts to define the ground-water flow system in southwestern King County, the permeable, water-bearing deposits were not segregated into distinctly separate aquifers, and all water levels measured in wells, regardless of the depth, were attributed to a single aquifer (Luzier, 1969; Cline, 1969). In this study, discrete aquifer and confining units were delineated to allow the construction of water-table or potentiometric-surface maps for each aquifer. These maps allow some description of the vertical components of flow in the system as well as a better understanding of the lateral flow. Separate water-level maps also allow a more precise definition of the relation between well pumpage in aquifer units and its effects on discharge points such as lakes, springs, and streams.

Ground-water flow systems can be divided loosely into three categories--local, intermediate, or regional (Toth, 1963; Freeze and Cherry, 1979). Local flow systems generally have short flow paths, commonly involve shallow aquifers, and usually are controlled by local topography of relatively low relief. Thus, a large number of closely spaced water-level measurements is required to delineate a local ground-water flow system. In contrast, regional flow systems generally have long flow paths, commonly involve deep aquifers, and usually are controlled by large-scale topographic and drainage features such as the Cascade Range, Olympic Mountains, and Puget Sound. The characteristics of intermediate flow systems are somewhere in between. For this study, the regional flow system is defined conceptually by long, deep flow lines, mainly within bedrock, that may originate near the crest of the Cascade Range. The local flow system is defined by those flow lines controlled by the relief between the Covington and Des Moines Plains, the Cedar-Green/Duwamish Rivers, and Puget Sound. The intermediate flow system is defined conceptually as comprising that flow above the bedrock surface and below the deepest part of the local system. This arbitrary differentiation of flow systems was useful in placing available data into a larger conceptual framework. However, detailed analyses, such as would be provided by numerical models, that would define the precise boundaries between the three flow systems were not within the scope of this study. This report focuses on the movement of ground water within the local and intermediate flow systems.

A cross-sectional diagram of the study area (fig. 6) demonstrates the relation between the local and intermediate flow systems. The intermediate flow system is represented by bold flow lines that are assumed to pass across and under some of the hydrologic boundaries of the local flow system. The intermediate flow lines originate east of the study area, implying that some (deep) water may be imported across the boundaries of the study area. If such underflow does take place, studies such as that completed by Lum (U.S. Geological Survey, written commun., 1988) in an analogous area north of Seattle suggest that this deep, intermediate-scale underflow is small in comparison with the quantity of recharge to the local system from precipitation. Note that a boundary beneath the Green River, shown in figure 6, separates the local flow system into two principal parts: one beneath the Covington Plain and a second beneath the Des Moines Plain. Arbitrary boundaries of the study area do not necessarily coincide with hydrologic boundaries of the aquifer system. However, it is assumed that there is underflow to or from the study area, but that these fluxes are minor compared with the total flow in the system.

The ground-water flow system is affected by the complexity and heterogeneity of the sediments that underlie the study area. A glacial aquifer may be composed of predominantly sand- and gravel-sized sediments, but at a small scale, it probably also contains relatively thin and discontinuous lenses of silt and clay or intermixed coarse- and fine-grained sediments. The occurrence and movement of ground water locally is influenced by these small-scale variations in lithology and by their extent. The water-level data presented below define a generalized ground-water flow pattern that may not reflect local conditions.

To assess more fully the movement of water within and between aquifers, water-level contour maps were developed from static water levels measured in approximately 400 wells during April 1987. The following discussion concerns flow within the Vashon recessional outwash (Qvr) and Vashon till (Qvt), the lateral flow components that can be mapped within deeper aquifers, and the vertical flow between hydrogeologic units.

The water-level data available for the Qvr aquifer were too sparse to contour. The unit was deposited in topographic lows on the till surface and is assumed to constitute a water-table aquifer in most places where it is thick and saturated.

A much debated and yet unresolved issue is whether the Qvt unit is saturated throughout the entire study area and, in a related sense, whether the water table occurs above, within, or below the till. Available data suggest that in areas where Qvt is overlain by thick saturated sections of Qvr sediments, it is logical to conclude that Qvt is fully saturated. Two factors support this assumption. First, the Qvr sediments constitute a water-table (unconfined) aquifer where they are thick enough to provide storage for precipitation that infiltrates quickly through overlying porous soils. Thus, in many areas where Qvr is present, the Qvt sediments have a continuous natural supply of water above them available for downward movement. Secondly, water-level data indicate that the Qva aquifer, which underlies the Qvt unit, is confined over most of the study area. Consequently, where aquifers above and below the till are saturated under natural conditions, the till is most likely to be saturated.

In a number of areas where till is at land surface, shallow dug wells draw domestic supplies from water-bearing zones within the upper part of the till. Hundreds of these wells were inventoried and their water levels measured by the USGS more than 25 years ago (Luzier, 1969). At that time it was reported that many of the till wells contained water during the winter but would be nearly dry by late summer. The well inventory done for the present study during the summer of 1986 indicated that many of these shallow wells currently are unused or have been destroyed; water is now supplied to the owners of these wells by small public suppliers or water districts. However, some of these wells are still in use, which is an indication that the upper part of the Qvt unit is saturated and yields an appreciable volume of water to wells where the

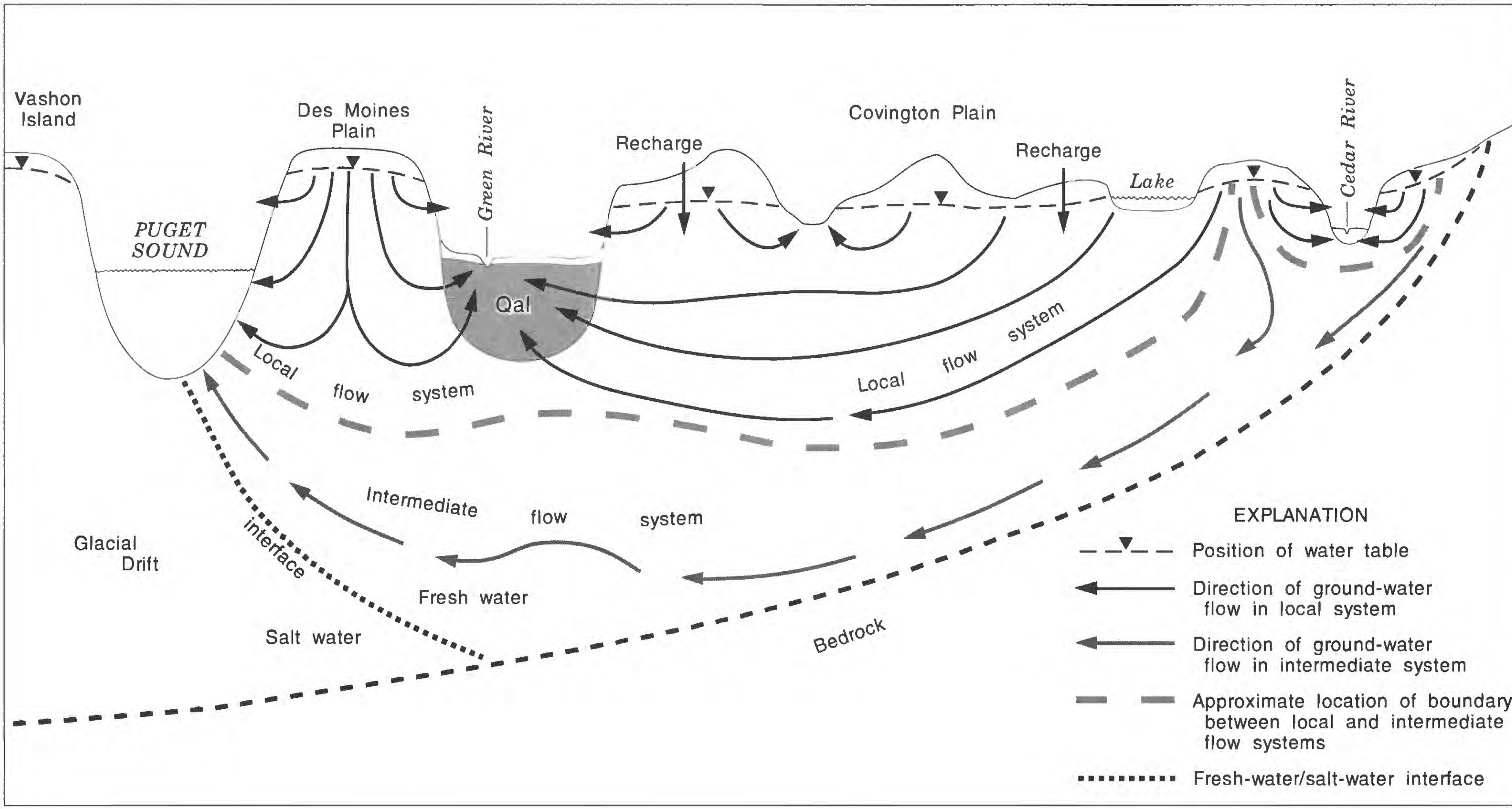


Figure 6.--Diagrammatic sketch showing location and types of boundary conditions for the study area in cross-sectional view.

sediments are permeable. This fact alone does not verify that the lower part of the till is saturated. In areas where the top of the till provides water to shallow wells all year long or contains perennial lakes or wetlands, and where the Qva aquifer below is confined, saturation of the lower till is expected. However, where the Qvr is absent and the top of the Qva aquifer is unconfined, the Qvt probably is not saturated. (This was the case in a study done by Dion and others (1983) in the Pine Lake area, located about 8 miles northeast of Renton.) In areas beneath the two plains where the Qvt is at land surface and the Qva aquifer is saturated, data are insufficient to determine if the till is saturated or not.

Lateral Flow Components

Water-level information for the Qva and Q(A)c aquifers is shown on plates 3A and 3B, respectively. The general shape of the water-level contours for both aquifers is similar and reflects the influence of land-surface topography. These aquifers terminate along bluffs adjacent to the major alluvial valleys of the Cedar and Green Rivers and along some smaller tributary streams. As a consequence, some water within these aquifers discharges from springs and seeps along these slopes and bluffs. Beneath the Des Moines Plain, lateral ground-water flow is radially outward from two highs--one located north of Angle Lake and the other centered east of Federal Way. In like manner, beneath the southern part of the Covington Plain, lateral ground-water flow is from where the aquifers pinch out against underlying bedrock along the eastern margin of the drift plain, westward to discharge points along the Green River Valley or Big Soos Creek. In the northern part of this drift plain, a ground-water high is centered in the vicinity of Lake Youngs, with lateral ground-water flow outward in all directions.

In areas where data were lacking, contours on plates 3A and 3B were drawn on the basis of the authors' conceptual understanding of ground-water movement in the overlying aquifers. For example, water-level data indicate that aquifers below the Qvr unit are confined--that is, water levels generally are above the top of the aquifer. However, where these confined aquifers have been truncated by post-Pleistocene erosion, as along major river valleys or along secondary tributaries, data indicate that the aquifers thus exposed have been partly dewatered by seeps and springs for a short distance (about 0.3 mile) back from the seepage face. In the central parts of the two drift plains where water-level data are sparse, water levels in Qva and older units were assumed to be above the tops of the aquifers by a distance equal to that in nearby wells. In bluff areas where these aquifers are truncated, water levels were assumed to lie below the top but above the base of the aquifer unit. In the southern Des Moines Plain area, water-level measurements in the Qva and Q(A)c aquifers made by water-district personnel (D. Matlock, The Hydrogroup, written commun., 1989) support the pattern of the contoured potentiometric surfaces shown on plates 3A and 3B. In some areas, however, sparse geologic and water-level data precluded contouring of water levels. Similarly, water-level contours have not been drawn for the Q(B)c aquifer because the data are too sparse.

Water-level data for the Holocene Qal aquifer, shown on plate 3A for convenience, indicate that ground-water flow in this aquifer is generally toward discharge points along the major river channels. However, in an area near Auburn, ground-water gradients in the Qal aquifer are away from the Green and White Rivers. This implies that, in these reaches, the rivers are losing water to the surrounding alluvial aquifer. There are two possible explanations for this unexpected phenomenon, and both may be correct. One explanation is that local ground-water pumpage from the productive Qal sands and gravels has lowered ground-water levels and has induced flow from the rivers toward the pumping centers. As will be discussed later in this report, the Qal aquifer is pumped extensively in this area. A second explanation relates to the local geologic setting in which the White and Green Rivers both flow out from narrow, steep valleys onto a delta at the head of the broad, relatively flat Duwamish Valley. In an analogous deltaic framework, results of studies indicated that the Dungeness River (Drost, 1983) and Cowlitz River (Packard and others, U.S. Geological Survey, written commun., 1989) lose water to the ground-water system at the head of their respective deltas.

Vertical Flow Components

The water-level data collected in April 1987 indicate that the vertical ground-water flow between hydrogeologic units is from upland recharge areas (the till plains) downward and laterally to the major alluvial valleys. Much evidence is available to support this concept. For instance, in the Lake Sawyer and Wilderness Lake areas of the Covington Plain, water levels of lakes in till basins and in wells completed in the Qvr aquifer are at a higher altitude than water levels of nearby wells that were completed in the deeper Qva aquifer. Likewise, water levels measured in Qva wells were found to be above those of nearby deeper Q(A)c wells in the Midway area and at locations south of Lake Youngs, north of Lake Meridian, and along Jenkins Creek. The same pattern holds true for adjacent wells completed in the Q(A)c and Q(B)c aquifers in the Midway, Federal Way, and southern Covington Plain areas.

In the major alluvial valleys, water levels in deeper wells are higher than those in shallower wells, indicating an increase in water-level altitude with depth, or upward flow. For example, along the eastern side of the Duwamish Valley between Kent and Renton, several shallow observation wells drilled to depths of less than 50 feet have water levels generally within 10 feet of land surface. Three nearby wells drilled to depths of 149 to 182 feet have water levels above land surface (that is, they are flowing wells). Thus, the available water-level data in the major river valleys support the concept that ground water here flows upward to discharge into the rivers. The only apparent exception to this is in the Auburn area, where the water-level data indicate that shallow ground water flows downward and away from the Green and White Rivers, as discussed earlier. It is assumed that in this anomalous area, the regional ground-water system discharges upward and into the alluvium on either side of the Green River at the locations where the water table is low, rather than directly into the rivers. From these low points, this deep discharge is interpreted to flow downvalley and into the Green River, where it is once again a gaining river.

Water-Level Changes

Ground-water levels fluctuate naturally in response to seasonal changes in the distribution and rate of recharge and discharge. Water levels from observation wells measured during this study illustrate this fluctuation (fig. 7). In general, the largest annual fluctuations are in shallow aquifers with small values of specific storage; fluctuations generally decrease and are delayed over time with depth. In the study area, seasonal cyclic fluctuation in the observation wells ranged from 1.5 to 12 feet. Changes in mean annual ground-water levels over a long term (20 to 30 years) also take place in response to long-cycle changes in recharge; hydrographs of wells in the Federal Way area for which long-term data are available are shown in figure 8. In addition to natural fluctuations, ground-water levels change in response to the distribution and rate of pumping through time and to changes in boundary conditions.

Hydraulic Characteristics

An estimate of the magnitude and distribution of horizontal and vertical hydraulic conductivity and storage of each aquifer is needed to understand the movement of ground water and, ultimately, to calculate its availability. Hydraulic conductivity is defined as the volume of water that will move in unit time through a unit cross-sectional area under a unit hydraulic gradient at a temperature of about 15°C (degrees Celsius). The storage coefficient of an aquifer is defined as the quantity of water that is released per unit area per unit decline in water level.

In his discussion of the major drift aquifers of the area, Luzier (1969) gave generalized ranges of well yield and drawdown for selected wells completed in various deposits. He also included a table of records for more than 1,500 wells; information concerning well yield and drawdown was listed for about one-third of the wells. However, because individual aquifers were not defined in that study, these pump-test data were not associated with distinct aquifer units.

In the present study, pump-test data were compiled and used to calculate the specific capacity and, in some instances, the average hydraulic conductivity values for an aquifer. These data then were plotted by aquifer (plates 3C and 3D) to determine whether there were distinct patterns of high and low hydraulic conductivity within each aquifer. A frequency distribution analysis was used to divide the specific-capacity data into four quartiles, where 25 percent of the data are below the 25th quartile mark, 25 percent are between the 25th and 50th quartile marks, and so forth. Hydraulic-conductivity values were analyzed statistically to determine medians, ranges, and differences between aquifers (table 2).

The largest specific-capacity and hydraulic-conductivity values for the Qal aquifer were near Renton and near Auburn (plate 3C). Qal in these areas includes the coarse, highly permeable fan deposits discussed earlier in the Hydrogeologic Framework section of this report. The lower values for wells drilled along the northern and central parts of the Duwamish Valley reflect the finer grained character of the alluvium in a central and downvalley direction.

Because specific-capacity data were sparse for wells in the Qvr aquifer, no hydraulic conductivities were calculated. However, the sediments in this unit are likely to be lithologically similar to those grouped with Qal deposits buried beneath Auburn, and their hydraulic conductivities probably are high.

Specific-capacity and lateral hydraulic-conductivity data for the Qva and Q(A)c aquifers are shown on plates 3C and 3D, respectively. Where the aquifers exist as separate units, specific capacity increased roughly in

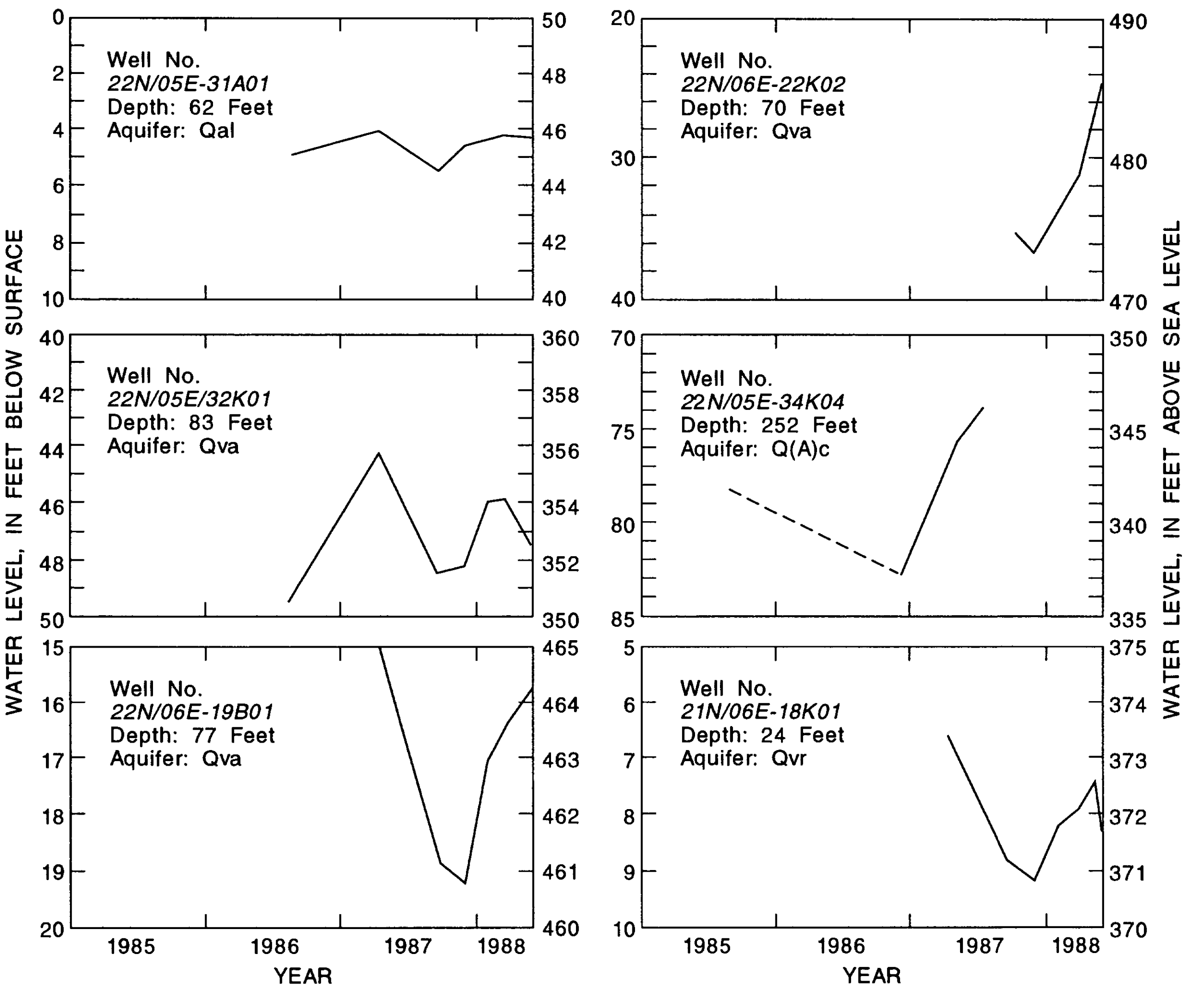
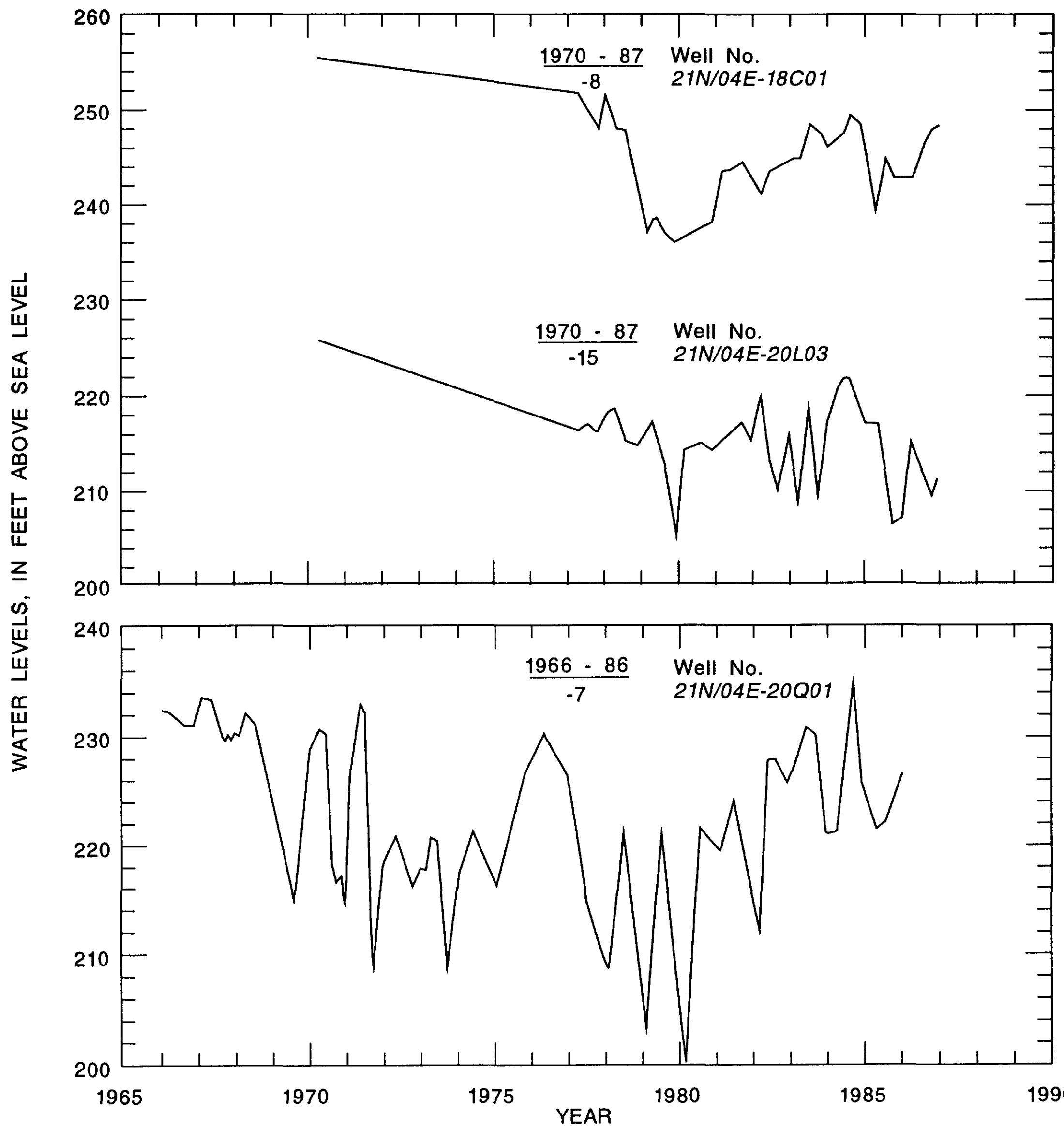


Figure 7.--Water-level fluctuations in selected wells measured during study. (Hydrographs from Pacific Ground Water Group)



EXPALANTION

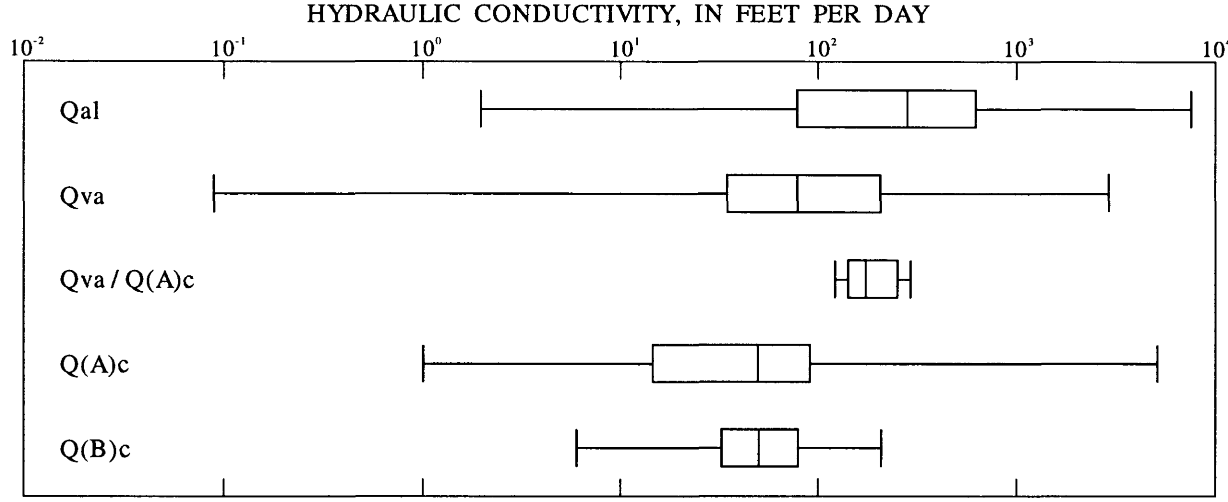
1966 - 86 — Period of water-level information

-7 — Net water-level change, in feet, during period

Figure 8.--Water-level changes for wells in the Federal Way area completed in the Qva/Q(A)c aquifer.

Table 2.--*Statistical analyses of hydraulic-conductivity values for the Quaternary aquifers in southwestern King County. (A) Box plots of, and (B) values of range and quartiles for hydraulic conductivity for all wells and for each aquifer; and (C) matrix of confidence levels for difference in median hydraulic conductivity between aquifers*

(A)



(B) HYDRAULIC CONDUCTIVITY, IN FEET PER DAY

Aquifer	Quartiles					Cases
	Low	25	50	75	High	
Qal	2	78	290	613	7,569	51
Qva	0.09	36	83	216	2,990	68
Qva / Q(A)c	127	141	174	261	298	6
Q(A)c	1	15	51	92	5,174	74
Q(B)c	6	33	51	80	201	19

(C)

	Qal	Qva	Qva / Q(A)c	Q(A)c	Q(B)c
Qal					
Qva	100				
Qva / Q(A)c	36	95			
Q(A)c	100	100	100		
Q(B)c	100	96	100	8	

proportion to the thickness of the aquifer units. The relation between thickness and specific capacity was demonstrated for the Qva aquifer by a statistical comparison of specific-capacity data in the thickest parts of the aquifers (the shaded areas on plate 3C) with data from the rest of the aquifers. The results of a nonparametric Mann-Whitney test showed that the median value of specific capacities in the thickest parts of Qva was significantly higher than those outside, at a 99-percent level of confidence. These statistical results could merely indicate increased transmissivity due to increased thickness without a significant increase in hydraulic conductivity. However, it is also possible that these areas of increased thickness exhibit increased hydraulic conductivity, a concept that should be tested with additional work. Data from such work possibly could be useful in the search for high well yields and could be important to understanding steady-state and transient flow in the Pleistocene deposits. For the Q(A)c aquifer (plate 3D), median specific capacities also were higher in zones of thicker deposition, but the statistical confidence was only 57 percent. The lower confidence level may be due to less accurate thickness maps because of sparser well control data. The correlation of higher specific-capacity values with sections of thicker sediments also was found in Island County (Sapik, 1989). Specific-capacity and lateral hydraulic-conductivity data for the Q(B)c aquifer are not shown in map format because of the paucity and poor distribution of that data.

Results of the statistical analyses of hydraulic conductivity for the major aquifers are shown on table 2; the median hydraulic conductivities for the aquifers generally decrease with depth and age. A nonparametric Mann-Whitney evaluation of the confidence levels for differences between median values of hydraulic conductivity for all aquifers is presented in table 2c. In general, probabilities above 95 percent indicate that the median values are significantly different and that the sediments and depositional processes of the respective aquifers were significantly different. From this matrix, it is apparent that the Qal and Qva/Q(A)c aquifers are similar and that the Q(A)c and Q(B)c aquifers are similar.

No data were available to estimate the vertical hydraulic conductivity of aquifers or confining units. Theoretical vertical hydraulic conductivities of the confining units, which are composed chiefly of glacial till and interglacial silts and clays, are 10^{-1} to 10^{-7} ft/d (Freeze and Cherry, 1979) and probably have a great deal of lateral variability over short distances.

GENERALIZED GROUND-WATER BUDGET

A water-budget analysis for a ground-water system typically would include measurements or estimates for all inputs (recharge) and outputs (discharge) to the system under study, as well as estimates of the change in storage. This analysis can be done as a lumped-parameter estimate (Domenico, 1972) for the system as a whole, or it can involve a distributed-parameter analysis in which the distribution and rate of flux and change for recharge, discharge, and storage are described in three dimensions across the entire area.

The predominant elements of a generalized ground-water budget for the study area were examined. The bulk of the recharge to the ground-water system is derived from the infiltration of precipitation, and the distribution and average rate of annual recharge solely from precipitation has been estimated. Recharge from any other natural or human-induced sources was not determined. Discharge from the ground-water system occurs as baseflow to streams and as springflow, seepage along bluffs, withdrawals from wells, evapotranspiration, and underflow (submarine seepage) to Puget Sound. Distributed-parameter estimates of annual stream discharge (baseflow) were made for some streams at selected points and of annual well discharge (pumpage) at selected points (major high-capacity wells). Additional lumped-parameter estimates were made of annual well discharge (pumpage) from domestic wells for the whole area and of the annual rate and distribution of spring and diffuse seepage-face discharge along major bluff areas. Annual baseflow discharge to the major rivers and submarine seepage to Puget Sound were not estimated, nor was the change in storage in any area over time. However, in order to improve the understanding of the relative magnitude of the ground-water-budget components in the study area, a more detailed analysis was done in a subset of the study area--the Big Soos Creek ground-water basin. A discussion of this water budget is presented at the end of this section.

Recharge

Natural recharge to the aquifer system is largely from the infiltration of precipitation and, to a lesser degree, from the infiltration from some of the streams, lakes, and wetlands. In order to estimate natural recharge from precipitation, a computer model was used to estimate the amount and the spatial distribution of that type of recharge in selected basins in the project area. Recharge from precipitation for the remainder of the study area was estimated using regression equations based on the model results.

The deep-percolation model (DPM) used in this study initially was designed for application in eastern Washington to estimate ground-water recharge from precipitation (Bauer and Vaccaro, 1987; 1990). The DPM is a grid-based model that computes daily deep percolation below the root zone for each grid block within a basin, and then accumulates the daily values to provide estimates of monthly, annual, and long-term average annual values. The DPM functions as a collection of subroutines that simulates the physical processes that control recharge rates, such as soil-moisture accumulation, evaporation from bare soil, plant transpiration, surface-water runoff, snow accumulation and melt, and accumulation and evaporation of intercepted precipitation. Daily changes in soil moisture, plant interception, and snowpack are computed and accumulated by the model; deep percolation below the root zone is computed when soil moisture exceeds field capacity. Bauer and Vaccaro (1990) used the average annual values of deep percolation as estimates of the distribution of long-term average annual recharge rates. Likewise for this study, average annual values of deep percolation calculated by the DPM for selected basins in southwestern King County have been used as estimates of ground-water recharge from precipitation.

For the application of the DPM, "surface-water runoff" refers to that part of rainfall or snowmelt that quickly runs off the surface of a modeled grid block; the term is equivalent to "overland flow" as defined by Chow (1964). Surface-water runoff for each block is computed by apportioning the difference between stream discharge from the basin (as measured at a gaging station) and baseflow to the stream (as estimated by hydrograph separation), in direct proportion to a hypothetical runoff value calculated by the U.S. Soil Conservation Service (SCS) curve-number method modified by Wight and Neff (1983). Some of the aforementioned subroutines were modified to better represent the particular characteristics found in a specific area.

Dinicola (1990) constructed rainfall-runoff models for the Big Soos Creek Basin and for other areas in southwestern King County. Most of the basic data for precipitation and runoff used for our DPM came from Dinicola. Results of the rainfall-runoff models were compared with the results of the DPM derived for this study area. Although the procedures used by Dinicola differ somewhat, the overall basin assessments of runoff, actual evapotranspiration, and recharge were similar.

The recharge model (DPM) was run for the Big Soos Creek Basin and for seven smaller basins in the Federal Way area--East Hylebos, West Hylebos, Lakota Creek, Joes Creek, an unnamed creek near the Redondo Shores development (Redondo #1), an unnamed creek near Redondo Heights Condominiums (Redondo #2), and an unnamed creek at Salt Water State Park (see fig. 9). More than 20 years of discharge data (1967-87) are available for Big Soos Creek, but only 1 year (1987) of discharge data is available for the smaller basins in the Federal Way area. Only the annual recharge rates were computed for these smaller basins using the DPM. Long-term recharge for the study area outside of the Big Soos Creek Basin was estimated using regression equations developed from the DPM model input and results for the Big Soos Creek Basin.

Weather and streamflow data were obtained from National Weather Service (NWS) and USGS records, respectively, and were interpolated to each grid block. Surface-water runoff from each block was determined from the discharge data, baseflow estimates, and an apportioning factor computed from equations developed by the SCS. Other data were assigned to blocks by overlaying the grid system onto appropriate maps. For example, soil data were obtained from SCS publications (Snyder and others, 1973; Zirlauf, 1979; and U.S. Soil Conservation Service, 1986), and land cover was interpreted by the authors from aerial photographs and from land-use maps provided by King County. Soil and land cover for each grid block were coded by the predominant soil or land-cover type.

For southwestern King County, three changes were made in the program code of the DPM model to reflect local characteristics of runoff and vegetation.

(1) If a grid block had the Qvr aquifer at the surface (rather than the Qvt confining bed), then the model assigned zero units of surface runoff from that block. The assumption that Qvr sediments are quite permeable, and therefore capable of receiving water at rates that exceed precipitation rates, is derived from Dinicola's work (1990) in the area.

(2) The calculation of potential plant transpiration for forest and grass in each grid block was changed so that the maximum Blaney-Criddle crop coefficient (for alfalfa) was used for the entire year. This change led to higher plant transpiration and lower (more conservative) recharge values.

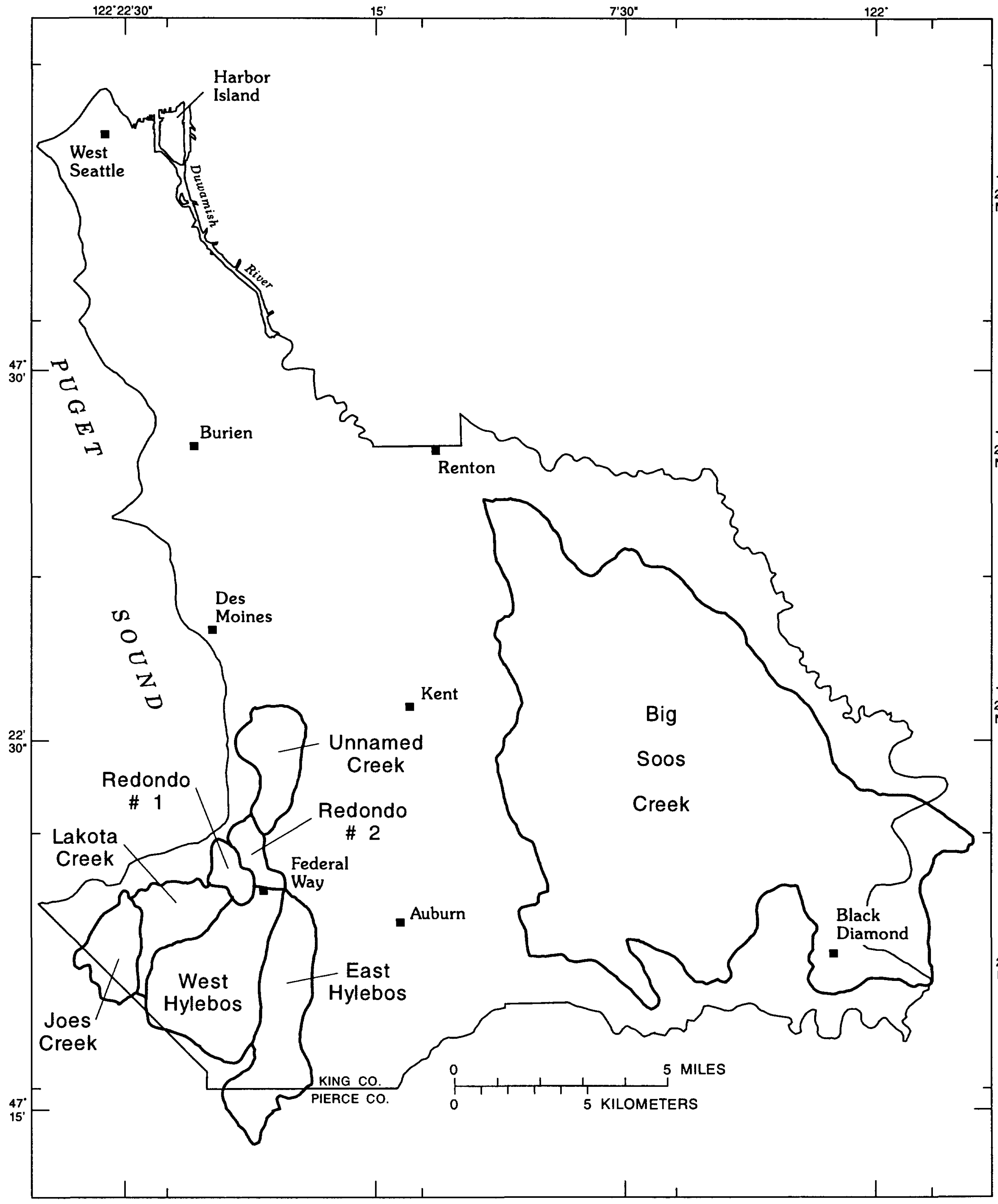


Figure 9.--Location of basins modeled for recharge determinations.

(3) If the block consisted of poorly drained soils--a Class D soil defined by the U.S. Soil Conservation Service (1986) as having a high runoff potential--or consisted of a lake, then most of the precipitation falling on that block was assumed to run off, with little available for recharge. In these cases, the SCS apportioning factor was raised so that more runoff was generated from these blocks by the model than would have been allowed based solely on soil characteristics.

The results of the modeling are shown in table 3, and the distribution of recharge in the modeled basins is presented on plate 4A. The block size used in most of the basins was a 500-foot square, but a 1,320-foot square was used in the Big Soos Creek Basin to limit the computing time during simulations to a reasonable level. The authors believe that the larger blocks still provided reasonable definition of input data and accuracy of model results.

To extrapolate model results to unmodeled areas, regression equations were developed using data and model results from the Big Soos Creek Basin for the period 1967-87. The independent variables for the regression analyses were annual precipitation, available water capacity of the soil, land cover, and soil type (outwash or till). These data were tested for linearity using a least-squares analysis (SAS Institute, Inc., 1985a); the regression equations also were derived from SAS procedures (SAS Institute, Inc., 1985b). Because land use and soil type are considered class (or nonparametric) variables, a separate regression equation was computed for each combination of land use and soil type. The regression equations for each of these combinations are shown in table 4. Some land covers in the Federal Way area are absent in the Big Soos Creek Basin. To obtain an equation in these cases, simple ratios based on model-computed recharge values were used to adjust the regression equations.

The unmodeled areas in southwestern King County were gridded into 1,320-foot square blocks, and annual precipitation, land use, and soil type were determined and coded for each block in the same manner that was used for the modeled areas. In some areas, however, estimates of available water capacity were based on interpretations of available maps of surficial geology (Liesch and others, 1963; and Luzier, 1969) and the types of soils normally associated with the geologic units in those areas. In the Green/Duwamish Valley, equations derived for outwash were used to estimate recharge because information from modeled alluvial basins was unavailable for extrapolation. Use of the outwash equations assumes zero runoff, which is reasonable given the low slopes and sandy soils in the valley. However, during heavy rainfall the lower parts of the valley become saturated to land surface, and for short periods of time all additional precipitation runs off in these areas. No reasonable algorithm could be constructed to simulate this phenomenon.

The recharge values for each block were averaged to give an annual recharge value for the entire basin for a particular year. The long-term recharge then was computed as the average of the annual recharge values.

The equations were evaluated by comparing the regression-based recharge for 1987 with the DPM-based recharge for the same year (table 5). In all but two basins, the recharge calculated from the regression equations was less than that calculated by the DPM. One possible reason for this difference is that the DPM uses daily values of precipitation and air temperature in its computation of recharge, whereas the regression equations use an annual precipitation value. Depending on when precipitation occurs, more recharge may result than at other times, and only the DPM can account for these temporal variations.

Long-term average annual recharge values, calculated by using the regression equations, also are presented in table 5 for the seven Federal Way basins that were modeled. These values ranged from 12.1 inches in the unnamed basin near Redondo (Redondo #1) to 18.3 inches in the Joes Creek Basin. For the remaining basins in the study area that were not modeled, long-term average annual recharge was calculated by regression equations to be 16.6 inches.

The distribution of long-term average annual recharge based on regression equations (plate 4B) can be divided roughly into three areas: (1) an area of high recharge rates (20 to more than 35 inches per year) in the eastern part of the study area, (2) an area of intermediate recharge rates (15 to 20 inches per year, with a few areas of 25 to 30 inches per year) primarily in the east-central and central parts of the study area, and (3) an area of low recharge rates (10 to 20 inches per year) along the western edge of the study area. The distribution of recharge shown on plate 4B reflects both the distribution of precipitation and the combined effects of soil characteristics, surficial geology, and land cover.

As mentioned previously, precipitation generally increases in an easterly direction as land-surface elevation increases in the foothills of the Cascade Range; therefore, more water becomes available for recharge. However, this straightforward relation is modified by other factors. Comparison of figure 1 (the distribution of soil associations) with plate 4B (the distribution of recharge) shows

Table 3.--*Results of recharge model runs for eight basins in southwestern King County*

[All units are in inches unless otherwise noted]

1	2	3	4	5	6	7	8	9	10	11	12	13
Basin	Area, in square miles	Precipi-tation	Surface-water runoff[1]	Base-flow[2]	Recharge	Actual soil evapo-ration	Subli-mation	Actual plant transpi-ration	Evapo-ration of inter-cepted moisture	Change in total soil moisture	Actual evapo-transpi-ration[3]	Error[4]
Big Soos Creek[5]	65.8	47.80	8.99	17.03	20.61	0.46	0.06	5.36	13.39	0.00	19.27	-1.07
East Hylebos[6]	5.89	32.82	8.06	4.13	10.54	.45	.02	5.67	8.53	.06	14.67	-.51
West Hylebos[7]	7.53	33.00	5.15	9.46	11.80	.37	.01	4.79	11.54	.03	16.71	-.69
Lakota Creek	2.19	33.01	2.92	11.03	15.83	.42	.02	6.73	7.54	.01	14.71	-.46
Joes Creek	2.53	33.31	6.86	21.25	13.90	.24	.01	6.07	7.03	.13	13.35	-.93
Redondo #1[8]	1.10	32.68	3.01	8.96	14.49	.32	.03	6.56	8.65	.04	15.56	-.42
Redondo #2[9]	.82	32.56	4.16	10.44	11.91	.27	.03	5.52	11.19	.04	17.01	-.56
Unnamed Creek (Saltwater State Park)	2.94	32.17	7.59	7.38	9.82	.35	.03	5.07	10.18	.04	15.63	-.91

[1] Surface-water runoff is the total surface-water runoff for all grid blocks in a basin. Surface-water runoff is the difference between stream discharge measured at a gaging station and baseflow that has been apportioned to each grid block in direct proportion to a computed, hypothetical runoff value derived from a method developed by the U.S. Soil Conservation Service (Wight and Neff, 1983).

[2] Baseflow is obtained by hydrograph separation.

[3] Actual evapotranspiration is the sum of columns 7 through 10.

[4] The error is the difference between the amount of precipitation (column 3) and the sum of column 4 and columns 6 through 11.

[5] Twenty-one years of data are available for Big Soos Creek (1967-87). Only 1 year of data (1987) was available for the other basins.

[6] Hylebos Creek upgradient of 5th Avenue, in Milton, Washington.

[7] West tributary to Hylebos Creek.

[8] Unnamed creek near Redondo Shores development.

[9] Unnamed creek near Redondo Heights condominium.

Table 4.--*Regression equations derived from data for Big Soos Creek Basin (1967-87) to compute long-term average recharge*

[rech, recharge; ppt, precipitation; and awc, available water capacity]

Soil type	Land cover	Equation
1. outwash	coniferous forest	rech = -9.79+0.896(ppt)-4.93(awc)
2. outwash	grass	rech = -8.27+0.887(ppt)-4.94(awc)
3. outwash	barren	rech = 2.495+0.972(ppt)-26.5(awc)
4. till	coniferous forest	rech = -3.091+0.551(ppt)-6.73(awc)
5. till	grass	rech = -1.57+0.542(ppt)-6.75(awc)
6. till	barren	rech = 9.195+0.627(ppt)-28.3(awc)
(The following equations have been adjusted based on ratios of model-computed recharge in the Federal Way area)		
7. outwash	deciduous forest	rech = 0.917[-9.79+8.96(ppt)-4.93(awc)]
8. till	deciduous forest	rech = 1.16[-3.091+0.551(ppt)-6.73(awc)]
9. till	row crops	rech = 0.975[-3.091+0.551(ppt)-6.73(awc)]
10. outwash	row crops	rech = 0.975[-9.79+0.896(ppt)-4.93(awc)]

Table 5.--*Comparison of recharge values derived from regression equations and recharge values calculated by the deep percolation model (DPM)*

[All units are inches; --, no data]

	1987 recharge		
	From regression equations	From DPM	Long-term annual recharge (21 years)
Big Soos	13.6	14.9	[1]20.6
East Hylebos[2]	10.9	10.5	13.9
West Hylebos[3]	10.5	11.8	11.9
Lakota Creek	13.0	15.8	15.8
Joes Creek	14.0	13.9	18.3
Redondo #1[4]	12.0	14.5	15.2
Redondo #2[5]	9.7	11.9	12.1
Unnamed Creek (Saltwater State Park)	9.5	9.8	12.4
Green River (between Auburn and Tukwila)	14.8	[6]--	18.6

[1] Long-term recharge for Big Soos Basin calculated by DPM; long-term recharge for all other basins derived from regression equations.
[2] Hylebos Creek Basin upgradient of 5th Avenue, in Milton, Washington.
[3] West tributary to Hylebos Creek.
[4] Unnamed creek near Redondo Shores development.
[5] Unnamed creek near Redondo Heights condominiums.
[6] Insufficient data exist to allow the DPM model to be run for this reach of the Green River.

the effects of soil characteristics. The Everett soil association in figure 1 is described by Snyder and others (1973) as highly permeable, a condition associated with relatively rapid infiltration of water. This association corresponds to the area of high recharge on plate 4B. The intermediate and low recharge areas on plate 4B correspond to the Alderwood and Oridia-Seattle-Woodinville associations, respectively (fig. 1). These soil associations exhibit moderate to moderately low permeability and a high available water capacity. The distribution of the soil associations is determined largely by geology.

The distribution of recharge is affected further by the extent and degree of land development within the study area. Areas of high and intermediate recharge occur in regions where land development is sparse to moderate. These areas include forests, grass lands, and suburban areas with a large percentage of permeable land surface. Areas of low recharge occur where land development includes a larger percentage of impermeable surfaces such as roads and sidewalks. Areas of low to no recharge (0 to 5 inches on plate 4B) include those regions where most, if not all, of the land surface is impermeable (such as shopping centers, industrial areas, major highways, and, as mentioned previously, surface-water bodies). However, due to the method used in assigning values to land cover, a block showing little or no recharge may include small areas where some recharge does occur.

Areas of higher relative recharge commonly are singled out for protection from land-use activities that might degrade the quality of ground water. The relative patterns of high, intermediate, and low recharge rates inferred on plate 4B could be used to identify areas that are susceptible to degradation. The highest recharge rates are in the eastern part of the study area where precipitation is relatively high and soils developed on the Qvr unit have low water-holding capacity and high infiltration rates. These areas overlie aquifers that are relatively sensitive to pollution. Conversely, many of the low recharge values on plate 4B are in areas underlain by till where aquifer vulnerability is likely to be lower. Intermediate relative recharge rates are associated with the valley fill within the Green/Duwamish Valley. Thus, the recharge map could be used in conjunction with programs such as DRASTIC (Aller and others, 1985) that evaluate aquifer vulnerability.

Some of the minimum-recharge (0 to 5 inches) blocks on plates 4A and 4B are associated with lakes and wetlands (class D soils) where model assumptions force most of the precipitation to run off. In like manner, other minimum-recharge blocks are associated with high-density population areas that are largely paved and where model assumptions again force most of the precipitation to run off.

The recharge estimates discussed thus far are based largely on natural factors. Consequently, they do not include recharge from septic-tank leachate, dry-well infiltration, irrigation, influent streams, or from lakes. Each of these sources of recharge is potentially important in some areas, but a quantitative evaluation of these sources was outside the scope of this study.

Discharge

Flow from the ground-water system into the surface-water system constitutes a large part of the discharge side of the water budget. In addition, pumping of ground water from a number of high-capacity wells and through many small well fields and domestic wells is included as discharge.

Data necessary to determine natural discharge to Puget Sound above the saltwater interface are not available. Also, data are inadequate to evaluate baseflow to the Green/Duwamish Rivers. However, baseflow to some streams draining the drift plains, ground-water evapotranspiration, and springflow across the seepage faces along bluffs surrounding these drift plains have been estimated. In addition, data exist to quantify most of the ground-water pumpage within the study area.

Baseflow from the eight basins modeled with the DPM (table 3) was derived by hydrograph separation. In all except for Joes Creek Basin, baseflow was less than the calculated long-term annual recharge for the basin. This indicates that for Joes Creek Basin, either ground-water underflow from adjacent basins is recharging Joes Creek Basin through the Qvr aquifer that is prevalent along the basin boundaries, or that ground-water storage in Joes Creek Basin decreased, or both.

In a broader sense, regionalized results from the rainfall-runoff modeling within the present study area, and within similar Puget Sound Lowland basins just north of the study area (Dinicola, 1990), provide insights about baseflow in Puget Sound drift-plain environments. Dinicola (U.S. Geological Survey, written commun., 1989) related the amounts of runoff/interflow and baseflow to various combinations of geology (till/outwash), vegetation (forest/grass), slope, extent of wetlands, and extent of impervious surface. Because basins comprise different mixes of these elements, baseflow will vary and, in many cases, will require sophisticated models for its measurement. In general, Dinicola (1990) found that forest cover produced lower runoff/interflow and higher baseflow than grass cover, and that areas underlain by till produced much higher runoff/interflow and lower baseflow than those areas underlain by outwash (table 6). To illustrate this, two of Dinicola's hydrographs of unit runoff, one from a predominantly forested till terrain and the other from a predominantly forested outwash terrain, are shown in figure 10. The hydrograph of the outwash basin is much smoother, has smaller peak flows, and has less runoff.

Table 6.--*Unit runoff data showing annual values of runoff and baseflow for till and outwash basin segments (from Dinicola, 1990), expressed as a percentage of the annual precipitation (1985-86 data)*

Basin segment	Runoff and interflow	Baseflow
Till, forested	22 percent	29 percent
Till, grassed	40 percent	20 percent
Outwash, forested	0 percent	56 percent
Outwash, grassed	0 percent	63 percent

Springflow and Seeps Along Bluffs

Locations of known spring discharge are shown on figure 11. The springs include those inventoried by Luzier (1969) in the early 1960's and additional springs recorded in USGS data bases.

Total discharge across the seepage faces along bluffs was estimated for six bluff segments (see table 7). These estimates are based on discharge measurements and qualitative discharge descriptions by Luzier (1969) during 1960-63. The bluff segments (see fig. 11) are (1) the coastal bluffs, at the western edge of the Des Moines Plain; (2) the eastern edge of the Des Moines Plain, from the King County line to Renton; (3) the western edge of the Covington Plain, from Big Soos Creek to Renton; (4) the southern edge of the Covington Plain, from Big Soos Creek to the eastern edge of the study area; (5) the northern edge of the Covington Plain, from Renton to the south line of T.23 North; and (6) the northeastern edge of the Covington Plain, from the south line of T.23 North to the eastern edge of the study area. The spring discharge, which is irregularly distributed, comes mostly from a few scattered springs whose locations probably are controlled by local stratigraphy. The first three segments have similar discharge rates, and the fourth and sixth segments have much lower discharge rates than the first three. Luzier (1969) found no flow along the fifth segment, and this may be related to the presence of a bedrock ridge just south of the east-west-trending bluff, which probably diverts flow away from the bluff face.

Table 7.--*Estimate of inventoried springflow along six bluff segments in southwestern King County*

		Estimated discharge		Estimated discharge per mile	
Bluff segment and number[1]	Segment length (miles)	(cubic feet per second)	(gallons per day)	(cubic feet per second per mile)	(gallons per day per mile)
1. Coast, west edge of Des Moines plain	15.1	2.61	1.69×10^6	0.17	1.12×10^5
2. East edge, Des Moines plain	15.0	3.99	2.58×10^6	.27	1.72×10^5
3. West edge, Covington plain	12.6	2.97	1.92×10^6	.24	1.52×10^5
4. South edge, Covington plain	9.2	.07	4.3×10^4	.01	4.67×10^3
5. North edge, Covington plain	9.0	0	0	0	0
6. Northeast edge, Covington plain	8.5	.06	3.7×10^4	.01	4.35×10^3

[1] See figure 11 for locations.

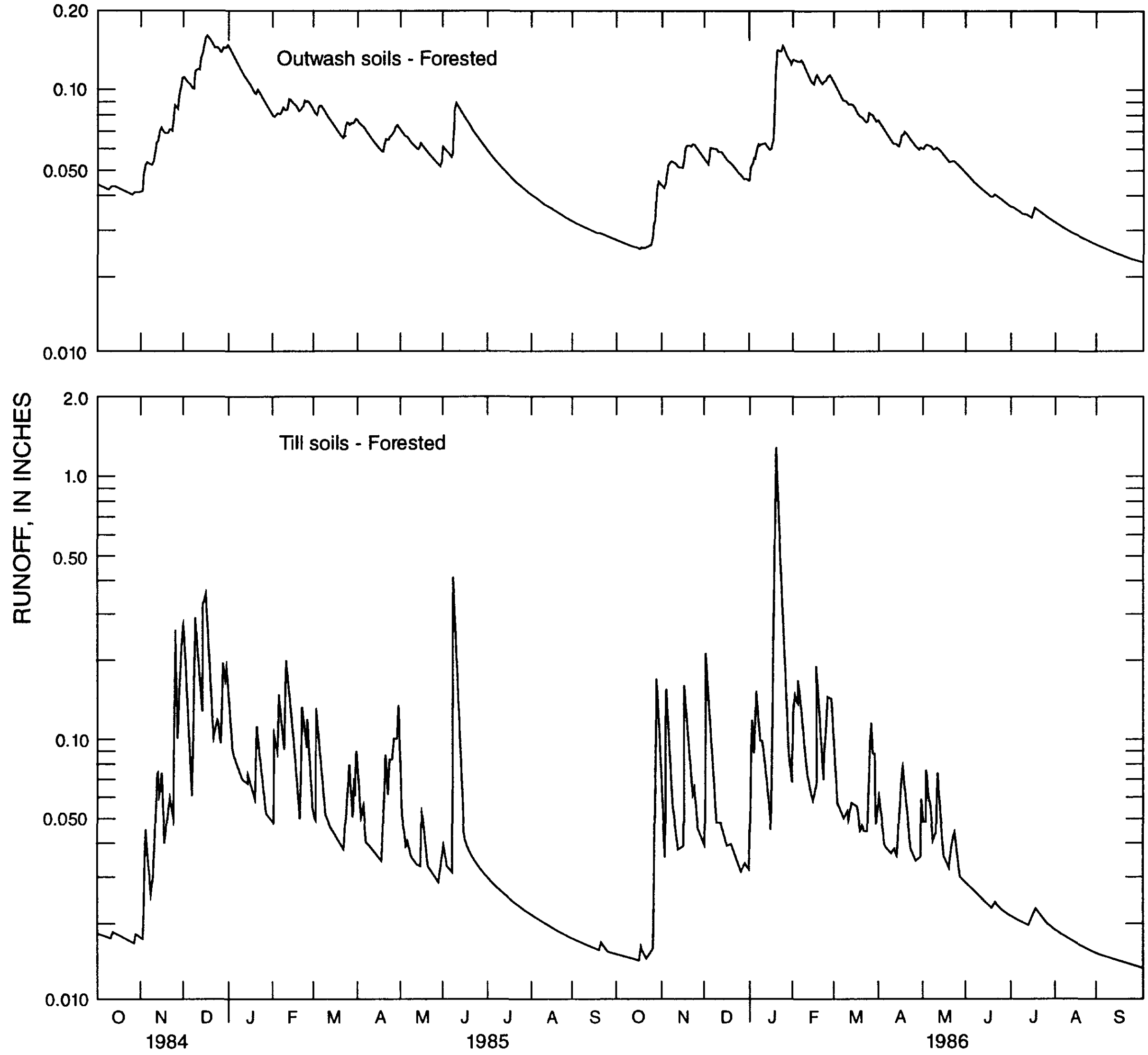


Figure 10.--Unit runoff for outwash and till terrains (Dinicola, 1990).

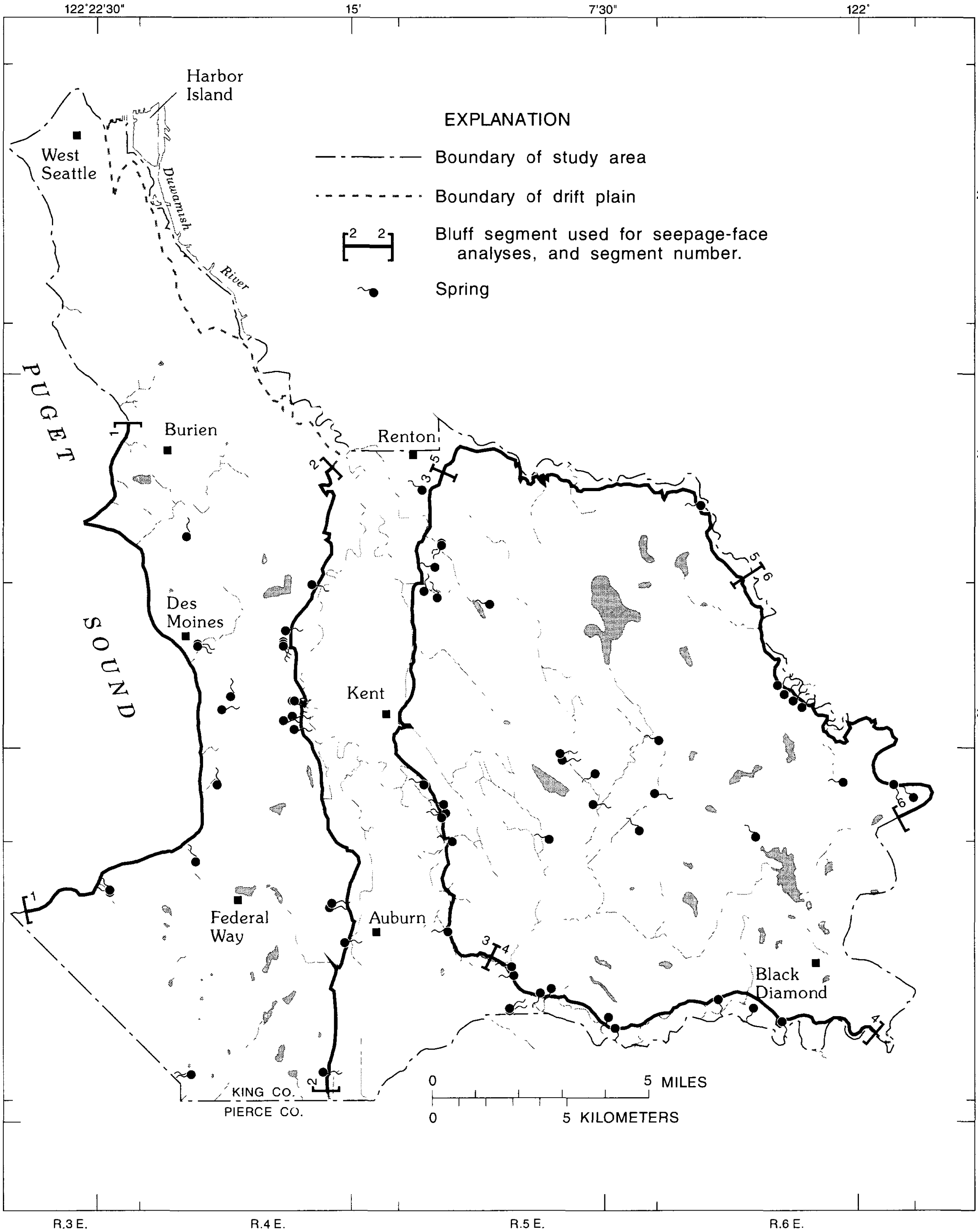


Figure 11.--Location of springs and seepage-face segments.

In addition to discharge by discrete springs, diffuse discharge also occurs from seepage faces along the bluffs; this discharge is important but difficult to measure in an inventory such as Luzier (1969) carried out. One method to assess this diffuse discharge is to estimate a minimum seepage rate based on the potential evapotranspiration (PET) rate for the area and the surface area of the bluffs. An estimated 25 percent of the bluff area is wet or is covered by vegetation whose roots tap water from saturated rock; that is, 25 percent of the bluff section transmits water to the atmosphere. PET is estimated to be about 27 inches per year (fig. 2), and assuming that water discharges along the wet portions of the seepage face at least at the rate of PET and that the bluffs average about 350 ft in height, then 0.03 ft^3/s of diffuse discharge is taking place along each mile of bluff wall. This is a minimum rate of flux and is possibly much lower than the actual rate.

Well Withdrawal and Water Use

Water use, as discussed in this report, refers to that water utilized for public-supply, domestic, irrigation, commercial, industrial, and institutional purposes. Although surface-water sources supply some of the water for these purposes in southwestern King County, most of the water is supplied by ground-water sources. Of the 459,600 people estimated to have resided in the study area during 1986, only those 138,700 people living in the south Seattle area had their household water needs supplied by surface water; the remaining 70 percent of the population, about 320,900 people, was supplied by ground water--either from public-supply wells or from private, individual wells.

A summary of all ground water withdrawn from the study area during 1986 (table 8), compiled by use category, indicates that approximately 13,221 million gallons (Mgal) was withdrawn and that about 97 percent (12,793 Mgal) of that total was used for public-supply and domestic purposes. Slightly less than 3 percent (389 Mgal) of the total ground water withdrawn during 1986 was used for irrigation, and the remaining 40 Mgal was used for commercial, industrial, and institutional purposes.

The locations of the 163 high-capacity wells known to withdraw water from Quaternary aquifers for public-supply (including the one institutional well), irrigation, and commercial/industrial purposes are shown on plate 4C, along with the volume of water withdrawn in 1986. Where these high-capacity wells are close together, only one approximate location is shown for the well group.

Table 8.--*Summary of ground-water withdrawals in southwestern King County during 1986, by water-use category*

[--, no data available]

Water use	Withdrawal (million gallons)	Percent of total withdrawal	Population served
Public supply	9,013.8	68.2	[1]217,320
Private domestic	3,779.2	28.6	[1]103,540
Irrigation	389.1	2.9	--
Commercial[2]	38.6	.3	--
Industrial[2]	1.0	.007	--
Institutional[2]	.4	.003	--
Totals	13,221.1	100	[1]320,860

[1] Estimates based on extrapolation of population projections by the Puget Sound Council of Governments (1987).

[2] Most commercial, industrial, and institutional water users in the study area are supplied by public water systems; withdrawals presented here are supplied by private wells.

Few of these wells are located in the northern part of the drift plains. Determining the number and location of private domestic wells was beyond the scope of this study.

Ground-water withdrawals during 1986 from high-capacity wells only are included in table 9, accumulated for each hydrogeologic unit. During that year, the Qal, Qva, and Q(A)c aquifers supplied 34, 27, and 18 percent, respectively, of the ground water withdrawn by high-capacity wells in the study area. All other aquifers each supplied 10 percent or less of the ground water withdrawn.

Water Budget for Big Soos Creek Basin

The water budget for the Big Soos Creek Basin was analyzed in detail in order to gain a better understanding of the water budget of the entire study area. The basin is the most appropriate to study in detail because much is known about its surface-water budget. In this analysis, the basin was considered to be lumped; that is, the quantities of

Table 9.--*Summary of ground-water withdrawals during 1986 from public-supply/institutional, irrigation, and commercial/ industrial wells, by hydrogeologic unit*
[--, no data available]

Hydro-geologic unit	Number of wells	Withdrawal (million gallons)	Percent of total withdrawal	Withdrawals (million gallons) from: Public-supply/ institutional wells	Irrigation wells	Commercial/ industrial wells
Qal aquifer	41	3,247.0	34.4	3,120.3	86.8	39.9
Qvr aquifer	6	66.5	.7	4.4	62.1	--
Qva aquifer	60	2,509.4	26.6	2,378.7	130.6	.1
Q(A)f	2	48.5	.5	48.5	--	--
Qva/Q(A)c aquifer	6	812.2	8.6	805.8	6.4	--
Q(A)c aquifer	31	1,736.3	18.4	1,706.1	30.2	--
Q(B)f	2	16.2	.2	16.2	--	--
Q(B)c aquifer	12	976.4	10.3	933.8	42.6	--
Q(C)u	3	30.4	.3	--	30.4	--
Total	163	9,442.9	100	9,013.8	389.1	40.0

water in each component were summed for the basin as a whole, with no description of their areal (distributed) variation. The topographic boundaries defining the Big Soos Creek Basin are shown in figure 12, along with the exit point for surface-water flow at a stream-gaging station. Shallow ground-water divides are assumed to coincide with the surface-water divides along the southern, western, northwestern, and northern topographic boundaries. Some shallow ground water may recharge the basin from the east and southeast. There may be deeper, intermediate-system ground-water underflow into the basin from the northeast, and deep underflow out of the basin to the south and southwest.

A diagrammatic sketch of the distribution of water in the water budget for the Big Soos Creek Basin is shown in figure 13. The average annual volumes of flux in the basin during the 21-year period (1967-87), as estimated for four budget components by the Bauer-Vaccaro DPM (1987), are shown in the DPM equation below. Values are in inches.

$$PRECP = SRO + ET + RECH \pm ChangeSTOR \pm ERROR,$$

$$47.8 = 8.99 + 19.27 + 20.61 + 0 + 1.07 \qquad (1)$$

The error term, explained in the DPM documentation (Bauer and Vaccaro, 1987), is an artifact of the inaccuracies inherent in modeling complex hydrologic systems.

Results of the DPM model run for the Big Soos Creek Basin indicate that of the 20.61 inches of recharge (table 3) to the surficial till (the Qvt unit) and recessional outwash (the Qvr unit), about 17.0 inches--or about 80 percent--is returned to the streams within the basin as baseflow and is carried out of the basin as surface outflow. Assuming no change in shallow ground-water storage, the remaining 3.6 inches of recharge water moves from the Qvt and Qvr surficial units as downward flow to deeper glacial aquifers, or as underflow across the basin boundaries.

About 40 percent of the precipitation on the Big Soos Creek Basin becomes ground-water recharge and 40 percent becomes evapotranspiration; the remaining 20 percent becomes overland flow. As discussed in the recharge section, the distribution of precipitation after it reaches the earth is primarily a function of the distribution of Qvt and Qvr units at land surface. Another basin of similar size and similar distributions of precipitation, vegetation, and land use, but with a different surficial geology could have markedly different values of ground-water recharge, evaporation, and overland flow. In like manner, if land use and

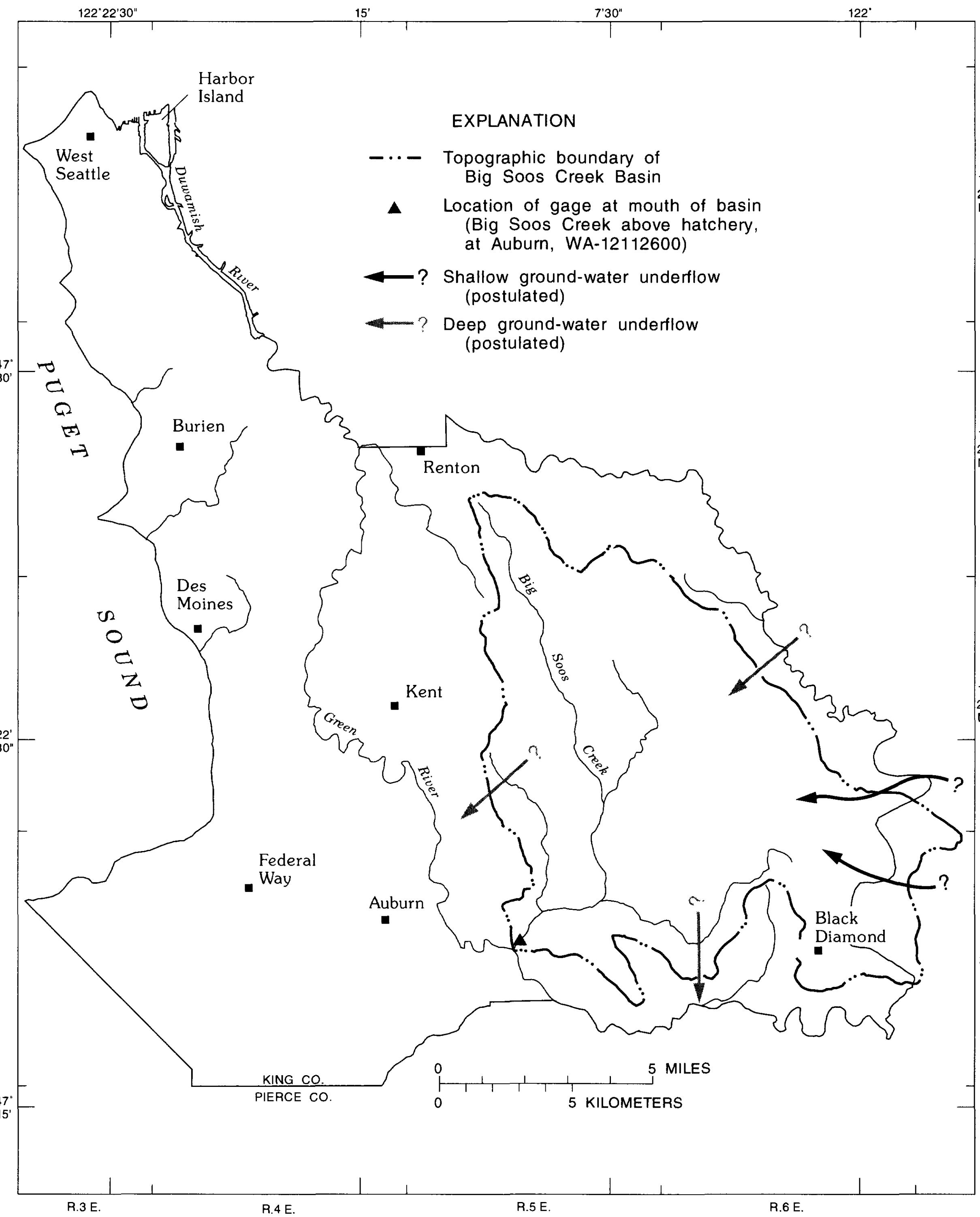
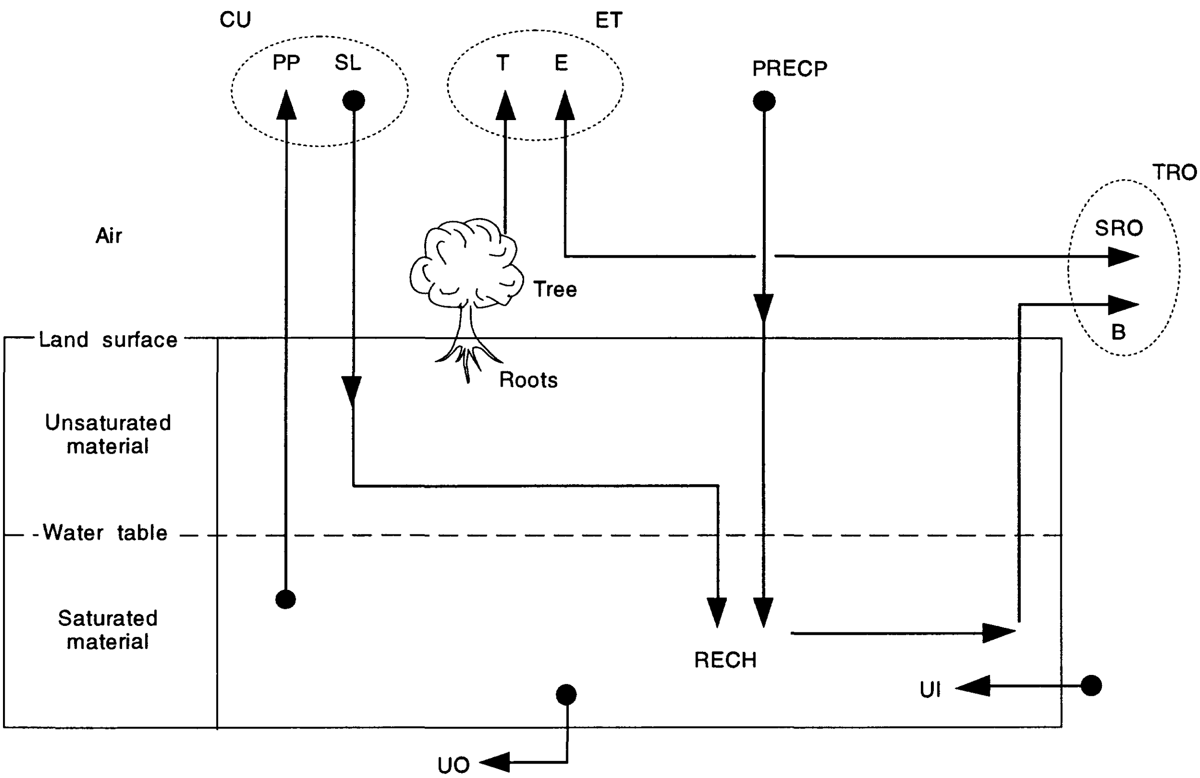


Figure 12.--Topographic boundary of Big Soos Creek Basin.



EXPLANATION

INTO BASIN
- PRECP = Precipitation
- UI = Ground-water underflow, in

OUT OF BASIN
- SRO = Surface-water runoff
- B = Baseflow (from ground-water system)
- TRO = Total surface-water flow (SRO+B)
- E = Evaporation from surface-water sources
- T = Transpiration from plants
- ET = Evapotranspiration (E+T)
- UO = Ground-water underflow, out
- PP = Ground-water pumpage
- CU = Consumptive use of pumped water (PP-SL)

RECH = Ground-water recharge
SL = Septic leachate as recharge
● = Point of origin, in or out of basin

Figure 13.--Diagram showing distribution of water in generalized water buget for Big Soos Creek Basin.

vegetation were significantly altered in the Big Soos Creek Basin through extensive urbanization, runoff probably would increase and recharge probably would decrease.

Ground water is pumped from the Big Soos Creek Basin at a rate of about 2 inches per year, most of which is used for domestic supplies. Most of the withdrawals are from aquifers below the Vashon till. Because only a small part of the basin is sewered, most of this deep pumpage returns to the shallow ground-water system as septic-tank leachate. Thus, the net or consumptive use is probably much less than 2 inches. Extended periods of intensive pumping from deep aquifers could lead to significant water-level declines in the deeper aquifers of Big Soos Creek Basin, increasing vertical head gradients across the Vashon till. This would increase downward flow from the shallow system and gradually would decrease springflow and baseflow to streams.

GROUND-WATER QUALITY

The quality and character of ground water in the Quaternary aquifers of southwestern King County were determined by studying the results of selected chemical and biological analyses. A total of 242 water samples from 217 wells was collected and analyzed for the presence of selected constituents. Water samples were collected from 125 wells in early autumn 1987 and from 117 wells in late winter 1988. In order to assess the magnitude of seasonal water-quality changes or fluctuations, 25 of the wells selected for sampling in 1988 had been sampled previously in 1987. Historical water-quality data were compared with those resulting from this study in order to detect long-term changes. Although water samples were obtained from all major aquifers, the number of samples taken from a particular aquifer reflected that aquifer's importance as a source of ground water; the more important aquifers were sampled more extensively. The criteria for well selection included broad geographic coverage and representation of diverse land-use activities at land surface above each aquifer. The locations of the sampling sites are shown by hydrogeologic unit on plate 4D. The individual results of the chemical analyses for inorganic constituents, including duplicate analyses, are listed by well and by hydrogeologic unit in table 20, at the end of the report, and are summarized by aquifer in table 10.

A review of the ground-water-quality statistics in table 10 indicates two important generalizations: (1) The quality of ground water in southwestern King County is good and is suitable for most intended purposes; and (2) the quality of water as represented by the median concentration or value of a variety of constituents is not appreciably different between the aquifers. Notable exceptions are dissolved oxygen, dissolved iron, dissolved manganese, and pH; these differences will be discussed later in this report. Because the quality of water in the Quaternary aquifers in the study area is relatively consistent, the following discussion of ground-water quality is structured on a constituent-by-constituent basis rather than on the aquifer-by-aquifer basis that has been followed thus far in this report. In most discussions of chemical data, the median is used in preference to the arithmetic mean (or "average"). The median is the middle value (or halfway point) when all values have been ranked in order of size; that is, half the values are larger than the median and half are smaller. The chief advantage of the median over the mean is that the median is less affected by a few extreme values. For the 25 wells that were sampled twice, only one value (that of the first sampling) was used to calculate the median. Likewise, multiple analyses from a single well are treated as a single analysis in the discussion of water quality because of their relative consistency.

General Character of Ground Water

The chemical character of water, or the water type, is determined by the relative amounts of major cations (positively charged particles) and anions (negatively charged particles) in the water. The principal cations in ground water are usually calcium, magnesium, and sodium; the principal anions are usually sulfate, chloride, and bicarbonate (commonly expressed as alkalinity). A summary of water types for the study area, by hydrogeologic unit, is presented in table 11. In general, calcium, magnesium, or both, are the dominant cations in the ground water and bicarbonate (alkalinity) is the dominant anion. The dominant ion was determined as the one that exceeded each of the others in its group by 16 percent or more. When no single ion was dominant but two ions greatly exceeded the rest, they were considered co-dominant. A few wells yielded water in which sodium was either dominant or co-dominant with calcium, but in all such cases bicarbonate was the dominant anion. Many of these wells were completed in the Qal and Q(B)c aquifers. The reason for the relatively higher proportion of sodium in the samples from these wells is unknown, but may be related to ground-water flow paths. In a study of ground water in the Columbia Plateau of eastern Washington, Bortleson and Cox (1986) observed a progressive decrease in calcium and magnesium in ground water along a particular flow path and a progressive increase in sodium. Although their study concentrated on the basalt aquifers of eastern Washington, the same geochemical reactions may occur in

Table 10.--*Ground-water-quality statistics in southwestern King County, by aquifer*

[Values are concentration medians and expressed in milligrams per liter except as noted; data ranges are in parentheses; all are dissolved concentrations]

Constituent	Aquifer						
	Qal	Qvr	Qva	Qva/Q(A)c	Q(A)c	Q(B)c	All
Specific conductance (microsiemens per centimeter, at 25°Celsius)	184 (51-712)	134 (104-227)	166 (66-465)	170 (156-237)	174 (70-480)	188 (152-290)	174 (51-712)
pH (units)	7.4 (6.2-8.8)	6.5 (6.2-7.6)	7.3 (6.1-8.4)	7.3 (7.2-8.0)	7.8 (6.8-9.1)	8.1 (6.1-8.7)	7.6 (6.1-9.1)
Dissolved oxygen	.6 (.1-6.4)	3.1 (.2-8.1)	1.8 (.0-9.9)	.5 (.0-2.4)	.9 (.0-9.9)	.4 (.1-.7)	1.0 (.0-9.9)
Hardness (as $CaCO_3$)	67 (17-310)	51 (36-75)	68 (13-170)	76 (63-98)	68 (4-150)	66 (48-92)	67 (4-310)
Calcium	17 (2.8-79)	13 (9.5-19)	15 (3.5-41)	14 (12-16)	16 (1.3-34)	17 (13-22)	16 (1.3-79)
Magnesium	5.7 (1.1-27)	4.6 (2.6-7.6)	7.3 (1.0-27)	10.2 (6.8-14)	6.8 (.3-19)	5.3 (3.1-8.9)	6.6 (.3-27)
Sodium	7.1 (2.9-67)	5.0 (3.7-9.7)	6.3 (3.5-47)	6.2 (5.9-8.3)	6.6 (2.0-29)	6.4 (5.9-46)	6.5 (2.0-67)
Percent sodium	18 (11-83)	17 (16-24)	16 (11-56)	15 (14-18)	16 (10-98)	23 (14-66)	16 (10-98)
Potassium	1.7 (.2-7.8)	.8 (.6-1.5)	1.6 (.4-7.3)	1.9 (1.5-2.8)	1.8 (.3-8.7)	2.4 (1.5-3.1)	1.7 (.2-8.7)
Alkalinity (as $CaCO_3$)	87 (20-229)	46 (28-80)	72 (17-190)	71 (69-74)	79 (27-224)	90 (73-139)	76 (17-229)
Chloride	3.3 (1.4-86)	4.2 (1.9-9.7)	3.1 (1.1-63)	5.0 (2.9-6.6)	2.2 (1.3-8.4)	2.7 (1.7-10)	2.9 (1.1-86)
Sulfate	7.2 (.6-27)	8.2 (3.1-11)	8.2 (.3-65)	13 (7.7-26)	6.5 (1.6-32)	7.5 (1.3-14)	7.7 (.3-65)
Nitrogen (NO_2 + NO_3)	<.10 (<.10-2.7)	1.4 (<.10-6.8)	.30 (<.10-6.4)	.14 (<.10-3.9)	<.10 (<.10-3.1)	<.10 (<.10-.10)	<.10 (<.10-6.80)
Fluoride	.1 (.1-.4)	.1 (.1-.1)	.1 (.1-2.1)	.1 (.1-.2)	.1 (.1-1.0)	.1 (.1-.2)	.1 (.1-2.1)
Silica	27 (12-53)	23 (18-31)	26 (10-44)	27 (30-41)	27 (7-53)	27 (18-36)	27 (7-53)
Iron (micrograms) per liter)	41 (<3-2,700)	26 (<3-2,800)	25 (<3-10,000)	11 (<3-190)	44 (3-4,399)	30 (15-310)	35 (<3-10,000)
Manganese (micrograms per liter)	25 (<1-800)	21 (<1-150)	19 (<1-810)	30 (<1-61)	70 (<1-1,000)	55 (23-310)	40 (<1-860)
Dissolved solids (residue at 180°C)	127 (38-415)	93 (65-151)	104 (44-303)	124 (102-159)	114 (59-271)	123 (106-186)	114 (38-415)
Number of samples	35	7	93	4	56	11	[1]206

[1] Does not include duplicate samples from same well and 11 samples from wells in hydrogeologic units Qvt, Q(A)f, and bedrock.

Table 11.--*Summary of water types of ground water in southwestern King County, by hydrogeologic unit*
[Ca, calcium; Mg, magnesium; Na, sodium; --, no data available]

Hydro-geologic unit	Number of samples (Principal anion is bicarbonate in all cases)					
	Ca	Ca/Mg	Mg	Ca/Na	Na	Total
Qal	19	6	--	5	5	35
Qvr	6	1	--	--	--	7
Qvt	1	1	--	--	--	2
Qva	33	53	3	3	--	92
Q(A)f	4	1	--	--	--	5
Qva/Q(A)c	0	4	--	--	--	4
Q(A)c	18	30	2	4	2	56
Q(B)c	6	1	--	2	2	11
Bedrock	1	1	--	--	2	4
Total	88	98	5	14	11	216

the unconsolidated aquifers of western Washington. The fact that sodium concentrations in the Q(B)c aquifer are generally larger than in all other aquifers (table 10) supports the theory of a regional flow path from the geologically younger aquifers (with the exception of aquifer Qal) to or through the Q(B)c aquifer. There was little or no correlation between sodium content (expressed as a percentage of all cations) and well depth within aquifer Q(B)c.

The concentration of dissolved oxygen (DO) in ground water varies greatly, but can be an important factor in determining the suitability of a domestic water supply. Small DO concentrations can lead to the introduction of chemically reduced "nuisance" constituents, such as iron and manganese, and can reduce the biodegradation rate of surfactants found in detergents. DO also is required for the biochemical oxidation of ammonia to nitrate; the elimination of ammonia increases the efficiency of the chlorination process commonly used in water-treatment systems. Excessive amounts of DO, however, can be a disadvantage in a water-treatment facility or distribution system. Such a condition could increase the rate of corrosion of metal surfaces, leading to an increase of iron particles in the water. For these and other reasons, a moderate concentration of DO in a water supply is a desirable feature.

DO concentrations in the ground water of southwestern King County ranged from 0.0 to 9.9 mg/L (milligrams per liter), and the median concentration for all aquifers was 1.0 mg/L (table 10). Concentrations in the Qal, Q(A)c, and Q(B)c aquifers were considerably less than in other aquifers, a fact that is consistent with the general ground-water flow pattern of the area as described earlier in this report. Even though the Qal aquifer is the youngest in the study area, this aquifer discharges a large quantity of water that has been in the ground-water system for an extended period. As pointed out by LeBlanc (1984), there is a natural tendency for DO to be depleted in ground-water systems as water moves away from the atmosphere, the original source of most oxygen, and as the residence time of water in the aquifer increases.

The specific-conductance value generally is used as an approximation of dissolved-solids content. In natural water, dissolved solids vary from 55 to 75 percent of specific conductance (Hem, 1985, p. 67). In southwestern King County, the dissolved-solids concentration of ground water, in milligrams per liter, is approximately 65 percent of the specific-conductance value, expressed as microsiemens per centimeter (μS/cm) at 25°C. Thus, a specific conductance of 250 μS/cm is approximately equal to a dissolved-solids concentration of 162 mg/L. This relation is valuable because specific conductance is a much faster and less expensive measurement and one that can be completed in the field at the time of sampling. Specific-conductance values of ground-water samples from all the aquifers in the study area ranged from 51 to 712 μS/cm, and the median value was 174 μS/cm (table 10).

The degree of water "hardness," which is the soap-consuming capacity of water, can restrict severely its suitability for domestic, municipal, and industrial purposes. Suds will not be produced in hard water until the minerals causing the hardness, chiefly calcium and magnesium, have been removed from the water by combining with soap. The material that is removed by the soap forms an insoluble deposit that forms the familiar ring in a bathtub. Calcium and magnesium also contribute to the incrustation that can develop when the water undergoes changes in temperature and pressure, such as in a water heater or hot-water pipe.

Hardness is expressed in terms of equivalent amounts of calcium carbonate. In general, ground water in southwestern King County is classified as "moderately

Table 12.--*Classification of well water with respect to hardness, southwestern King County*
[--, no data available]

Hardness, as $CaCO_3$, (in milligrams per liter)	Degree of hardness	Percent of wells						
		Aquifer						
		Qal	Qvr	Qva	Qva/ Q(A)c	Q(A)c	Q(B)c	All
0-60	Soft	40	57	37	--	27	36	36
61-120	Moderately hard	57	43	55	100	71	64	60
121-180	Hard	--	--	8	--	2	--	4
>180	Very hard	3	--	--	--	--	--	--
	Total	100	100	100	100	100	100	100
	Number of wells sampled for hardness	35	7	91	4	56	11	215

hard" and, to a lesser extent, as "soft" (table 12) according to the hardness classification proposed by Hem (1985, p. 159). Table 12 also suggests that the Qvr aquifer has predominantly soft water, based on a relatively small number of water samples.

Suitability of Ground Water for Drinking

Standards have been established for many beneficial uses of water, but because so much of the water used in southwestern King County is for public-supply and domestic purposes, drinking-water standards are used in this report for comparative purposes. Some of the standards adopted by the Washington State Department of Social and Health Services (1983) for public-water supplies are shown in table 13. The primary constituents relate to human health and are legally enforceable; the secondary constituents relate to odor, appearance, and other esthetic qualities and are not legally enforceable. The rationales behind these regulations differ. Most of the heavy metals are of concern because of their effects on humans. Arsenic, barium, cadmium, chromium, lead, mercury, and selenium are all highly toxic to humans in relatively small concentrations. In addition, arsenic is a known carcinogen. Silver is not toxic, but produces a condition in humans called argyria, a blue-gray discoloration of the skin, eyes, and mucous membranes. Zinc and copper, in addition to being toxic in excessive concentrations, impart a bitter taste to water in concentrations well below toxic levels. Of the 23 water samples analyzed for heavy metals in this study (table 14), almost all had metal concentrations far below the recommended maximum contaminant level (MCL).

Short-term exposure to concentrations of fluoride in excess of 250 mg/L has been shown to be toxic to humans (McNeeley and others, 1979). Long-term exposure to concentrations of only 8 to 20 mg/L can lead to changes in bone density and to crippling. These levels rarely occur in drinking water in the United States; concentrations in naturally occurring ground water seldom exceed 10 mg/L. Public-water systems that artificially fluoridate their water commonly maintain the concentration between 0.8 and 1.3 mg/L. The median fluoride concentration of water sampled from 223 wells in this study was 0.1 mg/L (table 13). The largest concentration was 2.0 mg/L, the only one that exceeded the drinking-water standard.

Nitrate is the principal form of combined nitrogen in natural water because it is the most stable form. It is an important constituent in fertilizers and is present in relatively large concentrations in human and animal wastes. Septic tanks, privies, landfills, and barnyards are rich sources of organic nitrogen that can readily oxidize to nitrate. Large concentrations of nitrate in shallow aquifers, therefore, may indicate leaching of nitrate from these sources. Nitrate is generally a mobile anion and, in some cases, may leach into deeper aquifers as well.

The consumption by infants of water having a large concentration of nitrate reduces the ability of their blood to carry oxygen. Thus, the drinking-water criterion of

Table 13.--*Number of ground-water samples that exceeded the primary and secondary standards for drinking water. (Based on criteria of Washington State Department of Social and Health Services, 1983)*

Constituent	Unit[1]	Number of wells sampled	Median concen- tration	Maximum contaminant level (MCL)	Samples exceeding MCL Number	Samples exceeding MCL Percent
			Primary			
Arsenic	µg/L	23	0.75	50	0	0
Barium	µg/L	23	3.0	1,000	0	0
Cadmium	µg/L	23	<1	10	0	0
Chromium	µg/L	23	<1	50	0	0
Fluoride	µg/L	223	.1	2.0	1	.5
Lead	µg/L	23	<5	50	0	0
Mercury	µg/L	23	<.1	2	0	0
Nitrate[2] (as nitrogen)	µg/L	222	<.1	10	0	0
Selenium	µg/L	23	<1	10	0	0
Silver	µg/L	23	<1	50	0	0
Fecal-coliform bacteria	number per 100 mL	216	<1	1	2	.9
			Secondary			
Chloride	µg/L	222	2.9	250	0	0
Copper	µg/L	23	1.5	1,000	0	0
Dissolved solids[3]	µg/L	222	113	500	0	0
Iron	µg/L	221	35	300	32	15
Manganese	µg/L	220	40	50	97	44
pH	units	223	7.5	[4]6.5-8.5	22	10
Sulfate	µg/L	223	7.7	250	0	0
Zinc	µg/L	23	22	5,000	0	0

[1] µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter.

[2] Analytical determination as nitrate plus nitrite; water-quality criterion as nitrate only.

[3] Residue on evaporation at 180°Celsius.

[4] This represents an allowable range for pH values.

Table 14.--*Concentrations of heavy metals in ground-water samples, by hydrogeologic unit*
[Values expressed as micrograms per liter; all are dissolved concentrations]

Local well number	Arsenic	Barium	Cadmium	Chromium	Copper	Lead	Mercury	Selenium	Silver	Zinc
Maximum contaminant level (MCL)	50	1,000	10	50	1,000	50	2	10	50	5,000
					Qal Aquifer					
21/4E-1D1	3	<2	<1	1	3	<5	<0.1	<1	<1	5
-25M1	<1	4	<1	1	3	<5	1.2	<1	<1	5
-25Q3	<1	3	<1	<1	1	<5	<.1	<1	<1	<3
21/5E-6R1	<1	3	<1	<1	2	<5	<.1	<1	<1	14
-19H1	<1	4	<1	1	2	<5	<.1	<1	<1	62
-31F3	1	3	<1	<1	<1	<5	<.1	<1	<1	15
22/4E-12H1	<1	5	<1	<1	<1	<5	<.1	<1	<1	4
22/5E-6B1	4	6	<1	<1	2	<5	<.1	<1	<1	180
-30K1	<1	<2	<1	<1	5	<5	<.1	<1	<1	7
-31A1	3	3	2	<1	<1	<5	<.1	4	1	50
22/6E-9K1	<1	<2	<1	<1	1	<5	<.1	<1	<1	21
					Qvr Aquifer					
22/4E-27J3	<1	3	<1	1	66	<5	<.1	<1	<1	63
					Qva Aquifer					
21/4E-27E1	2	5	3	<1	2	<5	<.1	<1	2	41
21/4E-32H1	1	4	<1	2	1	<5	<.1	<1	<1	290
21/5E-13Q2	<1	3	1	<1	4	<5	<.1	1	<1	48
22/5E-14K2	<1	<2	<1	<1	75	<5	<.1	<1	<1	370
22/6E-30B1	3	3	<1	<1	3	<5	<.1	<1	<1	26
					Q(A)f Unit					
21/5E-8B5	6	3	<1	<1	<1	<5	<.1	2	<1	23
					Q(A)c Aquifer					
21/4E-4J1	3	7	3	<1	4	<5	<.1	<1	<1	32
21/5E-4G1	2	8	<1	<1	<1	<5	<.1	<1	<1	3
					Q(B)c Aquifer					
21/4E-15B1	4	6	2	<1	<1	6	<.1	<1	<1	9
21/5E-5C1	3	2	<1	<1	1	<5	<.1	<1	<1	65
22/4E-9A4	<1	9	<1	<1	1	<5	<.1	<1	<1	<3
Mean[1]	1.8	3.8	.9	.6	7.8	2.6	.1	.7	.6	58
Median[1]	.75	3	<1	<1	1.5	<5	<.1	<1	<1	22

[1] "Less than" concentrations calculated as one-half the value indicated.

10 mg/L (as nitrate nitrogen) was established to protect infants. Older children and adults generally are unaffected by elevated nitrate in drinking water.

Ground-water samples were analyzed for concentrations of dissolved nitrite-plus-nitrate. Because the concentration of nitrite is usually negligible in comparison to nitrate, nitrite-plus-nitrate was assumed to be equivalent to nitrate alone and is referred to simply as nitrate in this report. As shown in table 10, the median nitrate concentration of water from all the project wells was less than 0.10 mg/L. The largest concentration detected was 6.8 mg/L, but the concentration in 90 percent of the water was below 2.0 mg/L. No water sample exceeded the drinking-water standard, despite the fact that many of the samples were collected from shallow wells in relatively dense residential areas served by septic tanks. As shown in table 10, however, the concentration of nitrate generally decreased in the older and, therefore, deeper aquifers, suggesting either that the sources of nitrate are at or near land surface or that nitrate is biochemically reduced with depth.

Pathogenic (disease-producing) bacteria that normally inhabit the intestinal tracts of warmblooded animals, including humans, are responsible for numerous serious diseases, including gastroenteritis, cholera, hepatitis, and typhoid. Even though organisms excreted into sewage or water encounter an environment that is frequently hostile to their survival, these organisms still may reach a drinking-water supply in concentrations sufficient to cause infection (Bitton and Gerba, 1984). Because of the problems in detecting pathogenic bacteria and viruses in water directly, normal nonpathogenic intestinal bacteria are used as indicators of the degree of pollution by fecal wastes. In other words, if fecal contamination of water is detected, contamination by pathogenic organisms is assumed.

The most commonly used indicators of fecal contamination are the fecal-coliform (FC) bacteria. Their presence in ground water suggests strongly that the resource may have become contaminated by leachate from septic tanks, privies, landfills, farmland runoff, or feedlots. Shallow wells are particularly susceptible. Soil can filter out many bacteria, but if a well is poorly sealed from the surface, the ground water may not be protected adequately from bacterial contamination originating at or near land surface. Of the 235 samples analyzed for FC bacteria, only two contained the bacteria, and the concentrations were only 1 and 10 colonies per 100 mL (milliliters) of sample (table 20). When the wells were resampled to confirm the results of the original tests, no bacteria were detected in either well. This relatively small detection level suggests that any ground-water contamination is of a local nature; the small colony counts further suggest that the local contamination problems are not severe.

The analyses for FC bacteria were accompanied by analyses for fecal streptococci (FS) bacteria. Like the FC bacteria, the FS bacteria also inhabit the intestinal tracts of humans and animals. Because FS bacteria tend to die more rapidly than FC bacteria, their absence or presence can be used in a general way to determine the relative distance to a potential contamination source. The FS bacteria, however, are less reliable than the FC bacteria as indicators of fecal contamination. In general, FS bacteria were found in a greater number of ground-water samples and in larger concentrations than FC bacteria. Of the 241 samples analyzed for FS bacteria, 22 contained bacteria, and the concentrations ranged from 1 to more than 100 colonies per 100 mL of sample (table 20). For unknown reasons, more of the samples collected in late 1987 contained FS bacteria than those collected in early 1988.

According to Bordner and others (1978), the ratio of the FC to FS bacteria in a water sample is indicative of the source of the bacteria. A FC/FS ratio greater than 4.0 suggests that the bacteria were derived from human wastes, and a ratio less than 0.7 suggests that the bacteria were derived from livestock and poultry wastes or some other nonhuman source. Ratios calculated for water samples in the study area that contained both FC and FS bacteria were significantly less than 0.7, suggesting animal sources of bacteria. Bordner and others (1978) pointed out, however, that the ratio should not be applied if the FS counts are less than 100 colonies per 100 mL of sample, as was the case for most of the project samples.

Chloride in ground water has many sources--sea spray in coastal areas, solution from chloride-bearing minerals in soils and aquifer materials, seawater trapped in sediments at the time of deposition, contamination from numerous land-use activities, and seawater in contact with freshwater aquifers. Given the diverse sources of chloride in the environment, concentrations in ground water typically vary widely. Large concentrations of chloride increase the corrosiveness of water; thus seawater, which typically contains about 19,000 mg/L of chloride, is highly corrosive to metal. Large chloride concentrations also adversely affect the use of water for food preparation, preclude the irrigation of certain fruit crops, and give water a salty taste. In addition, the sodium usually found in association with chloride may contribute to hypertension in some individuals.

The recommended limit for the concentration of chloride in drinking water has been set largely by taste preferences. The criterion of 250 mg/L, established as a secondary standard, is the level at which most people can begin to detect a salty taste in water. The median concentration of chloride in 222 water samples was only 2.9 mg/L (table 13), and more than 95 percent of the samples had chloride concentrations below 10 mg/L. Concentrations ranged from 1.1 to 86 mg/L (table 10), and no sample exceeded the drinking-water standard.

The dissolved-solids concentration of water, which is an indication of the degree of mineralization, is the total amount of substances dissolved in the water. Large concentrations of dissolved solids reduce the desirability of the water for drinking. The drinking-water standard of 500 mg/L has been established largely with regard to taste rather than health effects. Industrial water users generally prefer that concentrations be less than 1,000 mg/L, but this requirement varies considerably among individual industries. Dissolved-solids concentrations, measured as residue on evaporation at 180°C, were generally small throughout the study area. Concentrations ranged from 38 to 415 mg/L, and the median value was 114 mg/L (table 10). No sample exceeded the drinking-water standard (table 13).

Iron and manganese are derived naturally from the weathering of rocks and minerals; the two are similar in chemical behavior and are frequently found in association. Iron is especially common in clay soils, such as those found in the Puget Sound region. The small oxygen concentrations often found in well water produce an environment that is favorable for the dissolution of both iron and manganese.

Large iron and manganese concentrations in domestic water supplies are objectionable because of problems related to unpleasant taste, discoloration of clothes and porcelain plumbing fixtures, incrustation of well screens, and the formation of scale in pipes. These same elements also are objectionable in food processing, dyeing, bleaching, ice manufacturing, brewing, and certain other industrial processes. Iron in large concentrations produces a reddish-brown stain on porcelain and gives drinking water a bittersweet, astringent taste. Manganese causes stains that are dark brown or black and that are more difficult to remove than iron stains. Iron-bearing water also encourages the growth of filamentous iron bacteria in wells and water pipes. These bacteria eventually may clog the pipes and obstruct the flow. Frequently, the bacterial filaments break loose in large clogging masses. Ground water with large concentrations of iron may be completely clear and colorless when first pumped from the well. If the water is exposed to the atmosphere for a time, the dissolved iron gradually oxidizes and makes the water cloudy. Eventually, a rust-colored precipitate of iron oxide collects at the bottom of the container.

Iron concentrations ranged from less than 3 to 10,000 μg/L (micrograms per liter), and manganese concentrations ranged from less than 1 to 860 μg/L. The median concentrations of iron and manganese were 35 and 40 μg/L, respectively (table 10). Of the ground-water samples analyzed, 32 (15 percent) exceeded the 300 μg/L drinking-water standard for iron, and 97 (44 percent) exceeded the 50 μg/L standard for manganese (see table 13); water from 27 wells (12 percent) exceeded both standards.

As expected, iron and manganese concentrations were generally inversely proportional to dissolved-oxygen concentrations. That is, hydrogeologic units with smaller DO concentrations tended to have larger iron and manganese concentrations (see table 10). Despite being less abundant in nature than iron, manganese was present in generally larger concentrations than iron. This probably is because iron oxidizes and precipitates over a broad range of pH, and manganese only at high pH.

There did not appear to be any geographic trends in the occurrences of large iron or manganese concentrations. Moreover, the differences in iron concentrations between aquifers were small. The differences in manganese concentrations were somewhat greater; the largest concentration of manganese occurred in hydrogeologic unit Q(A)c (table 10), where the median DO concentration was only 0.9 mg/L. Although the exact sources of the iron and manganese are unknown, their concentrations in the ground water of the study area most likely are controlled, at least in part, by ambient conditions of DO concentration and pH.

The pH is an indication of the balance between acids and bases in water, and is a measure of the hydrogen-ion concentration in solution. As an index of hydrogen-ion concentration, pH values range from 0 to 14. A value of 7 indicates a neutral condition, values less than 7 indicate acidic conditions, and values greater than 7 indicate alkaline conditions. The pH of drinking water in public supplies usually is adjusted to prevent corrosion of the distribution system and to eliminate the introduction of toxic metals such as copper, lead, zinc, and cadmium. In addition, excessively high or low pH can interfere with the coagulation and chlorination processes of drinking water. Industries such as bleaching, brewing, photography, ore processing, and electroplating are sensitive to the pH of their water supplies (McNeely and others, 1979). A pH range of 6.5 to 8.5 generally is regarded as acceptable for drinking-water supplies in Washington.

Only 22 wells in southwestern King County contained water with pH outside the recommended range (table 13), and most of the 22 were below 6.5. Because none of the pH values outside the recommended range was excessively high or low, this occurrence is not considered a serious ground-water problem. With the exception of the Qal aquifer, pH values generally increased with depth (see table 10). This trend typically is caused by the hydrolysis of silicate minerals, a chemical reaction that consumes hydrogen ions and produces hydroxyl or bicarbonate ions.

Sulfate is leached naturally from rocks, especially sedimentary rocks, but certain industrial processes also contribute sulfate to ground water. In addition, both wet and dry atmospheric deposition contain sulfate generated by the combustion of fossil fuels. Concentrations of sulfate above 250 mg/L may give water a bitter taste. At concentrations above 500 mg/L, the water may have a laxative effect on humans. Livestock, however, usually can drink water containing up to 1,000 mg/L of sulfate without adverse effects. In combination with calcium and magnesium, sulfate forms a hard scale in steam boilers.

Concentrations of sulfate in water samples from all aquifers in the study area were small (table 10), ranging from 0.30 to 65 mg/L; the median concentration was 7.7 mg/L. All sulfate concentrations were below the drinking-water standard of 250 mg/L.

Ground-Water Contamination

An ancillary aspect of the water-quality phase of this study was to determine if ground water in southwestern King County is being contaminated presently (1986) as a result of development. For this report, contamination of water quality means that some use of the water has been impaired, but not necessarily to a degree that all beneficial uses are prohibited (Hughes, 1975). Some potential sources of ground-water contamination include the disposal of domestic wastes in septic tanks and landfills, the inducement of seawater intrusion, and the improper handling of hazardous chemicals in commercial or industrial endeavors. Because this study was designed to ascertain the general quality of ground water over a broad geographic area, occurrences of known ground-water contamination were not singled out for special consideration. The indicator constituents selected for analysis and discussion were chloride, nitrate, dissolved solids, and heavy metals (constituents that have been discussed previously), dissolved organic carbon, detergents, boron, and purgeable organic compounds.

As discussed previously, concentrations of nitrate, dissolved solids, and heavy metals in water samples were generally below the maximum contaminant level for drinking water for all samples analyzed as part of this study. Maps of the geographic distributions of those constituents (not included in this report) showed no spatial trends. The ground water in southwestern King County, therefore, in general cannot be considered contaminated with respect to these constituents.

Wells in many coastal areas are in a fragile balance between rates of ground-water pumping that safely provide fresh water supplies, and increased pumping rates that might induce the intrusion of seawater into nearshore aquifers. For seawater intrusion to occur, the aquifers in coastal areas must be in hydraulic connection with the sea, and the hydraulic head of the fresh ground water must be decreased relative to that of seawater, usually as a result of man's activities. Dion and Sumioka (1984), who described the causes of seawater intrusion in greater detail, report that intrusion in western Washington is indicated if ground-water chloride concentrations exceed about 100 mg/L.

Chloride concentrations in water from the sampled wells generally were quite small. The median concentration of 2.9 mg/L (table 10) suggests strongly that seawater intrusion in southwestern King County is not a problem. However, drillers of a prospective irrigation well at a golf course (section 14, T.23 N., R.4 E.) on the flood plain of the Duwamish River in early 1988 encountered highly saline water approximately 130 feet below land surface (110 feet below sea level). An analysis of that water provided by Ecology (Sally Safioles, written commun., March 14, 1988) indicates that the chloride concentration in the water from that well was 7,300 mg/L, and that sodium and chloride were the dominant cation and anion, respectively. Because the ratio of chloride to dissolved solids in this well water is approximately equal to that of seawater, it appears likely that the 134-foot well penetrated a tongue of diluted seawater in the alluvial deposits of the Duwamish River Valley. However, the question as to whether this body of saline water represents seawater intrusion is debatable. If the saline water is restricted to the alluvial deposits near the mouth of the river, it likely is of natural origin and not a result of seawater intrusion as described previously.

Seawater intrusion, however, constitutes a potentially serious threat to the quality of water from deep wells in the coastal parts of the study area. In order to detect the onset of seawater intrusion, water levels and chloride concentrations could be monitored on a regular and continuing basis in a network of wells completed below sea level within a few miles of the King County shoreline.

Dissolved organic carbon (DOC) is defined as that part of total organic carbon in water that passes through a 0.45-micrometer silver or glass-fiber filter (Thurman, 1985). Hughes (1975) reports that DOC reflects the presence of many individual organic compounds soluble in water, such as synthetic detergents, oil and grease, pesticides, and products of human-waste decomposition. The common sources of DOC in ground water are surface organic matter and kerogen, the fossilized organic matter present in geologic materials (Thurman, 1985). The standard DOC analysis, however, does not discriminate between the various types or sources of organic compounds.

Fifty-six water samples collected in this study were analyzed for DOC; the concentrations of those samples ranged from 0.3 to 3.1 mg/L (table 20). The median concentration was 0.7 mg/L, the same value presented by Thurman (1985) as the median for ground water in general. There appeared to be no correlation between concentrations of DOC and those of boron, detergents, or the volatile organic compounds, nor was there a consistent relation between DOC concentration and the depth of the aquifer. Even though the two wells (22N/05E-15P01 and 22N/05E-23F01; table 20) with the highest DOC concentrations (3.1 and 2.5 mg/L, respectively) are only about 1 mile apart, the cause of the relatively large concentrations is not known.

Detergents are manmade chemicals that are often one of the contaminants in ground water that has been degraded by wastewater disposal. The concentration of detergents in water is measured by the methylene blue active substances (MBAS) test, which determines the concentration of surfactants (or "surface active agents") in water. Prior to 1964, the principal surfactant was the nonbiodegradable compound alkyl benzene sulfonate (ABS); since 1964, the biodegradable surfactant linear alkyl sulfonate (LAS) has been used almost exclusively. Because the MBAS test currently being used cannot distinguish between the two surfactants, a positive response to the test implies the presence of either the relatively old, nonbiodegradable ABS, the relatively new biodegradable LAS, or a mixture of the two.

LAS can be removed from wastewater effectively by sewage treatment plants, but not by septic tanks. The rate of natural degradation of LAS is directly proportional to water temperature and oxygen content (Hughes, 1975). Removal of LAS from ground water also occurs by retardation as a result of adsorption onto earth materials (Freeze and Cherry, 1979).

Most (74 percent) of the 23 samples collected from wells in the study area had detergent concentrations below 0.02 mg/L (table 15), the level suggested by Hughes (1975) above which ground water can be considered contaminated; the maximum concentration detected was only 0.03 mg/L. Although there appears to be little correlation between well depth and detergent concentration, the two wells (21N/06E-18K01 and 22N/06E-27P02) with the largest concentrations (both 0.3 mg/L) are in unsewered areas and are relatively shallow (24 and 80 feet deep, respectively). The above data suggest that ground-water contamination from detergents is presently not a problem in the study area.

Elevated concentrations of boron in ground water can be used as an indicator of contamination because boron is pervasive in sewage effluent. Boron behaves "conservatively"; that is, like chloride, it migrates through the ground-water environment without being retarded by chemical reactions or being adsorbed onto aquifer materials. Major sources of boron include detergents and other cleaning agents, human wastes, and household and industrial chemicals.

Uncontaminated ground water generally contains less than 50 mg/L of boron (LeBlanc, 1984). Ten of the 23 samples analyzed for boron were below the detection level of 10 mg/L (table 15); the remainder ranged from 10 mg/L (five samples) to 30 mg/L (one sample). These data suggest that ground-water contamination in the study area, as indicated by boron concentrations, has not occurred. There did not appear to be a spatial trend with respect to boron.

Among the most common and pervasive ground-water contaminants nationwide are the manmade purgeable organic compounds in wide use in numerous commercial and industrial applications. To detect their presence in the ground waters of southwestern King County, 25 wells located primarily in commercial and industrial areas were sampled and each sample was analyzed for 36 purgeable organic compounds. A list of those compounds is provided in table 16. Purgeable organic contaminants in

Table 15.--*Concentrations of detergents and boron in ground-water samples, by hydrogeologic unit*
[--, no data available]

Local well number	Detergents, as MBAS[1] (milligrams per liter)	Boron (micrograms per liter)
	Qal Aquifer	
21/4E-25M1	0.01	20
22/4E-12H1	.01	20
22/6E-9K1	.01	20
23/4E-30P1	.01	10
	Qvr Aquifer	
21/6E-18K1	.03	<10
22/4E-27J3	.02	<10
	Qva Aquifer	
21/4E-2Q2	.01	<10
-27E1	.02	<10
21/5E-13Q2	--	10
21/4E-32H1	.01	<10
21/5E-13G2	.01	<10
21/6E-20F3	.02	<10
-22R8	.02	<10
22/5E-14K2	.01	--
-23P5	.01	<10
-35P1	.02	20
22/6E-6A4	.01	<10
-19E3	.01	10
-27P2	.03	30
	Q(A)f Unit	
22/6E-18D2	.01	10
	Q(A)c Aquifer	
22/5E-23F1	.01	20
22/6E-8F4	.01	20
22/6E-9P2	.01	20
22/6E-27P1	.01	10

[1] MBAS, methylene blue active substances.

Table 16.--*Purgeable organic compounds analyzed for in selected ground-water samples*

Benzene	Trichloroethylene
Bromoform	Trichlorofluoromethane
Carbon tetrachloride	Vinyl chloride
Chlorobenzene	Xylene
Chlorodibromomethane	1,1-Dichloroethane
Chloroethane	1,1-Dichloroethylene
Chloroform	1,1,1-Trichloroethane
Cis-1,3-Dichloropropene	1,1,2-Trichloroethane
Dichlorobromomethane	1,1,2,2-Tetrachloroethane
Dichlorodifluoromethane	1,2-Dibromoethylene
Ethylbenzene	1,2-Dichlorobenzene
Methyl bromide	1,2-Dichloroethane
Methyl chloride	1,2-Dichloropropane
Methylene chloride	1,2-trans-Dichloroethylene
Styrene	1,3-Dichlorobenzene
Tetrachloroethylene	1,3-Dichloropropane
Toluene	1,4-Dichlorobenzene
Trans-1,3-Dichloropropene	2-Chloroethyl vinyl ether

concentrations above detection levels were found in samples from only three wells and at small concentrations (see below).

Compounds	Concentration, in micrograms per liter (µg/L) Well 21N/04E-01D01	21N/04E-25M01	21N/05E-19H01
Chlorodibromo-methane	--	0.80	--
Chloroform	--	1.8	--
Dichlorobro-methane	--	1.3	--
Methylene-chloride	0.90	--	--
1,1,1,-trichloro-ethane	--	--	1.6

The U.S. Environmental Protection Agency (written commun., 1988) has set an MCL for only one of the constituents detected (1,1,1-trichlorethane); that concentration has been set at 200 µg/L.

On the basis of the discussion presented above and the discussion of other selected constituents presented earlier with respect to drinking-water suitability, there does not appear to be any widespread contamination of ground-water quality in southwestern King County. To detect any future contamination, however, a water-quality monitoring network could be designed and implemented for the study area. Such a network is discussed in greater detail in a later section of this report.

Temporal Water-Quality Changes

The question of whether ground-water quality in southwestern King County has changed with time is not an easy one to answer. To do so satisfactorily, current water-quality conditions must be compared with those of some prior time or period. Obstacles to such a comparison include:

* a lack of common wells in the data set;

* differences in the number of wells sampled;

* changes in analytical techniques or concentration units over time; and

* ignorance of the natural seasonal variations in the concentrations of the constituents in question.

Despite such complications, seasonal water-quality changes were examined by comparing data pairs for samples collected from 25 wells in early autumn 1987 and again in late winter 1988. Those comparisons, presented in table 17, indicate that there was almost no difference in water quality between samples collected at those two times.

To assess water-quality changes over a longer period of time, comparisons were made among data sets from 1963 (Van Denburgh and Santos, 1965), 1981 (Turney, 1986), and from 1987-88 (this study). Because the two earlier reports lacked sufficient data for heavy metals, boron, detergents, and purgeable organic compounds, the comparisons were limited to major inorganic constituents. Data in table 18 provide little evidence of temporal trends, although hardness and magnesium appear to have increased. These inconclusive findings are undoubtedly due to some or all of the obstacles detailed above. For instance, none of the wells is common to all three data sets; fewer wells were sampled in 1963 and 1981 than in the 1987-88 period; concentration units for alkalinity, nitrogen, iron, manganese, and dissolved solids are inconsistent; and the natural seasonal fluctuations in ground-water quality in southwestern King County are poorly understood.

To minimize the effects of the complications, comparisons were made of analyses of samples from three selected wells known to have been sampled twice over a span of several years; those data are presented in table 19. As shown, there appears to be an increase in most of the constituents for all three wells, but the validity and significance of these increases are unclear. If the increases are real, the causes are unknown.

ADDITIONAL DATA NEEDS

In late 1986, Ecology established a Ground Water Management Area (GWMA), encompassing the same area as this study, and this added impetus to the work currently being done for this study. Ecology requirements stipulate the following requirements and documentation:

(1) The establishment of the relation between water withdrawal distribution and rates, and water-level changes within each aquifer or zone and predict the likelihood of future problems and conflicts if no action is taken; and

(2) A problem definition section that discusses land and water-use activities potentially affecting ground-water quantity and quality.

In light of these requirements, plus Ecology regulations that have closed most streams in the area to further appropriations of streamflow, local planners have recognized the need to optimize the use of local water resources. Such optimization could include conjunctive use of surface-water and ground-water resources--artificial recharge, for example--to meet future demands. It is reasonable to consider the advantages of numerical ground-water flow modeling to test the feasibility of possible management schemes. The additional data needs described below are based on the assumption that a three-dimensional, steady-state numerical model, which includes a representation of a saltwater interface, could be built for use in evaluating the effects of alternative optimized management schemes. Although it is probable that most of the data needed for a transient calibration are currently available, it would seem advisable to wait until after the steady-state model was completed before proposing additional data acquisition for building a transient model. Pre-

Table 17.--*Comparison of 25 pairs of water-quality data for wells sampled in early autumn 1987 and in late winter 1988*

[Values expressed as milligrams per liter unless otherwise noted; all are dissolved concentrations]

Constituent or property	Mean concentration (milligrams per liter) 1987	1988	Average difference, in percent	Standard deviation of difference
Specific conductance (microsiemens per centimeter)	183	183	2.3	4.1
Hardness (as $CaCo_3$)	71	71	3.1	4.8
Calcium	16	16	4.4	5.3
Magnesium	7.3	7.6	2.8	4.9
Sodium	8.5	9.0	2.8	3.8
Potassium	2.2	1.7	14	19
Alkalinity (as $CaCo_3$)	80	80	3.2	6.4
Chloride	3.3	2.8	12	13
Sulfate	8.4	9.5	8.0	14
Silica	28	29	2.2	1.5
Iron (micrograms per liter)	326	308	54	170
Manganese (micrograms per liter)	122	118	13	20
Dissolved solids	115	120	3.4	2.9

Table 18.--*Temporal changes in ground-water quality, southwestern King County*

[Values are medians and expressed in milligrams per liter except as noted; all are dissolved concentrations; --, no data available]

	Date and reference		
Constituent	1963 Data; Van Denburgh and Santos (1965)	1981 Data; Turney (1986)	1987-88 Data; This study
Specific conductance (microsiemens per centimeter)	164	158	172
Hardness (as $CaCO_3$)	55	62	67
Calcium	14	14	16
Magnesium	4.8	5.7	6.6
Sodium	6.5	6.5	6.5
Percent sodium	18	18	16
Potassium	2.0	1.7	1.7
Alkalinity (as $CaCO_3$)	[1]70	[2]68	[2]76
Chloride	3.4	2.5	2.9
Sulfate	6.0	<5.0	7.7
Nitrogen	[3].25	[4].08	[4]<.10
Silica	23	28	27
Iron (micrograms per liter)	[5]515	[6]39	[6]35
Manganese (micrograms per liter)	--	[6]50	40
Dissolved solids	[7]127	[7]107	[8]113
Number of samples	10	13	218

[1] field value
[2] lab value
[3] total NO_3
[4] $NO_2 + NO_3$, dissolved
[5] total recoverable
[6] dissolved
[7] sum of constituents
[8] residue on evaporation at 180°C.

Table 19.--*Temporal changes in ground-water quality in samples from selected wells*
[Values expressed in milligrams per liter except as noted; all are dissolved concentrations; --, no data available]

Local well number	21/4E-25Q3		21/5E-18B1		21/6E-4B5	
Depth of open interval of well, in feet	42 to 47		242 to 291		73 to 83	
Date of sample collection	8/21/81	3/9/88	11/16/70	9/24/87	7/9/81	9/23/87
Constituent or property:						
Specific conductance (mirosiemens per centimeter)	155	160	195	225	136	150
Hardness (as $CaCO_3$)	59	64	90	88	49	53
Calcium	16	17	21	22	13	14
Magnesium	4.7	5.2	6.6	8.1	3.9	4.5
Sodium	5.5	6.2	7.6	11	7.7	8.3
Percent sodium	16	17	17	21	25	25
Potassium	2.1	2.2	1.6	2.1	.6	.7
Alkalinity (as $CaCO_3$)	43	56	75	94	46	55
Chloride	3.2	4.6	4.6	3.2	2.1	2.4
Sulfate	17	14	12	15	13	15
Nitrogen (NO_2 +NO_3)	1.2	.89	--	1.1	--	.32
Silica	33	36	24	27	13	11
Iron (micrograms per liter)	<10	3	--	13	<10	2
Manganese (micrograms per liter)	<1	1	--	4	<1	1
Dissolved solids (residue at 180°C)	--	115	128	152	--	88

liminary optimization analysis could be accomplished with the steady-state model, and later refined after a transient model had been calibrated.

Water Quantity

Additional new data needs for estimating water quantity fall within several categories.

(1) Hydrologic boundaries--It is likely that the Cedar and Green Rivers would be adequate hydrologic boundaries for a steady-state model, as would the Puget Sound and the bedrock near Black Diamond. However, the model would need to be extended to the Puyallup and White Rivers south of the King County-Pierce County line. This extension would entail the use and modification of geologic and hydrologic information from a model study of the Puyallup River Valley by the USGS (R. C. Lane, U.S. Geological Survey, written commun., 1989), as well as additional work to define the flow system, hydraulic characteristics, and water budget items there. The adequacy of these boundaries would need to be tested with a preliminary version of the model constructed early in the project.

(2) Geology--Some subdivision of the alluvial aquifers (Qal) along the major river valleys might be needed to adequately represent this unit in a model. This might be done in a manner similar to the above-mentioned Puyallup River Valley study.

(3) Flow system--A second mass measurement of water levels for all wells would be needed at the same time of year as before; average water levels for the two periods would need to be calculated. Elevations for a number of wells near the shoreline and near some reaches of major streams would need to be surveyed, along with water levels in adjacent rivers. Water-level changes over time would need to be calculated if a time-averaged, steady-state calibration were attempted.

(4) Water-budget--(a) Recharge--Man-induced recharge from septic systems, dry wells, irrigation, and other sources would need to be calculated and added to the natural (precipitation) recharge array already completed. (b) Discharge--Springflow and some spring discharges, originally measured by Luzier (1969), would need to be remeasured a number of times over a year's period to obtain the annual variation. Baseflow estimates for selected streams not modeled in the rainfall-runoff studies (Dinicola, 1990) would need to be estimated with miscellaneous discharge measurements and with regionalized extrapolation from streams already modeled. Well pumpage would need to be re-estimated for the same wells, and some scheme devised to obtain the distribution of domestic well pumpage. Pumpage from those areas added to the present study area from the Puyallup and White River Valleys would need to be estimated. A more accurate estimate of diffuse seepage from the bluffs would be needed.

A ground-water monitoring network for water quantity in southwestern King County would be needed to accomplish several things (Heath, 1976):

(1) Provide baseline information on natural long-term water-level changes for use as reference comparisons with other changes;

(2) Provide a more frequent assessment of the local water-level changes due to ground-water pumpage or artificial ground-water recharge;

(3) Provide a periodic regional assessment of the change-in-storage capacity of the ground-water system; and

(4) Provide periodic evaluation of the efficiency of the monitoring network.

Water Quality

In addition to monitoring the quantity of ground water in southwestern King County, a program to monitor the quality of ground water would allow determination of the magnitude and rate of change in the chemical and bacterial quality of the water with time.

Constituent selection is important in the design of an effective water-quality monitoring program. Assuming that the major-ion chemical data collected as part of this project are adequate to characterize the general water types of the study area, additional chemical constituents can be selected for monitoring that can be characterized as (1) general-contamination indicator constituents; and (2) specific chemical contaminants.

The selection of specific chemical contaminants for monitoring could be based on (1) a knowledge of previous ground-water-quality problems; (2) the likelihood of contamination from known patterns and by-products of residential, agricultural, commercial, or industrial land uses; and (3) regulations developed by county, State, or Federal law, such as those contained in drinking-water standards.

SUMMARY AND CONCLUSIONS

The 250-mi^2 study area in southwestern King County is underlain by sediments as much as 2,200 ft thick deposited during at least four glacial/interglacial periods. Generally, the land surface consists of a relatively featureless plain composed of glacial drift, which is commonly at an altitude of 400 to 600 ft above sea level; this drift plain is dissected by a network of incised major drainageways, the most prominent of which is the Duwamish Valley at an altitude of about 10 to 75 ft. Thus, the study area can be characterized by three dominant physiographic subdivisions--the Des Moines Plain to the west, the Duwamish Valley in the center, and the Covington Plain to the east. The plains are elevated from the major river valleys and from Puget Sound by steep bluffs up to 400 ft high.

Subsurface stratigraphy of the unconsolidated sediments was correlated using lithologic information from published surficial maps, from the interpretation of approximately 700 drillers' logs, and from 28 generalized cross sections oriented across the study area. Nine hydrogeologic units were delineated that correspond with the large-scale geologic events that occurred during and after the Pleistocene Epoch. Five aquifers--Q(B)c, Q(A)c, Qva, Qvr, and Qal--consisting of predominantly coarse-grained sediments of higher permeability deposited as alluvium and as glacial advance and recessional outwash, were delineated as being separated by three confining beds--Q(B)f, Q(A)f, and Qvt--consisting of predominantly fine-grained sediments of lower permeability deposited as interglacial silt and clay and as glacial till. These eight units are underlain by a thick sequence of undifferentiated and unconsolidated sediments of unknown hydrologic characteristics. Two aquifers--Qvr (Vashon recessional outwash) and Qal (Quaternary alluvium)--occur at land surface, and the extent of these aquifers is shown on the map of the surficial geology. Maps depicting the configuration of the tops of the three buried aquifers--Q(B)c, Q(A)c, and Qva (Vashon advance outwash)--show the extent and the geometry of those aquifers; maps showing the thickness of the Q(A)c and Qva aquifers also were prepared.

The Q(B)c aquifer is the deepest unit studied, and exists throughout all but the northern part of the study area. The aquifer has an average thickness of about 50 ft and slopes westward towards Puget Sound. The Q(A)c aquifer, separated from the Q(B)c aquifer by the Q(B)f confining bed, exists throughout the study area except for the northern part of the Covington Plain. The Q(A)c aquifer ranges in thickness from 0 to 200 ft and averages about 85 ft; regionally, the aquifer tends to be thicker in structurally "low" areas. This aquifer generally is overlain by the Q(A)f confining bed, but that confining bed is not present in the northwestern and southwestern parts of the Covington Plain and in the northeastern and southwestern parts of the Des Moines Plain. In these areas, the Q(A)c unit is in direct hydraulic connection with a shallower aquifer (the Qva unit), forming a combined aquifer unit--the Qva/Q(A)c unit.

The Qva aquifer represents advance outwash deposits and is usually overlain by the Qvt (till) confining bed. The top of the Qva aquifer is generally within 100 ft of land surface, and the aquifer generally slopes downward from east to west. Aquifer thickness ranges from 0 to 200 ft, with the thicker deposits generally in the northern half of the study area. The Qvr aquifer, composed of recessional outwash sediments, was deposited in topographic "lows" of the irregular surface of the Qvt till plain. Thus, the aquifer has a sporadic distribution and where present averages about 30 ft in thickness. For these reasons, the Qvr is considered to be a minor aquifer in the study area. The Qal aquifer is composed of alluvium found in the valleys of the Green, Cedar, Duwamish, and White Rivers. Few wells fully penetrate the Qal in the study area, so thickness of the aquifer generally is not known.

Maps of the potentiometric surfaces of the Q(A)c and Qva aquifers, and of the water table of the Qal aquifer, show the regional lateral movement of ground water in those units. Ground-water movement in the Qva and Q(A)c aquifers has a similar pattern; flow is generally westward, toward the major rivers, and away from "highs" located north of Angle Lake and east of Federal Way in the Des Moines Plain, and near Lake Youngs in the Covington Plain. Water-level data for the Q(B)c aquifer are sparse, but ground-water movement is assumed to have a pattern similar to that of the Q(A)c aquifer. In the Qal aquifer, flow is generally toward the major river channels, except near Auburn where flow is away from the Green and White Rivers.

Hydraulic characteristics of each major aquifer were inferred from maps showing values for more than 1,100 specific-capacity calculations and about 240 hydraulic-conductivity determinations from selected wells in the area. These maps suggest that the specific-capacity and hydraulic-conductivity values are roughly proportional to the thickness of the Q(A)c and Qva aquifers. The thicker sections of these aquifers may occur along preglacial drainage channels cut into interglacial sediments, and that depositional regime might also explain the higher values of hydraulic conductivity. Additionally, the data indicate that the median hydraulic conductivity for the aquifers studied generally decreases with depth.

Most of recharge to the ground-water system is derived from the infiltration of precipitation, and the distribution and rate of average annual recharge from precipitation has been estimated for the study area. A deep-percolation model (DPM) was applied to eight basins in the study area, including the Big Soos Creek Basin. Estimates of long-term recharge to the Big Soos Creek Basin from the DPM (about 20.6 inches per year) agreed closely with recharge estimates calculated for other areas in the Puget Sound Lowland using a rainfall-runoff model. Long-term average recharge from precipitation for the remainder of the study area was estimated, using regression equations based on the DPM results, to be 16.6 inches per year.

An assessment of springflow, seepage from bluffs, and withdrawals from high-capacity wells was done to quantify some of the ground-water discharge in the area. Bluffs along the periphery of the Des Moines and Covington Plains were divided into six segments;

estimated discharge, in gallons per day per mile, ranged from 0 (for the segment on the north edge of the Covington Plain) to 1.72×10^5 (for the segment along the eastern edge of the Des Moines Plain). Additionally, a minimum of 0.03 ft^3/s of diffuse seepage may be discharging along each mile of bluff wall.

Approximately 13,200 million gallons (Mgal) of ground water was withdrawn from the study area in 1986. About 97 percent of that total was used for public-supply and domestic purposes, slightly less than 3 percent was used for irrigation, and the remainder was used for commercial, industrial, and institutional purposes. The Qal aquifer supplied most (3,250 Mgal) of the water, followed by the Qva (2,510 Mgal) and the Q(A)c (1,735 Mgal) aquifers.

A total of 242 water samples from 223 wells was collected during two mass samplings and analyzed for the presence of common constituents. In addition, samples also were collected for heavy metals, boron, detergents, and volatile organic compounds. There were no significant chemical differences in water quality among the hydrogeologic units. An analysis of the water-quality data indicates that there is no widespread degradation of ground-water quality in southwestern King County.

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Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County*

[All are dissolved concentrations and in milligrams per liter (mg/L) except as noted; mL, milliliters; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; M, analyzed for heavy metals (see table 15); O, analyzed for purgeable organic compounds (see table 17); B, analyzed for boron (see table 16); D, analyzed for detergents (see table 16); --, no data available; <, not detected at the given concentration]

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
											Qal Unit												
21N/04E-01D01	03-14-88	177	7.8	--	37	10	2.8	25	60	0.8	90	1.9	1.3	0.05	0.1	22	150	54	114	<1	<1	1.3	MO
21N/04E-25M01	03-02-88	171	6.6	1.4	66	17	5.7	7.2	19	2.5	56	4.1	20	.05	.2	39	11	12	125	<1	<1	--	MOBD
21N/04E-25Q03	09-25-87	155	6.6	2.5	60	15	4.9	6.0	17	1.2	53	3.6	14	.96	.1	35	3	1	103	<1	<1	--	--
	03-09-88	160	6.6	1.2	64	17	5.2	6.2	17	2.2	56	4.6	14	.89	.1	36	3	1	115	<1	<1	--	MO
21N/05E-06R01	03-11-88	315	8.7	.4	39	11	2.7	61	76	3.4	158	14	.8	.05	.1	30	18	16	214	<1	<1	1.6	MO
21N/05E-16N01	10-08-87	202	6.7	.9	85	22	7.2	6.8	15	1.0	97	5.1	1.9	.05	.1	27	2,000	430	126	<1	<1	.6	--
21N/05E-18B01	09-24-87	225	6.9	.5	88	22	8.1	11	21	2.1	95	3.2	15	1.10	.1	27	13	4	152	--	<1	--	--
21N/05E-19E01	09-23-87	182	6.4	5.0	71	20	5.0	7.1	17	1.9	65	3.0	10	2.50	.1	38	19	2	129	<1	<1	--	--
21N/05E-19H01	03-02-88	210	6.6	3.2	89	25	6.5	7.0	15	1.5	74	4.8	17	2.70	.1	23	27	1	135	<1	<1	--	MO
21N/05E-20B01	09-23-87	346	6.6	.6	86	22	7.5	32	43	3.2	99	37	6.1	.05	.1	27	22	6	202	<1	<1	--	--
21N/05E-21C01	03-03-88	165	7.0	.1	69	18	5.9	5.9	16	.9	77	4.1	7.3	.05	.2	27	1,300	420	107	<1	<1	--	--
21N/05E-25A01	03-04-88	712	7.3	6.0	310	79	27	32	19	1.9	229	86	27	.05	.1	23	670	800	415	<1	<1	--	--
21N/05E-27A02	09-23-87	137	6.4	.9	57	16	4.2	5.1	17	.7	58	7.3	5.1	.05	.1	21	17	6	86	<1	<1	--	--
21N/05E-28M01	03-04-88	209	8.0	.3	100	29	7.1	5.6	11	2.4	103	2.0	8.6	.05	.1	23	30	100	135	<1	<1	--	--
21N/05E-30J03	03-07-88	99	6.6	6.1	34	9.6	2.4	4.7	23	1.2	31	3.3	10	.63	.1	20	3	1	69	<1	<1	--	--
21N/05E-31F03	03-07-88	150	7.6	4.3	67	14	7.8	6.6	18	1.7	70	2.5	7.1	.05	.2	41	3	1	116	<1	<1	--	MO
21N/06E-29C06	09-24-87	79	6.6	.6	28	8.1	1.8	4.3	25	.4	33	6.4	5.4	.05	.1	13	91	6	51	--	<1	--	--
	03-07-88	51	6.6	5.5	17	4.9	1.1	2.9	28	.2	20	1.6	3.1	.05	.1	12	30	1	38	<1	<1	--	--
22N/04E-10J01	09-25-87	343	7.7	1.0	26	2.8	4.6	64	83	.9	134	24	6.4	.05	.4	53	1,200	270	219	<1	87	--	--
22N/04E-12H01	03-09-88	228	8.2	.4	100	26	9.1	7.5	14	2.3	119	2.6	1.4	.05	.2	30	700	160	138	<1	<1	--	MOBD
22N/04E-24G01	09-30-87	222	8.1	2.7	57	17	3.6	14	34	2.3	114	11	1.1	.05	.2	29	18	12	152	<1	<1	1.6	--
22N/04E-36M01	09-25-87	201	7.4	.2	40	7.9	4.9	23	55	1.0	102	2.3	8.2	.05	.4	49	2,700	160	145	<1	K5	1.6	--
22N/05E-06B01	09-14-87	193	7.5	.0	80	14	10	6.0	14	2.7	73	4.1	15	.05	.1	35	539	140	114	<1	K10	--	--
	03-11-88	189	7.2	2.4	80	14	11	6.0	14	2.5	73	4.3	17	.05	.1	36	640	150	132	<1	<1	--	MO
22N/05E-18M01	10-08-87	184	7.6	.3	55	14	4.8	15	36	2.9	96	2.2	.6	.05	.2	38	90	50	113	<1	<1	--	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
22N/05E-30K01	03-11-88	175	7.6	0.3	60	15	5.4	14	33	3.5	90	1.8	2.7	0.05	0.1	38	1,100	200	128	<1	<1	--	MO
22N/05E-31A01	09-17-87	144	7.6	.8	58	15	5.2	5.9	17	1.4	66	1.7	5.3	.05	.1	25	83	5	91	<1	<1	0.9	--
	03-04-88	145	7.7	.8	59	15	5.2	6.2	19	1.4	66	2.3	5.4	.05	.1	26	41	2	98	<1	<1	--	MO
22N/06E-04E02	03-18-88	156	6.9	3.5	67	13	8.3	5.1	15	1.2	67	1.7	8.7	.82	.1	27	13	4	104	<1	<1	--	--
22N/06E-09G04	09-28-87	196	7.8	.2	73	19	6.2	9.8	20	7.7	87	1.4	11	.05	.1	24	100	250	126	<1	<1	--	--
22N/06E-09K01	03-18-88	205	7.6	.6	87	22	7.7	8.5	18	1.4	98	1.5	7.0	.05	.1	30	75	250	130	<1	<1	--	MOBD
22N/06E-15R01	03-14-88	179	8.04	.4	43	14	1.9	18	47	1.6	83	2.4	3.6	.05	.1	15	55	25	104	<1	<1	--	--
23N/04E-30P01	03-16-88	182	8.2	.8	84	17	10	6.2	14	1.8	88	3.8	8.4	.05	.2	33	50	210	127	<1	<1	.6	BD
23N/04E-34F01	10-06-87	234	6.3	6.4	93	28	5.7	9.7	19	1.1	91	4.8	20	1.20	.1	27	40	1	148	<1	>100	1.4	--
23N/05E-17F03	09-29-87	170	6.2	3.1	69	17	6.5	5.9	16	1.2	63	5.5	10	.46	.1	24	7	1	95	<1	<1	--	--
23N/05E-23F01	03-18-88	170	8.2	.4	68	15	7.3	6.9	18	1.8	82	1.4	7.2	.05	.1	34	78	110	121	<1	<1	--	--
23N/05E-23L01	09-29-87	206	6.4	.7	86	18	10	6.3	14	1.7	82	3.5	15	.48	.1	24	68	39	148	<1	<1	1.1	--
23N/06E-19H02	03-14-88	121	7.8	.5	49	12	4.6	5.1	19	.9	59	2.1	2.8	.05	.2	29	330	170	83	<1	<1	.7	--
23N/06E-32C03	09-28-87	335	8.8	.2	38	10	3.1	67	76	7.8	178	4.8	4.8	.05	.1	18	35	15	228	<1	<1	--	--
											Qvr Unit												
21N/05E-13M02	09-21-87	108	6.5	--	39	9.5	3.7	3.7	17	.8	41	3.6	3.1	.77	.1	19	26	11	65	<1	<1	--	--
21N/05E-14F01	09-24-87	169	7.6	.2	71	17	6.9	4.5	--	1.4	80	1.9	8.2	.05	.1	20	160	130	103	--	<1	.7	--
21N/06E-18K01	09-23-87	140	6.4	8.1	53	14	4.7	5.0	17	.9	48	9.7	4.2	2.50	.1	21	3	1	91	<1	<1	.6	--
	03-08-88	134	6.6	7.6	51	13	4.6	5.0	18	.8	45	4.2	5.0	2.80	.1	23	200	3	93	<1	<1	--	BD
22N/04E-27H01	09-29-87	227	6.3	6.5	75	19	6.7	9.7	22	1.5	59	5.2	11	6.80	.1	31	7	21	151	<1	<1	--	--
22N/04E-27J03	03-17-88	165	6.6	1.2	69	15	7.6	6.1	16	1.2	62	3.4	9.8	1.40	.1	28	18	36	109	<1	<1	--	MOBD
22N/06E-20H06	03-15-88	104	6.3	4.8	36	10	2.6	5.2	24	.5	28	5.1	5.6	2.10	.1	18	15	3	72	<1	<1	--	--
22N/06E-28A02	09-30-87	124	6.2	1.4	44	12	3.3	4.6	19	.6	46	6.3	10	.05	.1	26	2,800	150	71	<1	<1	--	--
											Qvt Unit												
21N/04E-34E01	09-30-87	171	6.5	9.6	61	17	4.5	7.8	21	.8	41	11	13	2.60	.1	29	10	2	122	<1	6	--	--
22N/05E-16Q02	09-14-87	213	7.5	.0	88	17	11	6.5	14	1.7	93	6.1	9.8	.05	.1	31	650	300	116	<1	<1	--	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
											Qva Unit												
21N/04E-02Q02	03-02-88	213	6.8	2.6	85	16	11	6.9	15	1.9	90	4.5	19	0.05	0.1	33	5,200	310	127	<1	<1	--	BD
21N/04E-15K01	09-30-87	240	7.0	6.3	99	23	10	8.0	15	1.5	78	6.8	8.6	6.40	.1	31	2	1	146	<1	<1	--	--
21N/04E-17N02	03-07-88	145	6.6	4.1	60	11	7.9	5.7	17	1.4	58	3.8	9.2	.55	.1	30	3	41	100	<1	<1	--	--
21N/04E-19R01	10-07-87	127	7.6	.3	--	--	--	--	--	--	83	4.6	8.4	.05	.1	--	--	--	93	<1	62	--	--
21N/04E-20P03	03-18-88	205	7.6	.6	84	18	9.4	6.0	14	2.4	84	3.7	16	.05	.1	28	200	160	131	<1	<1	--	--
21N/04E-20Q02	10-02-87	173	6.9	2.0	75	15	9.2	6.6	15	1.5	71	3.7	11	.68	.1	29	3	20	110	<1	<1	--	--
21N/04E-27E01	03-07-88	205	6.5	2.8	84	17	10	7.2	16	1.7	81	6.4	7.3	1.70	.1	35	8	1	135	<1	<1	--	MOBD
21N/04E-30H02	03-18-87	180	7.0	1.2	70	16	7.3	6.1	16	1.9	73	3.2	11	.14	.1	33	19	1	120	<1	<1	--	--
21N/04E-32H01	10-08-87	165	7.0	2.4	65	10	9.8	5.9	15	2.5	56	9.5	10	.75	.1	31	43	10	120	<1	<1	--	--
	03-02-88	175	7.3	2.8	69	11	10	6.2	16	1.9	57	10	10	.66	.2	33	47	10	118	<1	<1	--	MOBD
21N/04E-32M01	10-02-87	465	8.4	1.1	110	28	8.6	47	49	2.8	135	63	1.8	.05	.1	31	38	100	303	<1	<1	--	--
21N/04E-33A02	09-29-87	173	6.8	2.7	65	12	8.5	5.8	15	7.3	70	2.7	8.3	.28	.1	29	2	1	107	<1	<1	--	--
21N/04E-33G01	10-07-87	152	7.8	1.0	62	14	6.5	6.5	17	3.0	74	1.6	3.7	.05	.2	31	38	220	100	<1	K2	0.7	--
21N/05E-01P01	10-05-87	142	7.2	.2	56	13	5.8	5.5	18	1.1	63	2.7	7.0	.37	.1	25	85	67	92	<1	<1	--	--
21N/05E-02E03	03-04-88	150	8.1	.6	62	14	6.6	5.7	17	2.0	68	1.2	7.9	.05	.1	24	92	120	99	<1	<1	--	--
21N/05E-05G02	09-25-87	118	7.0	.5	40	11	3.1	6.3	23	5.3	42	4.0	11	.05	.2	25	81	50	76	<1	<1	--	--
21N/05E-05J01	10-08-87	167	8.0	.3	68	17	6.1	6.3	17	2.0	81	2.1	5.0	.05	.1	25	110	120	100	<1	26	--	--
21N/05E-09E01	03-09-88	166	7.4	1.6	70	13	9.0	6.5	17	1.7	69	5.6	9.1	.64	.1	31	69	3	108	<1	<1	--	--
21N/05E-09H01	03-03-88	280	7.1	2.2	78	13	11	7.6	17	2.8	78	5.9	9.6	.24	.2	43	3	1	132	<1	<1	.5	--
21N/05E-09L03	09-24-87	185	7.9	.5	76	18	7.6	7.7	18	2.4	80	1.7	12	.05	.1	38	180	130	138	--	K11	.6	--
21N/05E-12D01	10-05-87	144	6.2	2.8	51	13	4.5	6.7	21	.8	45	5.8	6.2	2.60	.1	25	140	2	93	<1	<1	--	--
21N/05E-13G02	03-04-88	135	7.9	.8	54	17	2.9	4.1	14	1.7	59	1.6	7.2	.05	.1	18	28	28	88	<1	<1	--	BD
21N/05E-13Q02	03-08-88	54	6.2	.4	18	4	1.6	3.6	30	.6	17	5.3	18	--	.1	11	9,300	340	59	<1	<1	--	MOB
21N/05E-14E02	09-22-87	140	6.4	9.4	43	12	3.1	6.2	24	.9	31	4.8	9.0	4.60	.1	20	9	9	92	<1	K1	--	--
21N/05E-15R02	09-22-87	235	7.8	4.5	98	16	14	6.5	12	2.2	106	4.6	9.2	.05	.1	25	190	170	129	<1	<1	--	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
21N/05E-26M04	03-03-88	246	7.2	0.2	89	--	--	--	--	3.6	89	7.9	22	1.70	0.3	--	--	--	163	<1	<1	--	--
21N/06E-04B05	09-23-87	150	6.7	4.9	53	14	4.5	8.3	25	.7	55	2.4	15	.32	.1	11	2	1	88	<1	<1	--	--
21N/06E-04Q03	09-24-87	152	6.6	5.6	50	14	3.6	8.8	28	.8	50	3.5	10	1.70	.1	14	19	4	92	--	<1	--	--
21N/06E-06K02	10-05-87	66	6.1	.2	13	3.5	1.0	4.0	40	.4	23	3.9	5.0	.05	.1	10	4,500	46	44	<1	<1	--	--
21N/06E-07P01	09-23-87	168	7.0	.2	67	17	5.9	6.9	--	--	80	--	4.7	.05	.1	26	700	--	--	<1	<1	--	--
21N/06E-18Q01	03-17-88	115	6.4	7.8	40	10	3.6	4.5	20	.7	29	5.4	4.3	3.50	.1	22	4	1	88	<1	<1	--	--
21N/06E-19H02	03-08-88	112	7.5	.6	46	9.6	5.3	3.9	16	1.3	42	2.3	11	.05	.1	23	53	21	75	<1	<1	0.5	--
21N/06E-19L02	03-08-88	143	7.9	1.0	58	16	4.5	4.1	13	1.8	60	1.8	.3	.05	.1	20	14	18	92	<1	<1	--	--
21N/06E-20F03	09-23-87	138	7.0	9.6	51	14	4.1	4.0	14	1.6	53	2.1	4.1	.05	.1	20	4	2	82	<1	<1	--	--
	03-08-88	128	6.9	8.6	55	15	4.3	4.2	14	.8	53	3.0	4.0	1.20	.1	21	4	1	88	<1	<1	--	BD
21N/06E-20G03	03-08-88	151	7.9	.6	63	17	5.1	4.8	14	2.2	67	2.0	7.2	.05	.1	26	33	9	97	<1	K1	--	--
21N/06E-22R07	09-25-87	142	7.3	4.0	58	12	6.9	6.5	17	6.2	60	3.5	2.2	1.70	.1	24	37	8	86	<1	K4	--	--
21N/06E-22R08	03-07-88	137	6.8	6.9	52	12	5.4	5.5	19	.6	51	5.1	1.9	2.20	.1	23	36	1	92	<1	<1	.4	BD
21N/06E-24M02	09-25-87	220	8.2	.2	97	27	7.2	6.6	12	2.2	95	1.1	17	.05	.1	20	220	210	127	<1	K11	.8	--
	03-17-88	210	8.3	.4	88	24	6.8	6.3	14	1.1	90	1.3	16	.05	.1	21	180	200	130	<1	<1	--	--
21N/06E-27B01	03-17-88	362	7.7	.3	150	36	14	20	23	1.2	190	3.0	5.9	.05	.2	33	480	110	221	<1	<1	--	--
22N/05E-09A02	03-14-88	224	7.8	.6	97	19	12	6.7	13	.9	95	4.0	15	.05	.1	37	49	67	147	<1	<1	--	--
22N/05E-10A03	09-14-87	184	6.9	6.9	73	11	11	6.4	15	1.4	67	4.0	6.5	1.80	.1	29	11	4	100	<1	K2	--	--
	03-10-88	183	6.8	6.4	79	12	12	6.6	16	1.3	71	4.5	7.0	1.90	.1	30	9	4	108	<1	<1	.5	--
22N/05E-10H03	03-16-88	195	6.9	4.5	80	14	11	6.3	15	1.4	79	3.7	5.1	2.70	.1	26	4	1	122	<1	<1	--	--
22N/05E-11N02	03-10-88	144	6.9	5.2	58	11	7.4	5.3	17	.9	55	3.7	6.4	1.30	.1	23	17	17	89	<1	<1	--	--
22N/05E-12R07	09-14-87	150	7.7	2.9	63	13	7.5	6.1	17	1.7	72	1.9	5.1	.56	.1	29	2	1	92	<1	<1	--	--
22N/05E-13H02	03-15-88	175	7.2	4.0	73	18	6.9	6.7	17	2.2	81	2.1	3.9	.21	.2	27	25	47	110	<1	<1	.7	--
22N/05E-14K02	03-15-88	144	7.0	1.6	60	12	7.4	5.2	16	1.0	57	4.2	5.4	.95	.1	21	18	2	89	<1	<1	--	MOD
22N/05E-15E01	03-09-88	198	7.1	5.7	83	19	8.7	8.4	18	2.7	95	2.5	6.0	.05	.2	21	54	810	111	<1	<1	--	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
22N/05E-15P01	03-09-88	367	8.0	0.5	150	41	12	21	23	3.0	187	2.8	13	0.05	0.1	24	190	80	214	<1	<1	3.1	--
22N/05E-16M03	09-16-87	195	7.4	9.2	86	18	10	6.1	14	1.6	87	2.7	8.3	.34	.1	26	2	1	118	<1	<1	--	--
22N/05E-16M04	09-16-87	136	7.4	3.5	53	11	6.2	5.4	17	1.1	54	3.4	7.2	1.00	.1	22	21	5	89	<1	<1	--	--
22N/05E-17H02	03-11-88	230	7.7	.5	110	21	13	6.1	11	2.0	99	3.2	16	.05	.1	27	210	190	142	<1	<1	--	O
22N/05E-17K01	03-11-88	170	7.8	5.0	68	14	8.0	5.4	15	1.8	74	2.9	8.2	.05	.2	22	20	95	105	<1	<1	--	--
22N/05E-22N02	09-15-87	327	7.3	.8	140	33	14	8.3	12	2.4	108	9.4	38	.24	.1	23	35	250	187	<1	<1	--	--
22N/05E-22R02	09-21-87	182	7.9	.2	70	17	6.8	9.6	21	2.9	80	2.3	8.8	.05	2.1	35	250	84	124	<1	<1	--	--
22N/05E-23E03	09-18-87	213	7.2	.6	80	19	7.8	8.8	17	6.2	86	8.3	11	.22	.1	23	20	50	126	<1	<1	--	--
22N/05E-23P05	03-16-88	168	6.9	2.6	72	13	9.5	5.9	15	1.5	73	3.2	5.7	.91	.1	24	10	1	103	<1	<1	--	BD
22N/05E-24E01	09-18-87	149	7.4	5.2	61	12	7.5	5.5	17	1.2	66	3.0	3.5	.98	.1	24	5	1	91	<1	<1	--	--
22N/05E-24E04	09-18-87	161	7.5	3.3	69	13	8.8	5.8	15	1.5	75	2.5	12	.78	.1	26	7	2	101	--	--	--	--
22N/05E-27M01	03-10-88	212	8.0	3.2	96	22	10	6.9	13	3.7	96	5.0	12	.05	.2	29	18	44	137	<1	<1	--	--
22N/05E-32K01	09-15-87	206	7.2	4.5	90	18	11	7.3	15	1.9	82	4.6	11	.62	.1	27	3	9	122	<1	<1	1.3	--
	03-18-88	208	7.3	1.3	83	17	9.9	6.9	15	1.7	85	4.4	12	--	.1	27	3	11	131	<1	<1	--	--
22N/05E-34K03	09-16-87	154	7.8	.0	58	14	5.7	5.2	15	1.3	72	1.6	11	.05	.1	31	1,200	280	106	<1	<1	--	--
	03-08-88	150	7.8	.0	61	15	5.8	5.4	16	2.8	70	2.1	8.7	.05	.1	33	1,800	300	102	<1	<1	--	--
22N/05E-34L04	09-16-87	172	8.1	.8	70	14	8.5	5.1	14	1.3	77	2.1	9.4	.05	.1	23	33	190	111	<1	K3	.9	--
22N/05E-35B03	09-22-87	147	8.2	.2	52	13	4.8	7.8	24	2.0	69	1.1	3.2	.05	.1	29	76	80	96	<1	<1	--	--
	03-08-88	141	8.3	.4	52	13	4.8	8.1	25	1.7	70	1.6	3.0	.05	.1	30	110	82	110	<1	<1	.5	--
22N/05E-35M02	03-09-88	250	8.1	.5	90	24	7.3	16	27	3.7	127	1.8	2.3	.05	.2	43	10,000	210	162	<1	<1	--	--
22N/05E-35M03	03-09-88	200	7.4	.2	79	20	7.0	8.1	18	3.0	91	2.9	10	.05	.2	39	10,000	190	154	<1	<1	--	--
22N/05E-35P01	03-09-88	147	6.5	9.9	55	12	6.1	6.5	20	1.5	47	5.8	9.9	2.30	.1	21	24	12	98	<1	<1	--	BD
22N/06E-06A04	03-14-88	170	7.1	6.6	68	14	8.1	6.3	17	1.2	71	3.6	5.3	.05	.1	27	11	1	107	<1	<1	.3	BD
22N/06E-06Q03	03-11-88	188	7.6	.4	79	16	9.4	6.4	15	4.2	79	2.2	13	.05	.1	39	1,100	520	133	<1	<1	--	--
22N/06E-18H01	09-18-87	161	7.6	1.2	67	13	8.5	6.2	17	2.3	74	1.4	5.7	.20	.1	22	28	26	96	<1	<1	--	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
22N/06E-19B01	09-18-87	205	7.2	1.3	84	17	10	5.8	12	1.5	78	6.1	7.3	2.60	0.1	23	2	1	117	<1	<1	0.7	--
22N/06E-19E03	03-11-88	185	8.2	.6	38	6.0	5.6	23	56	1.9	86	2.0	5.9	.10	.2	20	370	120	107	<1	<1	.6	MBO
22N/06E-19N01	03-10-88	104	6.4	3.3	33	8.1	3.0	5.8	28	.8	25	5.7	6.8	2.60	.1	14	25	4	68	<1	<1	--	--
22N/06E-20E01	03-10-88	116	8.1	.3	46	12	3.9	4.8	19	1.1	54	1.6	3.4	.05	.1	21	76	56	78	<1	<1	--	--
22N/06E-22K02	10-07-87	122	6.8	1.0	48	15	2.6	4.9	18	.6	55	1.7	2.9	.26	.1	27	9	1	86	<1	<1	--	--
22N/06E-27D08	03-14-88	85	6.8	7.8	33	9.1	2.6	3.5	19	.5	33	2.2	4.9	.33	.1	18	13	1	63	<1	<1	--	--
22N/06E-27P02	03-15-88	147	6.5	8.6	55	15	4.2	6.7	21	.8	33	7.7	7.6	5.00	.1	19	9	1	99	<1	<1	--	OBD
22N/06E-28B01	09-17-87	151	8.1	1.1	67	18	5.3	4.5	12	1.2	72	1.7	6.2	1.80	.1	24	62	99	92	K1	<1	.8	--
22N/06E-29G01	09-17-87	126	7.8	4.5	49	12	4.7	5.1	19	.7	51	2.6	4.3	.99	.1	23	6	1	85	<1	K1	--	--
22N/06E-30B01	09-17-87	138	8.0	.2	58	14	5.5	5.9	17	1.0	68	1.2	3.4	.05	.1	23	95	43	87	<1	<1	--	--
	03-14-88	138	--	.5	58	14	5.7	5.9	18	1.0	68	1.3	3.6	1.55	.1	23	110	44	88	<1	<1	.4	MO
22N/06E-32A02	03-18-88	98	7.7	1.3	36	8.8	3.4	4.8	22	1.1	44	1.8	3.6	.15	.1	29	9	23	73	<1	<1	--	--
22N/06E-32H01	09-16-87	97	7.1	8.0	36	9.2	3.1	3.9	19	.6	36	3.5	4.1	1.20	.1	21	5	2	66	<1	<1	--	--
22N/06E-32Q03	03-16-88	154	7.7	3.5	62	17	4.7	5.2	16	1.2	59	2.5	12	.64	.1	26	8	1	104	<1	<1	--	--
22N/06E-33C01	09-15-87	122	7.5	6.6	46	11	4.6	4.5	17	.7	43	3.5	4.1	1.70	.1	22	11	2	73	<1	<1	--	--
22N/06E-33J04	09-16-87	108	7.1	9.2	39	11	2.8	4.3	20	.7	37	1.5	7.7	1.00	.1	19	21	4	72	<1	<1	.7	--
22N/06E-34R01	03-16-88	260	8.2	.5	110	31	8.5	9.4	16	1.8	133	1.6	4.4	.05	.2	18	150	100	152	<1	<1	--	--
22N/06E-34R02	09-17-87	242	8.2	.1	100	34	4.8	6.6	12	1.6	97	1.5	23	.05	.1	15	33	61	139	10	<1	--	--
22N/06E-36F01	03-14-88	350	6.8	6.8	150	29	18	13	17	1.2	98	2.5	65	1.10	.2	11	130	4	211	<1	<1	--	--
23N/04E-16D02	11-06-87	347	7.1	--	160	30	20	11	13	3.1	111	7.0	60	1.30	.1	44	9	330	234	<1	K1	--	--
23N/04E-22A01	10-01-87	368	7.1	.6	160	22	25	12	14	3.5	128	11	33	2.40	.1	32	54	150	221	<1	<1	--	--
	03-16-88	408	7.1	.3	170	25	27	13	14	3.6	143	13	42	2.40	.1	32	220	160	240	<1	<1	--	--
23N/04E-28H02	10-01-87	300	7.0	6.5	130	19	20	8.5	12	2.9	110	7.4	21	3.70	.1	38	2	1	185	<1	<1	--	--
23N/04E-33J01	10-01-87	261	6.6	5.9	110	20	14	9.9	17	1.4	87	5.2	19	4.00	.1	35	5	4	190	<1	<1	.9	--
23N/05E-28H01	09-28-87	211	8.0	.3	91	20	10	6.9	14	9.7	86	2.0	11	.05	.1	30	200	46	146	<1	<1	--	--
23N/05E-34D01	09-28-87	147	6.8	2.1	56	11	6.9	4.9	15	2.3	57	2.5	9.4	1.60	.1	26	14	11	95	<1	<1	--	--
23N/06E-31A02	09-29-87	138	6.8	8.4	51	11	5.7	5.0	18	1.1	47	2.3	9.3	1.50	.1	20	15	1	88	<1	<1	--	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
									Qva and Q(A)c Combined Unit														
21N/04E-07Q06	10-02-87	185	7.3	0.5	83	15	10	6.1	14	1.6	72	6.4	18	0.05	0.2	33	17	57	131	<1	<1	--	--
21N/04E-20L01	10-02-87	156	7.2	2.4	69	12	9.4	5.9	15	1.5	70	2.9	7.7	.18	.1	30	4	2	102	<1	<1	0.9	--
23N/04E-21C01	11-06-87	156	8.0	.0	63	14	6.8	6.4	18	2.8	69	3.5	7.8	.10	.1	41	190	61	118	<1	<1	.7	--
23N/04E-21C02	11-06-87	237	7.4	--	98	16	14	8.3	16	2.2	74	6.6	26	3.90	.1	38	3	1	159	<1	<1	--	--
										Q(A)c Unit													
21N/03E-14A01	10-02-87	167	6.8	4.3	120	18	19	8.1	12	2.8	107	8.4	27	2.00	.1	37	120	52	175	<1	<1	--	--
21N/04E-04J01	10-02-87	178	8.0	.8	76	15	9.4	6.1	15	1.7	86	1.8	3.6	.05	.1	35	150	539	121	<1	<1	1.2	--
	03-07-88	180	7.6	.6	79	16	9.5	6.2	15	1.8	88	2.0	4.0	.05	.2	36	110	540	130	<1	<1	--	MO
21N/04E-07R01	03-07-88	268	6.8	2.0	110	19	15	7.5	13	2.2	97	7.7	20	1.20	.1	30	23	190	164	<1	<1	.5	--
21N/04E-09J01	10-06-87	164	7.3	.4	64	14	7.1	6.9	19	1.9	79	1.8	5.0	.05	.2	42	16	370	116	<1	<1	--	--
21N/04E-15B01	10-02-87	150	8.0	.4	65	15	6.1	5.3	15	1.4	70	1.7	5.2	.05	.1	28	24	129	100	<1	<1	--	--
	03-07-88	153	8.1	.6	65	16	6.1	5.4	15	1.4	71	2.0	5.3	.05	.2	29	30	130	105	<1	<1	--	MO
21N/05E-01B02	09-16-87	132	8.2	4.0	52	14	4.1	4.2	15	2.1	62	1.3	4.1	.05	.1	30	46	40	92	<1	<1	--	--
	03-17-88	132	8.0	5.0	51	14	3.9	4.2	15	2.0	62	1.3	4.4	.05	.1	29	41	36	93	<1	<1	--	--
21N/05E-03A04	09-21-87	185	8.3	.3	79	18	8.2	6.4	15	1.7	86	2.2	7.9	.05	.1	27	77	160	106	<1	<1	--	--
21N/05E-04G01	03-07-88	181	8.4	9.1	86	20	8.8	7.0	15	2.3	94	3.0	2.5	.05	.2	27	40	82	117	<1	<1	--	MO
21N/05E-05C01	09-21-87	180	7.8	1.8	73	20	5.8	8.9	20	1.5	85	1.5	7.4	.05	.1	20	4	1	106	<1	<1	.8	--
	03-17-88	183	7.5	1.6	74	20	5.9	8.6	20	1.4	86	1.7	7.7	.05	.1	21	3	2	114	<1	<1	.3	MO
21N/05E-10R02	03-04-88	215	8.5	.6	65	19	4.2	21	40	3.5	107	2.7	4.3	.05	.1	21	9	20	134	<1	<1	.7	--
21N/05E-10R03	03-03-88	211	8.3	2.8	58	17	3.7	29	51	3.2	117	3.4	7.3	.05	.2	20	43	17	150	<1	<1	--	--
22N/04E-04B01	09-30-87	70	8.7	1.3	28	9.3	1.2	2.0	14	.3	27	5.2	2.6	.05	1.0	9	29	1	59	<1	<1	1.2	--
22N/04E-08K03	10-01-87	174	8.1	.3	70	19	5.4	6.7	17	2.1	81	2.1	4.4	.05	.1	37	210	40	110	<1	<1	--	--
22N/04E-27J02	09-29-87	210	6.9	8.1	81	16	10	7.4	16	2.9	81	2.8	11	3.10	.1	38	5	3	148	<1	K2	--	--
22N/04E-27J04	09-30-87	168	7.2	6.5	66	13	8.2	6.6	18	2.0	56	2.4	17	1.80	.1	34	12	2	114	<1	<1	--	--
22N/04E-34L02	09-28-87	164	7.7	.9	65	14	7.3	5.4	15	1.8	65	3.2	11	.05	.1	32	370	590	113	<1	<1	.7	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
22N/04E-34M02	09-16-87	165	7.8	3.3	66	16	6.4	6.4	17	2.4	73	2.1	9.5	0.05	0.1	25	19	30	104	<1	<1	0.9	--
22N/05E-03M01	10-01-87	131	7.6	.5	44	9.4	4.9	4.4	17	1.7	58	1.8	5.6	.22	.1	23	10	38	86	<1	K1	.7	--
22N/05E-12J01	09-14-87	136	7.4	1.2	53	11	6.3	5.1	17	1.5	62	1.6	3.9	.14	.1	31	13	11	83	<1	<1	--	--
22N/05E-14E01	03-11-88	163	7.3	.6	65	14	7.4	6.7	19	.7	74	2.5	6.2	.05	.2	40	350	280	125	<1	<1	--	--
22N/05E-14F02	03-14-88	185	7.1	.8	81	16	9.9	6.5	14	6.4	82	2.0	8.8	.05	.1	33	230	240	124	<1	<1	--	--
22N/05E-14N02	03-14-88	158	7.4	.6	65	16	6.1	6.2	16	5.9	73	2.0	6.9	.05	.1	38	130	120	118	<1	<1	1.1	--
22N/05E-15B02	03-10-88	142	8.1	--	56	12	6.2	5.7	16	8.7	65	2.1	4.1	.10	.1	38	280	220	107	<1	<1	--	--
22N/05E-15M01	03-09-88	252	7.9	1.4	110	24	12	6.6	12	3.6	114	3.9	12	.05	.2	26	31	45	148	<1	<1	--	--
22N/05E-21B04	09-17-87	256	7.6	--	120	28	11	6.9	12	2.9	127	2.1	2.1	.15	.2	30	48	430	151	<1	<1	--	--
22N/05E-22B02	03-10-88	140	8.2	.3	62	16	5.4	7.2	20	2.1	71	1.9	2.7	.05	.2	42	120	92	110	<1	<1	--	--
22N/05E-23F01	09-22-87	282	7.1	.1	120	30	10	5.8	10	2.5	135	1.7	2.4	.05	.1	53	4,399	1,000	196	<1	<1	--	--
	03-10-88	260	7.2	.1	120	29	11	6.2	11	2.5	136	2.4	14	.05	.2	52	3,100	860	184	<1	<1	2.5	BD
22N/05E-27D03	09-15-87	235	8.3	.5	73	19	6.3	21	36	4.3	123	1.8	1.6	.05	.1	25	31	29	138	<1	<1	1.4	--
22N/05E-27H02	09-22-87	157	8.2	.2	62	14	6.6	5.9	17	2.4	74	2.4	3.9	.05	.1	36	55	130	106	<1	<1	.8	--
	03-16-88	155	8.2	.5	60	13	6.6	5.8	17	2.4	73	2.4	3.4	.05	.2	36	8	140	113	<1	<1	--	--
22N/05E-28C01	09-22-87	156	7.5	3.8	63	13	7.4	4.8	14	1.6	57	4.0	13	.05	.1	27	30	130	97	<1	<1	.6	--
22N/05E-28J03	09-18-87	242	6.8	--	100	20	13	7.2	12	1.7	83	7.4	15	1.60	.1	28	6	5	144	<1	<1	--	--
22N/05E-32K03	03-09-88	163	8.4	.4	61	16	5.1	9.2	25	1.5	77	1.7	4.4	.05	.1	27	41	63	97	<1	<1	--	--
22N/05E-32Q01	03-07-88	208	7.2	2.9	87	20	9.1	7.3	16	1.4	76	5.6	16	1.70	.1	20	71	190	135	<1	<1	.7	--
22N/05E-34K04	09-16-87	181	8.4	.1	61	17	4.4	13	30	2.1	92	1.3	4.9	.05	.1	25	68	44	109	<1	K1	--	--
	03-08-88	184	8.4	1.2	63	18	4.4	13	31	1.2	91	1.8	4.9	.05	.2	26	44	41	114	<1	<1	--	--
22N/05E-34M03	03-08-88	240	8.0	8.5	100	23	11	7.7	14	1.9	99	5.0	18	.05	.2	29	17	110	147	<1	<1	--	--
22N/05E-34Q03	09-15-87	178	7.7	.3	74	16	8.2	5.7	15	1.8	81	2.2	7.5	.05	.1	25	170	140	102	<1	<1	--	--
22N/06E-05B01	09-30-87	157	7.0	.9	63	18	4.4	4.7	14	1.0	54	2.0	20	.05	.1	17	15	15	95	<1	<1	--	--
22N/06E-05P02	03-18-88	128	7.9	.8	50	9.3	6.5	4.5	16	1.5	51	2.9	10	.05	.1	20	44	130	82	<1	<1	.4	--

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
22N/06E-05Q01	03-14-88	145	8.0	0.6	59	13	6.5	4.8	15	1.6	63	2.0	8.3	0.05	0.2	26	45	65	100	<1	<1	--	--
22N/06E-08F04	09-28-87	165	7.2	1.6	66	12	8.2	5.7	14	9.7	61	3.7	10	.39	.1	17	109	12	109	<1	<1	--	--
	03-15-88	174	7.3	2.2	74	15	8.8	6.1	16	1.2	67	4.2	14	.53	.1	18	66	6	103	<1	<1	--	BD
22N/06E-08G01	09-29-87	264	8.0	--	110	22	13	9.3	16	3.3	112	1.7	21	.05	.1	33	130	140	170	<1	<1	--	--
	03-15-88	258	8.3	.4	110	23	13	9.5	16	3.0	111	2.2	22	.05	.1	33	150	140	163	<1	K1	--	--
22N/06E-08M01	03-18-88	332	7.8	.6	150	34	15	12	15	2.8	179	1.7	2.8	.05	.1	27	1,100	360	197	<1	<1	--	--
22N/06E-09P02	03-15-88	203	8.2	.4	85	20	8.5	6.3	14	1.5	97	1.4	6.8	.05	.1	26	110	190	123	<1	<1	--	BD
22N/06E-16D03	03-11-88	207	7.7	.0	91	20	10	8.0	16	1.6	108	1.7	7.9	.05	.2	28	930	220	128	<1	<1	0.9	--
22N/06E-16P01	03-10-88	150	8.6	.4	62	17	4.7	5.5	16	1.9	72	1.5	3.9	.05	.2	24	65	65	98	<1	<1	--	--
22N/06E-17K04	09-18-87	165	7.6	6.9	71	15	8.2	6.1	15	1.5	76	1.6	5.3	.53	.1	23	3	2	95	<1	<1	--	--
22N/06E-17P01	09-29-87	99	7.0	9.9	38	9.3	3.7	3.8	18	.8	36	2.5	2.7	1.30	.1	21	8	2	64	<1	<1	.6	--
22N/06E-17Q03	03-15-88	139	7.3	.4	53	12	5.5	7.9	25	1.2	67	1.9	1.8	.05	.1	20	740	140	85	<1	<1	--	--
22N/06E-22L01	09-17-87	132	7.6	9.0	54	15	4.0	4.8	17	.7	52	2.9	3.9	1.40	.1	23	75	3	84	<1	<1	--	--
22N/06E-22L02	03-14-88	132	7.5	7.2	54	15	3.9	4.7	16	.7	52	3.0	4.2	1.40	.1	23	8	1	92	<1	<1	.4	--
22N/06E-27P01	03-14-88	163	8.0	1.6	71	21	4.4	5.2	14	1.3	76	2.0	4.8	.18	.1	18	25	1	106	<1	<1	--	BD
23N/04E-16D03	11-06-87	262	7.0	2.0	110	17	16	8.6	15	2.8	90	7.0	32	1.30	.1	35	60	10	169	<1	<1	--	--
23N/04E-19R01	10-06-87	188	7.8	--	71	16	7.6	10	23	3.4	95	2.2	1.8	.05	.1	44	55	98	139	<1	<1	--	--
23N/05E-33F01	03-17-88	177	8.1	5.6	69	14	8.3	5.7	15	2.4	76	3.1	11	.05	.1	34	59	74	121	<1	<1	--	--
23N/05E-33G01	03-15-88	199	7.9	.4	69	18	5.8	14	30	3.2	100	1.7	2.6	.05	.2	40	190	170	142	<1	<1	--	--
23N/06E-29M03	09-29-87	480	9.1	.3	4	1.3	.3	10	98	1.1	224	5.6	15	.10	.2	7	72	8	271	<1	<1	--	--
											Q(A)f Unit												
21N/04E-34P02	10-02-87	139	8.0	4.5	58	14	5.5	6.0	17	1.9	67	2.1	4.1	.05	.1	34	20	170	92	<1	<1	--	--
21N/05E-08B05	03-03-88	187	8.0	4.4	85	19	9.1	6.3	14	3.0	85	3.0	12	.05	.2	32	40	27	129	<1	<1	.8	MO
21N/06E-19J01	09-23-87	120	8.6	.2	49	14	3.3	3.7	14	1.1	47	1.5	10	.05	.1	24	44	37	81	<1	<1	--	--
22N/05E-21E03	03-15-88	210	8.1	.4	87	22	7.9	12	23	1.9	110	1.7	1.2	.05	.2	27	180	130	130	<1	<1	--	--
22N/06E-18D02	03-15-88	200	7.2	.4	86	20	8.8	7.3	16	1.6	85	3.8	12	.05	.1	36	1,300	610	135	<1	<1	--	BD

Table 20.--*Chemical analyses of ground-water samples from selected wells, by hydrogeologic unit, southwestern King County--Continued*

Local well number	Date of sampling	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen	Hardness (as $CaCO_3$)	Calcium	Magnesium	Sodium	Percent sodium	Potassium	Alkalinity (as $CaCO_3$)	Chloride	Sulfate	Nitrogen (NO_3+NO_2)[1]	Fluoride	Silica	Iron (µg/L)	Manganese (µg/L)	Dissolved solids (residue on evaporation at 180°)	Fecal-coliform bacteria[2] (colonies per 100 mL)	Fecal-streptococci bacteria[2] (colonies per 100 mL)	Dissolved organic carbon	Remarks
											Q(B)f Unit												
NONE																							
											Q(B)c Unit												
21N/05E-04E01	09-21-87	205	8.2	0.2	69	20	4.6	17	34	2.7	106	1.8	2.8	0.05	0.1	27	140	54	125	<1	<1	--	--
21N/05E-08F03	03-04-88	289	8.4	.6	49	13	4.1	46	66	2.9	139	10	2.4	.05	.1	30	30	30	186	<1	<1	1.2	--
21N/05E-10R04	09-21-87	290	8.7	.1	48	14	3.1	41	63	3.1	125	5.3	14	.05	.1	18	20	23	172	<1	<1	1.2	--
21N/05E-24E03	09-24-87	182	8.7	.3	60	17	4.2	17	38	2.1	91	2.7	8.0	.05	.1	19	22	31	119	--	<1	--	--
22N/04E-08A03	10-01-87	186	8.3	.7	62	16	5.4	9.4	24	2.7	74	3.9	12	.05	.1	32	23	90	124	<1	<1	--	--
22N/04E-08K07	03-10-88	193	7.8	.6	70	17	6.6	9.2	22	2.2	80	4.2	11	.05	.2	36	15	55	129	<1	<1	--	--
22N/04E-09A04	10-01-87	168	8.3	.1	58	15	4.7	8.3	23	2.3	78	2.1	1.3	.05	.1	30	35	46	109	<1	<1	--	--
	03-10-88	162	8.0	.6	66	18	5.0	9.1	23	2.4	81	2.4	1.3	.05	.2	33	32	50	110	<1	<1	.6	MO
22N/05E-07J03	09-17-87	175	7.8	--	67	18	5.3	9.7	24	1.5	90	2.2	3.0	.05	.1	24	18	75	107	<1	<1	--	--
22N/05E-21P04	03-16-88	152	6.1	.4	58	14	5.6	5.9	18	1.8	73	1.7	2.3	.05	.2	26	41	83	106	<1	<1	--	--
22N/05E-28E02	03-17-88	188	8.1	.5	76	18	7.5	6.5	16	2.9	90	2.6	7.5	.05	.2	26	43	110	122	<1	<1	--	--
22N/05E-30C01	09-15-87	216	8.0	.3	92	22	8.9	6.7	14	2.2	94	3.2	12	.05	.1	30	310	310	123	<1	<1	--	--
											Bedrock												
21N/06E-17R01	09-23-87	300	8.2	2.1	40	13	1.9	54	73	1.1	159	1.7	5.5	.70	.1	17	690	28	177	<1	22	--	--
	03-08-88	303	8.2	2.0	38	12	2.0	61	77	1.4	163	2.3	4.9	.05	.1	19	710	29	190	<1	<1	--	--
21N/06E-23D01	10-07-87	126	7.8	.2	47	11	4.7	6.7	23	2.9	62	1.5	8.4	.05	.1	27	1,300	180	86	<1	<1	--	--
22N/06E-33N01	09-16-87	146	6.8	.8	49	13	3.9	8.9	29	.7	58	7.6	10	.33	.1	16	32	30	103	<1	<1	--	--
23N/05E-25R02	03-14-88	225	7.7	.2	44	10	4.7	33	61	1.4	109	1.7	4.9	.52	.2	18	28	11	136	<1	<1	--	--

[1] Values of 0.05 were reported by the analyzing laboratory as 0.10 mg/L, and were halved for statistical purposes.

[2] Even if no bacteria are detected in a 100-mL sample, it cannot be assumed that the water is totally free of bacteria. Therefore, a zero count is expressed as less than one (<1). A "K" indicates a nonideal count. Ideal concentrations for counting purposes are 20-60 colonies/100 mL for fecal coliform bacteria and 20-100 colonies/100 mL for fecal streptococci bacteria.