Plan of Study for the Puget-Willamette Lowland Regional Aquifer System Analysis, Western Washington and Western Oregon

By John J. Vaccaro

With a section by Marshall W. Gannett

A contribution of the Regional Aquifer-System Analysis Program

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CONVERSION FACTORS AND VERTICAL DATUM

To convert from	To	Multiply by
	Length	
foot (ft)	meter (m)	0.3048
mile (mi)	kilometer (km)	1.609
	Area	
acre	square meters (m^2)	4,047.
square mile (mi^2)	square kilometer (km^2)	2.590
	Volume	
gallon (gal)	liter (L)	3.785
	Flow	
gallon per minute (gal/min)	liter per second (L/s)	0.0631

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.

PLAN OF STUDY FOR THE PUGET-WILLAMETTE LOWLAND REGIONAL AQUIFER-SYSTEM ANALYSIS, WESTERN WASHINGTON AND WESTERN OREGON

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By John J. Vaccaro

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ABSTRACT

In October 1989, the U.S. Geological Survey began a study of the ground water in the Puget-Willamette Lowland underlying part of western Washington and northwestern Oregon as part of its Regional Aquifer-System Analysis program. The Puget-Willamette Lowland is underlain by of two distinct, hydrologically separated aquifer systems, the Puget Sound Lowland aquifer system and the Willamette Valley aquifer system. The study area for the Puget Sound Lowland, which includes the Puget Sound drainage, encompasses about 16,200 square miles; about 5,700 square miles of this area is underlain by the aquifer system. The Willamette Valley study area includes all of the drainage area of the Willamette River, which is entirely in Oregon, and parts of adjacent drainages in Columbia County, Oregon, and Clark County, Washington. This study area encompasses about 11,200 square miles, of which about 4,100 square miles are underlain by the aquifer system.

The Puget Sound Lowland aquifer system comprises Quaternary alluvial, glacial, and interglacial unconsolidated sediment, whereas the Willamette Valley aquifer system comprises Tertiary and Quaternary consolidated and unconsolidated alluvial material and basalt lava flows. Tertiary sedimentary, volcaniclastic, volcanic, and metamorphic rock units underlie and also crop out east and west of each of the aquifer systems and define their basal and lateral boundaries.

Water problems in the Puget Sound Lowland generally are quantity problems. The surface-water supply is either fully appropriated or approaching that status and ground water is being viewed as the remaining source of water. The principal ground-water problems in the Willamette Valley includes inadequate well yields to meet demands of uses, ground-water level declines, and poor water quality.

The specific objectives of the study are to: (1) describe the hydrogeologic framework, (2) describe the hydrogeologic characteristics, (3) describe the regional ground-water flow system within each area and major controls to it, (4) estimate the water budget for selected areas and regional water budget relations based on that information; and (5) provide analytical capabilities necessary to allow for a synthesis of available knowledge of the ground-water flow systems. This report describes the generalized hydrogeologic setting, previous investigations, water problems, objectives, and the scope and approach of the study to meet those objectives of the study. Work elements and time lines are summarized at the end of the report.

INTRODUCTION

The U.S. Geological Survey began a nationwide RASA (Regional Aquifer-System Analysis) program in 1978 in response to congressional concerns about the availability and quality of the Nation's ground water (Sun, 1986). The purpose of the RASA program is to aid in the effective management of important ground-water resources by providing information on the hydrogeology of regional aquifer systems, as well as analytical capabilities necessary to assess management alternatives. A summary of the RASA program has been printed by Sun (1986). The Puget-Willamette Lowland was chosen as one of the regional aquifers to be studied in this program. This study will be the first comprehensive regional assessment of the ground-water resources of the Puget-Willamette Lowland.

The Puget-Willamette Lowland lies along the Puget Willamette Trough (McKee, 1972) and is located in western Washington, western Oregon, and a small part of southwestern British Columbia, Canada (fig. 1). The area extends from near the Fraser River, British Columbia, Canada to just south of Cottage Grove, Oregon. The Puget-Willamette Lowland is underlain by two distinct aquifer systems (subareas), those of the Puget Sound Lowland and the Willamette Valley. The Puget-Willamette Lowland study area includes about 27,400 mi^2 (square mile); the Puget Sound Lowland encompasses about 16,200 mi^2, about 2,500 mi^2 of which is saltwater, and the Willamette Valley encompasses about 11,200 mi^2. The two subareas include the Puget Sound and Willamette River, which drain parts of the Cascade Range, the Coast Range, and the Olympic Mountains. The extent of the principal aquifers to be studied in the Puget Sound Lowland is defined by the area underlain by Quaternary sediment; in the Willamette Valley it is the area underlain by the Quaternary sediment and upper Tertiary sediment and volcanic rocks. The lateral extent of these aquifers within each subarea is about 5,700 mi^2 for the Puget Sound Lowland and about 4,100 mi^2 for the Willamette Valley. Both of the aquifer systems consist of several structural ground-water basins.

The lithology of the aquifers in the Puget-Willamette Lowland is highly variable, owing to the complex geologic history of the area. Alluvium and glacial and interglacial sediment compose the aquifer system in the Puget Sound Lowland; these sediment consist principally of Quaternary river alluvium, recessional and advance outwash, till, and other glaciofluvial and interglacial sediment. In the Willamette Valley, alluvium, basin-fill sediment, and basalt materials compose the aquifer system. Older Tertiary sedimentary, volcaniclastic, volcanic, and metamorphic rock units define the lateral and basal boundaries of the aquifer systems in the study area.

About 70 percent of the population of Washington and Oregon reside in the study area, mainly within the metropolitan areas of Bellingham, Everett, Seattle and vicinity, Tacoma, and Olympia in the Puget Sound Lowland, and Vancouver, Portland and vicinity, Salem, and Eugene in the Willamette Valley. The burgeoning population is increasing the demand for the available water. In some areas, available water supplies are already fully appropriated, and supplies are limited, owing to contamination from anthropogenic sources and to saltwater intrusion from the Puget Sound in the Puget Sound Lowland and by brackish ground water in the Willamette Valley.

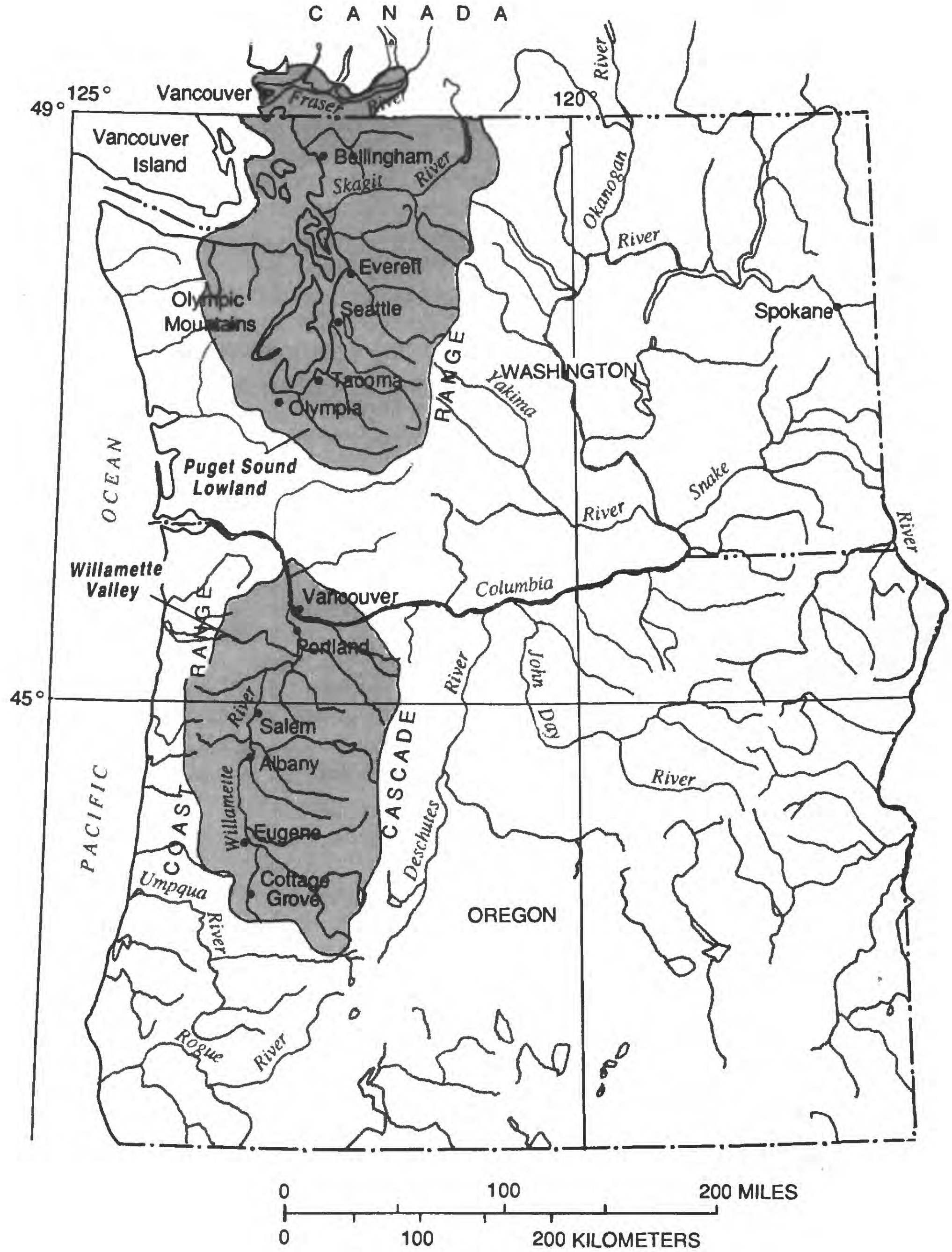

Figure 1.—Location of the Puget Sound Lowland and the Willamette Valley, which make up the Puget-Willamette Lowland Regional Aquifer-System Analysis study area.

Purpose and Scope

The purpose of this report is to describe the objectives of the Puget-Willamette Lowland RASA study, the approach, the major work elements, and the work schedule to attain these objectives. Because of the nature of the study, the work elements and schedule included in this report should be considered as a general guide that will be revised and updated periodically as information is compiled and new information is collected and analyzed.

In order to meet the overall RASA program goals, the major objectives of this study are to: (1) describe the geologic framework, (2) describe the hydrogeologic characteristics of the regional aquifer system, (3) describe the regional ground-water flow system within each subarea and major controls on it, and (4) estimate the water budget for selected areas and use this information to estimate the regional water-budget relations, and (5) provide analytical capabilities necessary to allow for a synthesis of knowledge of the ground-water flow systems.

The report first describes the physical and geologic setting and the major water problems. It then describes and discusses the scope and approach to be used to complete the major project objectives with respect to work elements. Last, the report includes a brief summary of the work elements and tasks, the project work schedule, and the reports being planned. For most of the discussions only that part of the Puget Sound Lowland within the United States will be covered.

As part of the planning stages of this study two bibliographies were compiled, one for each area. The Puget Sound Lowland bibliography (Jones, 1990) covers the relevant investigations in Puget Sound Lowland related to water resources. This bibliography also includes textbooks and investigations of other glacial aquifers that may be applicable to the study of the Puget Sound Lowland glacial aquifer system. A comprehensive bibliography was developed for the Willamette Valley (Morgan and Weatherby, 1992) because there was none available. This bibliography is indexed by subject and area and will provide information for many future investigations.

PHYSICAL SETTING

The Puget-Willamette Lowland is a structural basin that extends from just north of the Fraser River in British Columbia at about 49 degrees 15 minute latitude (hence the term Fraser-Puget-Willamette Trough) to about Cottage Grove in central western Oregon at about 44 degrees latitude; the southern boundary is a line of foothills where the Coast and Cascade Ranges merge (fig. 1). The Puget-Willamette Lowland is bordered by the Cascade Range on the east and the Coast Range and Olympic Mountains on the west. North of the Olympic Mountains the western boundary is defined by the Canadian-Washington border located in the waters south and east of Vancouver Island, British Columbia. The southern boundary of the Puget Sound Lowland is approximately defined by the extent of the Pleistocene glaciation, which is characterized by a series of low hills near the southern extent of the Puget Sound drainage; however, it extends beyond the Puget Sound drainage to include three drainages that encompass some 274 mi^2. The northern boundary of the Willamette Valley is located north of Vancouver, Washington and is defined by an outcrop of the Columbia River Basalt Group. The Puget Sound Lowland extends about 200 mi in a north-south direction; the lowland part ranges from about 5 to 50 mi in width and averages about 20 mi. The Willamette Valley extends about 120 mi in the north-south direction; the valley floor ranges from 12 to 15 mi in width in the southern part and widens gradually northward to a maximum of about 45 mi.

Altitudes of the valley floors or lowlands range from sea level to about 500 ft (feet). The foothills or uplands of both areas have altitudes ranging from 500 to about 1,500 ft. The altitude of the crest of the Cascade Range averages about 7,500 ft on the north to about 4,500 ft on the south, but a series of stratovolcanoes in the Cascade Range rise from 8,000 to 14,000 ft above sea level. The altitude of the Olympic Mountains in the northwest part of the Puget-Willamette Lowland averages about 3,000 ft. The rugged Coast Range in the southwest has lower altitudes, averaging less than about 2,500 ft, but altitudes are as high as about 4,100 ft.

In the Puget Sound Lowland, the lowlands typically comprise alluvial river valleys separating glacial outwash and till plains. These lowlands are separated from the bordering mountains by uplands with rolling hills and terraces. The transition from the uplands to the mountains generally is abrupt except near the southern boundary of each subarea. The Willamette Valley topography is interrupted in places by narrow, north and northwest trending basalt highlands which divide the north central part of the valley into unequal sized east and west segments. The topography is also interrupted in southwest Portland by irregular shaped low volcanic hills consisting of basalt lava flows. These volcanic hills and ridges range in altitude from a few hundred to as much as 1,200 ft. The geologic structures present in the Willamette Valley divide the valley into four structural and topographic basins.

The Puget-Willamette Lowland has a mid-latitude humid, Pacific Coast marine climate due to the eastward moving air masses derived from the Pacific Ocean. The adjacent mountains provide protection from the southward moving Canadian cold-air masses and from the Pacific Ocean winter storms. As a result, both summer and winter temperatures are moderated; there is a distinct winter precipitation season and summer dry season; and altitude and location have a large influence on the distribution of precipitation and on temperature.

Within the lowlands of the Puget Sound Lowland, precipitation ranges from about 16 in/yr (inches per year) in the "rain shadow" of the Olympic Mountains to about 46 in/yr near the foothills of the Cascade Range. Within the lowlands of the Willamette Valley precipitation ranges from about 37 in/yr near Portland, Oregon, to about 55 in/yr near Sandy, Oregon. Much of the lowlands receive about 40 in/yr.

In the Cascade and Olympic foothills of the Puget Sound Lowland, the annual precipitation ranges from 50 to about 100 in/yr, with the larger values being more typical of the Olympic Mountains. Correspondingly, the annual precipitation in the Coast and Cascade foothills in the Willamette Valley ranges from about 50 to about 100 in/yr.

Throughout the Cascade Range, at altitudes between about 1,500 and 2,500 ft, precipitation ranges from about 60 to 104 in/yr, and at higher altitudes precipitation is generally more than 90 in/yr. Precipitation at higher altitudes in the Coast Range bordering the Willamette Valley ranges from about 100 to about 200 in/yr.

Most of the precipitation falls during the winter season and is generally rain below about 1,000 to 1,500 ft, is rain and snow at altitudes up to about 2,500 ft, and is snow at higher altitudes. The summers within the Puget-Willamette Lowland are relatively dry; average July precipitation is generally less than about 0.75 in. in the lowlands.

Mean annual maximum air temperatures range from about 60°F (degrees Fahrenheit) in the lowlands to about 47°F in the mountains, while mean annual minimum temperatures range from about 40°F in the lowlands to about 31°F at higher altitudes. Summer temperatures in the mountains are cool because they are moderated by the high altitudes; winter minimum temperatures generally stay below freezing.

Generally, summer temperatures range from 60 to 80°F in the Puget Sound Lowland and from 60 to 90°F in the Willamette Valley; winter temperatures range from 30 to 50°F in both the Puget Sound Lowland and Willamette Valley. Below freezing temperatures in the Puget Sound Lowland occur 20 to 90 days per year at night during the winter and freezing temperatures are generally limited to 10 to 20 days per year during daytime.

In the Puget Sound Lowland, annual surface-water runoff from about 13,700 mi^2 averages about 46,000 ft^3/s [cubic feet per second] (45 in/yr). Runoff for the islands in the northern Puget Sound, which represent less than 3 percent of the total Puget Sound Lowland land area, averages about 10 in/yr. Runoff for the Willamette River drainage is similar and averages about 33,000 ft^3/s (40 in/yr) from about 11,100 mi^2. Runoff within selected basins in both subareas range from about 35 in/yr to 80 in/yr and represents a large part (70 to 90 percent) of the total precipitation.

The Puget Sound Lowland contains 21 major drainages or hydrologic units and Willamette Valley contains 14 (U.S. Geological Survey, 1976). Many of the surface-water drainage basin boundaries and ground-water basin boundaries are assumed to be equivalent. The runoff in parts of the Puget Sound Lowland is controlled by the presence of about 386 glaciers which cover about 116 mi^2 and contain about 13 million acre-feet of water. The glaciers help to provide consistent summer flows in some of the larger rivers.

Numerous natural lakes are present in the Puget Sound Lowland, while lakes in the Willamette Valley are few and generally manmade. About 24 major manmade reservoirs in the Puget Sound Lowland store about 3,100,000 acre-feet and 23 major reservoirs and lakes in the Willamette Valley have a storage capacity of about 4,000,000 acre-feet.

HYDROGEOLOGIC SETTING

The Puget Sound Lowland and the Willamette Valley share some common features, but in other respects, are quite different. Some of the common features include:

- -- alluvial aquifer/stream systems formed as a direct or indirect result of glaciation;
- -- received meltwaters from alpine glaciers;
- -- north-south elongated basin;
- -- bounded on the east by the Cascade Range;
- -- bounded on the west by the Olympic Mountains and Coast Range which separate the Puget Sound Lowland and Willamette Valley, respectively, from the Pacific Ocean;
- -- aquifer system composed of thick, extensive unconsolidated sediment which contain large volumes of potable ground water;
- -- geologic structure separates aquifer system into basins;
- -- base of aquifer systems is composed of Tertiary marine sediment and volcanic rock materials; and
- -- rivers drain water from the adjacent mountains through the lowlands.

Some of the major differences include:

- -- the Puget Sound Lowland was inundated by at least four continental glaciations; the continental glaciers did not extend into the Willamette Valley;

- -- alpine glaciers extended into the lowlands of the Puget Sound Lowland; alpine glaciers did not extend into the valley floor of the Willamette Valley;

- -- the unconsolidated deposits of the Puget Sound Lowland aquifer are predominantly glacial and interglacial deposits; the unconsolidated deposits of the Willamette Valley aquifer are predominantly basin-fill sediment and alluvial deposits;

- --The Puget Sound Lowland aquifer is composed of only unconsolidated sediment; the Willamette Valley aquifer includes consolidated rock materials (Miocene basalts of the Columbia River Basalt Group);

- --the bedrock underlying the Puget Sound Lowland is considered to be more intensely faulted, folded, and eroded than that underlying the Willamette Valley; there are hundreds of small earthquakes every year in the Puget Sound Lowland, earthquakes are rare in Willamette Valley;

- --the central drains of the Puget Sound Lowland are Puget Sound and Hood Canal, which are saltwater arms of the Pacific Ocean; the central drain of the Willamette Valley is the Willamette River, which is fresh water.

Geology

The topography and geology of the Puget-Willamette Lowland are largely the products of tectonic convergence of two lithospheric plates. The North American continental plate has been converging with the oceanic plates of the northern Pacific basin throughout much of Cenozoic time (Atwater, 1970; Engebretson and others, 1985). Pleistocene glaciation has further modified the regional geologic setting of the Puget Sound Lowland, and Tertiary basaltic lava flows have modified the regional setting of the Willamette Valley.

The Cascade Range is an active magmatic arc formed by the continuing subduction of the Juan De Fuca plate beneath the North American plate. Most of the western edge of the Cascade Range is bounded at depth by marine sedimentary and volcanic complexes of Eocene through Miocene age that have in part been accreted to the North American plate (Cady, 1975; Adams, 1984; Snavely, 1988). The Olympic Mountains, for example are part of an exotic terrane, a remnant of the upper part of the descending oceanic plate that was scraped off the subducting plate, became attached to the leading edge of the North American Plate, and uplifted; the mountains lie on the trench-slope break and are part of the trench system. The Puget-Willamette Lowland is a forearc basin (Dickinson, 1976), a geologic feature which commonly lies between the trench and magmatic arc (fig. 2). The subducting Juan De Fuca plate dips easterly about 11 degrees for a distance of about 110-135 mi, and then the plate dip steepens to 20-45 degrees east. It is hypothesized that the forces acting on the descending plate at this bend causes a surface depression above it, thus creating the Puget-Willamette Lowland (Spence, 1988).

The Cordilleran ice sheet, which originated in the Coast Range in British Columbia, advanced on the Puget Sound Lowland at least four times during the early Quaternary and several partial advances have been identified in the northern part of the Puget Sound Lowland (Blunt and others, 1987). The last glacial period is called the Fraser Glaciation. Advances of the ice sheet have occupied all of the lowland areas and have extended laterally into the lower mountain valleys. Alpine glaciers, from the Cascade Range and the Olympic Mountains, also extended into the Puget Sound Lowland. As a result, interlayered glacial drift and interglacial deposits, as much as 3,600 ft thick, mantle the older Tertiary rocks. The distribution and thickness of the unconsolidated glacial and interglacial sediment is related to the configuration of the preglacial bedrock surface, the lithology of the bedrock, and the positions of preglacial, glacial, and postglacial stream channels.

During the early stages of the structural development of the Willamette Valley, lava flows of the Miocene Columbia River Basalt Group, originating in the Columbia Plateau of eastern Washington and Oregon, crossed into the Willamette Valley. Many flows followed the ancestral Columbia River valley and other low areas and extend to the Pacific Ocean. Some of these flows also extended north into Washington and south into the Willamette Valley. Subsequent late Tertiary volcanism and uplift and Quaternary glaciation in the Cascade Range and uplift of the Coast Range provided the sediment sources and processes to deposit valley-fill sediment in the Willamette Valley.

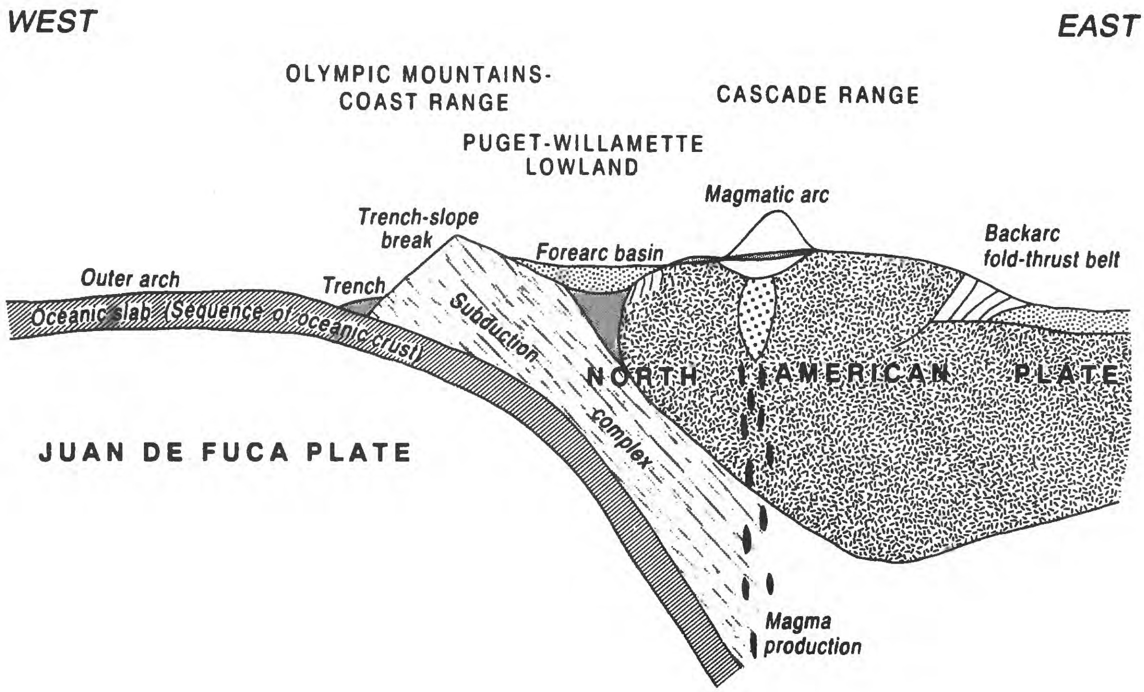

Figure 2.—Diagramatic section showing generalized tectonic features (modified from Dickinson, 1976).

At the northern part of the Willamette Valley, the Columbia River transported and deposited large amounts of sediment from source areas outside the Willamette Valley. The fine-grained character of much of the lower sections of this valley fill indicates a slow depositional rate. Volcanism in the Cascade Range gradually increased and resulted in the deposition of coarser grained valley-fill sediment. Volcanism also resulted in a number of eruptive centers and lava flows in the northern Willamette Valley during this stage. These volcanics, the Boring Lavas, are compositionally similar and related to volcanism of the High Cascades. Later Pleistocene events resulted in erosion and deposition of glacier-derived rock materials. Glacial flood-waters from the upper Columbia River basin (the Missoula Flood) inundated the Willamette Valley and created backwater lakes in the southern and western parts and deposited silt and fine sand throughout most of those areas below about 350 ft. The hills around the Portland area are veneered with deeply weathered thick silt of wind blown origin (Lentz, 1981). As a result of this geologic history, the northern part of the Willamette Valley aquifer system includes Tertiary lava flows, upper Tertiary fluvial sediment, and Quaternary alluvium. The Willamette Valley aquifer system south of about Albany, Oregon consists of the basin-fill alluvial materials as thick as 300 ft.

Aquifer System

Puget Sound Lowland

The U.S. Geological Survey currently divides the Quaternary sediment in the Puget Sound Lowland into aquifers and confining beds depending on whether they are predominantly coarse or fine grained and their mode of origin. The method of division generally consists of the following:

1. The uppermost coarse-grained deposits are considered to be one hydrogeologic unit--an aquifer. These deposits generally consist of advance or recessional outwash deposited during the most recent advance and retreat of the ice sheet. These units can be very localized or extensive.

2. Recent alluvial deposits comprise a separate hydrogeologic unit. This unit is present at the land surface in the large river valleys and can be quite extensive. It varies from fine-grained to coarse-grained. In the upper to middle river reaches, the unit is predominantly coarse-grained. In downstream reaches, the unit generally becomes more fine-grained and lenses of sand and gravels in this unit function as aquifers. Except for the areas where the sand and gravel lens have been developed, little information is available on the lithologic changes in the unit with depth owing to the sparse numbers of wells. Thus, this unit can be classified as a poor aquifer or a semi-confining unit based on its overall fine-grained character or as a productive aquifer where it contains more coarse-grained materials.

3. Fine-grained, cemented tills are generally classified as a semi-confining unit. Commonly, there can be several till units in a column of sediment at a specific locality. In some areas, these deposits overlie or underlie interglacial sediment and cannot be differentiated from them using information from well drillers' logs; in such cases, the tills are included in the interglacial hydrogeologic unit (see 4. below).

4. Interglacial and proglacial deposits generally are fine-grained and are classified as confining units. In some areas, these units contain lenses of sands and gravel which, if sufficiently thick, function as aquifers.

5. Coarse-grained sands deposited by glacial meltwaters during glacial interstades are classified as aquifers.

6. Deposits generally more than 200 to 500 ft below land surface are undifferentiated. In some areas where deep well information is available, these deeper deposits can be divided locally into hydrogeologic units, depending on whether they are predominantly coarse- or fine-grained.

   Deeper coarse-grained sediment generally include recessional and advance outwash sand and (or) gravel, and intervening till deposits. The deeper fine-grained sediment generally are interglacial deposits consisting of clay, silt, and fine sand.

Lithologic descriptions of materials listed on water-well drillers' logs are generally adequate for regional correlation of hydrogeologic units, but most water wells penetrate only the upper 100 to 500 ft out of a total thickness of more than 3,500 ft. On the basis of information in the U.S. Geological Survey's National Water Information System, of more than 23,000 wells in the Puget Sound Lowland, more than 50 percent are less than 100 ft deep, only about 2,300 or 10 percent are more than 250 ft deep, and only about 360 wells are more than 500 ft deep. As a result, the lithology of the deeper deposits is generally unknown. Drillers' logs from a few deep exploratory wells drilled for petroleum or for water are available, but these data are too sparse to adequately describe the deep deposits in the Puget Sound Lowland. Indeed, sequences of sedimentary units cannot be defined with enough accuracy using these deep well logs to identify the pre-Fraser glaciations.

The extent of the hydrogeologic units in the study area is highly variable, both locally and regionally. The localized uppermost recessional outwash deposits generally average about 10 ft in thickness. In a few areas, however, there are large, well-defined, relic recessional outwash channels filled with coarse-grained deposits; these deposits can be up to 150 ft thick, but generally average about 40 ft. The thickness of the upper till that mantles much of the Puget Sound Lowland is highly variable, reaching more than 125 ft in some locations, but it generally is about 20 and 40 ft thick. The thickness of the coarse-grained deposits present below the upper till averages between 40 and 50 ft. Although it reaches a maximum thickness of more than 400 ft in some areas, a maximum of 150 to 200 ft is more common. The underlying fine-grained deposits consist of glacial till or silt-clay interglacial sediment. Their thickness is known to exceed 150 ft in some areas and averages about 40 to 65 ft. The sequence of the deposits described above generally comprises the upper 200 to 500 ft of the aquifer system. The only study to date (Sapik and others, 1989) that has differentiated the deep Quaternary deposits indicates that, with increasing depth, the semi-confining and confining fine-grained deposits appear to compose a larger part of the aquifer system than the coarse-grained deposits. Near the boundaries of the aquifer system, the units are highly variable in extent.

Regional ground-water movement generally is from topographic highs to topographic lows which are typically stream drainages or saltwater bodies. That is, ground water moves from the glaciated uplands fronting the Olympic Mountains and Cascade Range to the surface-water drainages and to the saltwater bodies (Hood Canal, Puget Sound, the north Sound, and the Strait of Juan de Fuca) and ground water moves from topographic highs in the peninsular-island parts of the Puget Sound Lowland to the saltwater bodies.

The direction of ground-water movement is predominantly horizontal in the aquifers and vertical in the confining units. Vertical gradients generally are downward, except near streams and saltwater bodies, where gradients are upward. Generally, ground water moves downward to deeper units in the higher areas and upward from the deeper units to shallower units in lower areas. Ground water in the uppermost aquifer generally occurs under water-table conditions and ground water in the deeper aquifers generally occurs under semi-confined or confined conditions. Ground water in the aquifers that are intermediate in depth between the uppermost and deeper aquifers generally occurs under either water-table or semi-confined conditions. The Tertiary bedrock, although it may be permeable in some areas, is assumed to be a confining unit and is considered to be the basement or the lower boundary of the aquifer system.

Movement of ground water is controlled by topography and the geometry of the aquifer system and by the distribution and rate of ground-water recharge and discharge. The configuration of the water table in the uppermost aquifer generally parallels the surface topography and water levels are generally within 100 ft of land surface. The configuration of the potentiometric surface of each successively deeper aquifer unit is a more subdued replica of land surface. In aquifers near or below sea level, the relation between the potentiometric surface and topography diminishes and aquifer geometry and discharge locations become more important controls.

In areas where the vertical movement is downward, shallow wells will have water levels near land surface, and deeper wells will generally have water levels much below land surface. In areas where vertical movement of water is upward, shallow wells will have water levels near land surface and deep wells will generally have water levels above land surface or nearby surface-water bodies. Generally, the depth to water in the uppermost one or two aquifers will be greater in areas of high topographic relief and or high land-surface altitudes than in areas of flat topography or of low land-surface altitudes. Thus, at higher altitudes the water levels decrease with depth and at lower altitudes (near sea level) water levels increase with depth. Water levels in the aquifers above sea level will range from near sea level to land-surface altitude (maximum of about 400-500 ft in altitude) and water levels in the units below sea-level will range from sea level to a maximum of about 100 ft.

The rate of lateral ground-water movement in the aquifer units is a function of the lateral hydraulic gradients and hydraulic conductivity. In the upper aquifers, lateral gradients generally range from 30-60 ft/mi (feet per mile) and in deeper units the gradients range from 5-10 ft/mi. The sediment lithology and aquifer geometry add further control to these broad, regional ranges. For example, the lateral gradients in the upper aquifers composed principally of very coarse-grained recessional outwash are low, generally 10-20 ft/mi, and near bluffs, cliffs, or in steep terrain, where aquifer units are truncated, the lateral gradients can approach 500 ft/mi. Lateral hydraulic conductivity of the glacial aquifers generally is between 30 and 550 ft/d (feet per day), and conductivity of the coarse-grained alluvium generally is between 100 and 200 ft/d.

Natural, seasonal water-level fluctuations in the uppermost aquifer generally range from 4 to 10 ft; larger fluctuations are related to aquifer geometry and lithology. Water-level fluctuations in the deeper aquifers are generally smaller than 4 ft. Shallow wells tend to show rapid response to recharge during the winter precipitation season and deeper wells tend to show a time lag of 1 to 3 months. Ground-water levels also fluctuate in response to tides. Tidal effects have been found to vary from 0.02 ft to 7.5 ft and quickly approach zero at distances from 500 to 1,000 ft away from the shoreline (Drost, 1982; Lum and Walters, 1976).

The temporal and spatial distribution of recharge entering the ground-water system varies due to the distribution of precipitation, topography, soil permeability, land use and cover, and geology. Estimates of ground-water recharge vary widely (partly owing to the different estimation techniques used). Recharge has been estimated to range from about 10 percent to 100 percent of precipitation; the low estimates are for areas with a till cover and the high for areas with coarse-grained recessional outwash cover.

The quantity of recharge that enters the deeper aquifer units is difficult to determine and has only been estimated through water-budget or numerical ground-water modeling techniques. Drost (1982), in his study of the Gig Harbor peninsula, estimated that of the 222 ft^3/s of precipitation, 86 ft^3/s (39 percent of the total) became ground-water recharge; 34 ft^3/s of that quantity (15 percent of precipitation) recharged the deep aquifers. On Vashon Island, Carr and Associates (1983) estimated that of the 109 ft^3/s of precipitation, 14 ft^3/s (13 percent of the total) became ground-water recharge; about 3 ft^3/s (3 percent) of the precipitation recharged the deeper aquifers. Sapik and others (1989) estimated that between 40 to 50 percent of the precipitation falling on Whidbey Island recharged the uppermost aquifer. That quantity, 144 ft^3/s, was used as a boundary condition in a ground-water flow model. The model calculated that about 97 ft^3/s (67percent of the total recharge) entered an underlying aquifer and about 3 ft^3/s (2 percent of the total recharge) entered the two deepest aquifers.

The quality of water generally is suitable for most purposes. The dominant water types are calcium bicarbonate and magnesium bicarbonate in the upper aquifers. In addition, deeper aquifer units contain ground water of a sodium bicarbonate or a sodium chloride type. Generally, the occurrence of sodium bicarbonate water has been attributed to proximity with consolidated bedrock, to longer residence time in the ground-water system, and to the presence of fine-grained marine deposits of recent age. The sodium bicarbonate waters also contain larger concentrations of dissolved solids. Sodium chloride water generally is associated with mixing of native ground water with seawater; this water also has larger concentrations of magnesium.

Seawater has intruded some aquifers near the coast, most commonly in the island or peninsular areas of the Puget Sound Lowland and near large coastal pumping centers. Aquifers that are below sea level contain larger concentrations of chloride and show seasonal fluctuations in concentrations in selected locations. A chloride concentration value greater than about 100 mg/L (milligrams per liter) has been used as an indicator of seawater intrusion in the Puget Sound Lowland (Dion and Sumioka, 1984; Dion and others, 1988; and Sapik and others, 1989).

Elevated concentrations of iron and manganese are common in the glacial aquifers in the Puget Sound Lowland. Concentrations of iron and manganese greater than 2.5 mg/L and 0.65 mg/L, respectively, have been found in the aquifers in the region. Water-sample analyses in some of the coastal areas have shown that manganese can be more abundant than iron, an atypical condition for glacial aquifers.

Willamette Valley

By Marshall W. Gannett

The marine sedimentary rocks and associated volcanic and intrusive rocks that crop out in the Coast Range and underlie large parts of the Willamette Valley generally have very low permeability. These units are assumed to be a confining unit, the basement or lower boundary of the aquifer system, where they underlie major aquifer units. Similarly, the older Cenozoic volcanic and volcaniclastic rocks of the Western Cascades also appear to have very low permeability and are considered the basement confining unit where they occur. In the northern part of the Willamette Valley, these older volcanic and marine materials are overlain by basalt of the Columbia River Basalt Group. The basalt underlies younger Cenozoic sedimentary deposits throughout much of the northern part of the Willamette Valley and crops out on highlands within the valley and along parts of the periphery.

Ground water in the Columbia River Basalt Group occurs primarily in the interflow zones, which are composed of the top part of a basalt flow and the lower part of the overlying flow. The interflow zones contain very porous, highly fractured basal and flow-top breccias, clinkers, and, in places, interbedded coarse-grained sediment. The interior part of basalt flows are fractured and almost always exhibit jointing. The fractures and joints in flow interiors, however, are typically tight, have very low permeability, and restrict water movement. Basalts of the Columbia River Basalt Group, therefore, typically exhibit large lateral permeability, parallel to the interflow zones, and small vertical permeability across flow interiors. Because the volume occupied by fractures and joints in basalt is small in comparison with the total volume of the unit, the quantity of water stored in basalt is small when compared to sedimentary materials. Where basalt crops out, such as on the periphery of the Willamette Valley, ground water can occur under water-table conditions. Water in zones deep in a saturated basalt section or in basalt buried beneath fine-grained sediment is generally confined.

Collectively, the basalt flows of the Columbia River Basalt Group form a significant aquifer unit in western Oregon. Increased development of ground water in basalt for municipal, industrial, and agricultural uses has occurred in recent years. Basalt aquifers are still largely undeveloped in many places because overlying sediment are a more economically developed source of ground water.

The Columbia River Basalt Group is overlain by upper Tertiary and Quaternary continental sediment. In the southern part of the valley, where the Columbia River Basalt Group does not occur, continental sediment rests directly on the older Cenozoic marine sediment or volcanic materials. The stratigraphy, and possibly the age, of this sediment varies throughout the valley, reflecting a number of depositional regimes. The occurrence and movement of ground water within this sedimentary sequence varies accordingly. The general nature of sediment in the Willamette Valley is fairly well understood. However, with the exception of the Portland Basin, detailed hydrogeologic units have not been delineated.

In the northern part of the Willamette Valley, the lower part of the valley-fill sediment is predominantly fine-grained, consisting of moderately indurated mudstone, and siltstone with occasional thin sand and gravel layers. Previous ground-water investigators (Hogenson and Foxworthy, 1965; Price, 1967; Hampton, 1972) assign this fine-grained sequence to either the Sandy River Mudstone (Trimble, 1963) or the Troutdale Formation. Stratigraphically equivalent sediment in the Tualatin Valley is labeled "Tertiary and Quaternary valley fill, undifferentiated" by Hart and Newcomb (1965). In this report, this sediment will be referred to as Sandy River Mudstone. In the southern part of the Willamette Valley, no distinct fine-grained lower sequence has been mapped in the basin-filling sediment described in previous investigations (Frank, 1973, 1974 and 1976).

The Sandy River Mudstone generally is not considered an aquifer because of its overall low permeability. However, thin sand or gravel layers within this unit are permeable and, where present, can yield moderate amounts of water to wells. In the eastern part of the Portland Basin, the Sandy River Mudstone includes a large proportion of sand and gravel. This very coarse-grained facies was presumably deposited by the ancestral Columbia River. This important sand and gravel unit, known as the sand and gravel aquifer, is penetrated by several deep public-supply wells (Hartford and McFarland,1989; Swanson and others, 1991). Ground water in the Sandy River Mudstone occurs under confined conditions.

Overlying the Sandy River Mudstone in the northern Willamette Valley is a sequence of alluvial material consisting of variably cemented clay, silt, sand and gravel. Stratigraphically equivalent basin-fill material directly overlies marine sediment and Western Cascade volcanic material in the southern part of the Willamette Valley. This material varies in thickness in the axial part of the valley from a few tens of feet to several hundreds of feet and is assigned to various formal and informal geologic units. In the southern part of the valley, this sediment is typically referred to as "older alluvium" (Frank, 1973, 1974 and 1976). In the northern valley and the Portland Basin such sediment is typically assigned to the Troutdale Formation. In the Tualatin Valley, Hart and Newcomb (1965) refer to the alluvial material as Tertiary and Quaternary valley fill, undifferentiated.

The basin-fill sediment is generally the most important aquifer unit in the Willamette Valley. However, the occurrence and movement of ground-water flow varies throughout the valley due to changes in the overall lithology. Ground water occurs under confined or unconfined conditions in this sediment, depending on the stratigraphy at a particular location and the depth of the water-bearing zone in question. The distribution of permeability within the basin-fill sediment is only generally understood and, with the exception of the Portland Basin, no detailed mapping has been completed to delineate individual aquifer units or their characteristics. Detailed studies within the Portland Basin (Hartford and McFarland, 1989; Swanson and others, 1991) have delineated individual aquifer units within the basin-fill sediment of the Troutdale Formation. These units are known as the Troutdale sandstone aquifer and the Troutdale gravel aquifer. The stratigraphy of the basin-fill sediment in the Portland Basin is different from the remainder of the Willamette Valley owing to the influence of the Columbia River. Therefore, many of the hydrogeologic units recognized in the Portland Basin cannot be readily traced into other parts of the Willamette Valley.

Sediment deposited by the Missoula Flood overlies the basin-fill sediment and older rocks throughout the Willamette Valley up to an altitude of 350 ft. In the Willamette Valley south of the Portland Basin, the flood sediment primarily consists of bedded silt with interbedded clay and fine sand. This silt is known as the Willamette Silt (Allison, 1953). The Willamette Silt ranges from a few feet thick on the periphery of the valley to more than 100 ft. In the Portland Basin, where flood waters entered the Willamette Valley, the flood sediment is much coarser grained, and sands and gravels predominate; these materials are more than 300 ft thick in places.

The Missoula Flood sediment is an important component of the ground-water system in the Willamette Valley. The silt is unsaturated in many locations, but may be an important control on ground-water recharge. For example, Hampton (1972) points out that extensive areas covered by Willamette Silt lack developed surface drainages, suggesting that much of the precipitation that is not lost to evapotranspiration infiltrates through the silt into the underlying basin-fill sediment. The sands and gravels deposited by the Missoula Flood in the Portland Basin compose much of the unconsolidated sedimentary aquifer of Swanson and others (1991) as well as the Blue Lake gravel aquifer and part of the unconsolidated gravel/Troutdale gravel aquifer unit of Hartford and McFarland (1989). Ground water in the Missoula Flood sediment is probably unconfined.

Recent alluvial deposits along the Columbia and Willamette Rivers and major tributaries are locally important aquifers. These materials are generally hydraulically connected to streams and, where sufficiently permeable, will provide large quantities of water to wells. Ground water in recent alluvium generally is unconfined. Along the major streams, this alluvial aquifer consists of unconsolidated sand and gravel up to 70 ft thick but generally less than 50 ft thick. In the Portland Basin, recent alluvium forms part of the unconsolidated sedimentary aquifer of Swanson and others (1991) and part of the unconsolidated gravel/Troutdale gravel aquifer unit of Hartford and McFarland (1989). Specific capacities of wells completed in the recent alluvium commonly range between 25 and 100 gallons per minute per foot of drawdown.

Most regional ground-water flow in the Willamette Valley is currently thought to occur in the basin-fill sediment and overlying Quaternary deposits. Significant flow may also occur in the Columbia River Basalt Group. The quantity of water, if any, moving from the basement confining units is unknown but is assumed to be small in comparison. The high salinities of water contained in many of the basement confining units suggests that the movement of water within these units and across this boundary is negligible.

The degree of hydrologic connection between aquifers in individual basins in the Willamette Valley is not known. The basement confining unit forms the lower parts of the divides between the southern basin and the Willamette Valley north of Salem. This unit may tend to restrict ground-water movement between these two basins. The Portland Basin and most of the remainder of the Willamette Valley are separated by highlands consisting primarily of Boring Lavas and Troutdale Formation overlying Sandy River Mudstone and Columbia River Basalt Group rocks. A regional ground-water divide exists along at least part of this highland. There may be significant interbasin ground-water flow at depth below this highland through the underlying Columbia River Basalt Group rocks, but further work must be done before this can be evaluated.

Recharge in the Willamette Valley is primarily from precipitation. There may be some ground-water recharge from stream seepage in places, but the quantity and location of such seepage is unknown. Some suburban areas of Multnomah County in the Portland Basin are unsewered or lack storm sewers. In these areas, domestic-waste water is discharged to the subsurface through on-site waste disposal systems and storm water is discharged to the subsurface through drywells (sumps). These practices, which are generally being abandoned, apparently provide significant quantities of recharge in those areas.

Water-table maps indicate that ground water flows from the periphery of the valley and from highlands and flat areas within the valley toward surface streams. The ground-water flow system in the uplands is characterized by decreasing heads with increasing depth. Along major streams, heads increase with increasing depth in the ground-water system. The ultimate ground-water discharge area for the entire Willamette Valley is the Columbia River in the Portland Basin.

WATER PROBLEMS

Puget Sound Lowland

Most of the water problems in the Puget Sound Lowland generally are quantity problems. In many parts of the Puget Sound Lowland, the surface-water supply is either fully appropriated or approaching that status and it is recognized that the surface-water supplies are susceptible to both contamination and climate variations. Thus, over large areas, ground water is being viewed as the remaining source of appropriable water for the projected increase in water-use, especially for the islands and the peninsular land bodies in the Puget Sound Lowland. Also, it is recognized that the development of the ground-water resource can effect the available surface-water supplies, including springs, that some communities and individuals rely on. In some of the island/peninsular areas, streamflow is supported almost totally by ground water. This streamflow is generally of a small quantity (1 to 20 ft^3/s), fully appropriated, and relied on for fishery and wildlife management. Therefore, even a small capture of the streamflow by increased ground-water development may adversely impact instream flows.

Part of the water problem is related to well-yield. Ground-water storage appears to be large, but the variable geometry and hydraulic characteristics of the aquifer units results in small, discontinuous aquifers in many areas. As a result, widely distributed wells, rather than centrally located well fields, might be needed to meet the projected increase in water use. Identification of areas with a larger probability of having extensive aquifers is problematic. Similar to surface water, the shallow ground-water supplies are more susceptible than the deeper units to contamination and climate variations. If deeper aquifers are to be a future supply source, then more information on the hydrogeology of these units is needed. Water obtained from deeper aquifer units, in turn, might be of a poorer quality due to the geochemical evolution of the flowing ground water.

In some areas, aquifers have been contaminated by man and, in other areas, high concentrations of iron and manganese are present. The areas of man-caused contamination are generally predictable, while the areas of naturally occurring, poor quality ground water are not. Because of the extent and depth of the saltwater bodies in the Puget Sound Lowland, there is the potential for saltwater intrusion. The saltwater intrusion problem is greatest on the islands and in the peninsular areas of the Puget Sound Lowland.

Other local water-quality problems include the contamination and degradation of ground water through improper storage and disposal of wastes, and elevated concentrations of coliform bacteria and nitrate in shallow aquifers.

Willamette Valley

The principal surface-water problems in the Willamette Valley include inadequate flows to meet both instream and out of stream demands during low-flow periods, flooding, and water-quality degradation from urban, suburban, agricultural, and natural sources.

The principal ground-water problems include inadequate well yields to meet demands for domestic, irrigation, and other uses, ground-water level declines, interference among closely spaced wells, poor water quality, degradation and contamination of ground waters.

Problems with inadequate well yields are encountered most commonly in areas along the valley's west edge where basin-fill sediment is thin and fine grained and in the adjacent low hills which consist of low-permeability basement rocks. In such areas, up to 10 percent of the wells drilled for domestic supplies may yield inadequate supplies for household use, and development of irrigation wells is not possible.

Declining ground-water levels are associated with development of water supplies from the Columbia River Basalt Group in the northern half of the valley. Because the basalt aquifers can store only a relatively small quantity of water, pumpage can locally exceed recharge and lateral ground-water inflow and thus cause ground-water level declines. This is particularly true for ground-water development of the basalt near its updip margins. Locally declining water levels also may be due, in part, to local hydrogeologic boundaries such as faults and discontinuous basalt units.

Saline ground-water is encountered in parts of the valley, especially along the valley's west side where the basin-fill sediment is thin and overlies the marine sedimentary rocks. Large concentrations of arsenic, fluoride, boron, and chloride are reported in wells in selected parts of the southern part of the valley. Occurrences of arsenic appear to be related to the presence of marine-volcanic sediment. Such rocks are widespread in the southern part of the valley and are present in the foothills of the western Cascade Range; as a result, the problem may extend over a much wider area than is presently realized. The problem of upward flow of more mineralized older water is the most widespread natural ground-water-quality problem known in the Willamette Valley, and is poorly understood.

Contamination of ground water also is occurring from nonpoint sources such as agricultural and unsewered urban/suburban lands, as well as from point sources such as landfills and buried petroleum storage tanks. Ground-water contamination by a variety of hazardous materials has been reported in the Portland Basin at numerous locations. Contamination from accidental spills and from point sources appear to be more numerous in urban areas due to the concentrations of people, industry, and transportation networks. Because the soils over a large percentage of the urbanized part of the Portland Basin are highly permeable, the aquifer system there is susceptible to contamination from surface sources.

SCOPE AND APPROACH OF STUDY

Hydrogeologic Framework

A fundamental work element of the study is the determination of the hydrogeologic framework of the Puget-Willamette Lowland. The objective of this work element is to construct maps (where data exist) that show the configuration, thickness, and extent of the principal units that compose the aquifer system. Completion of this element will allow a three-dimensional representation of the hydrogeologic units including their lithologic character and extent. These data also will provide information for refining and improving the existing, preliminary conceptual models of regional flow.

The description of the hydrogeologic framework of the Puget-Willamette Lowland will proceed in four major steps: (1) Mapping of the structure contours of the altitude of the top of the basement confining unit), (2) delineation of the regional hydrogeologic units and their relation to geologic/stratigraphic units and previously defined hydrogeologic units, (3) preparation of selected hydrologic sections, and (4) the construction of regional structure contour maps for each hydrogeologic unit. This work will be integrated with previous and ongoing subregional ground-water investigations, with marine, land, and borehole geophysical surveys, with well inventory in areas currently without data, and with geologic investigations. The known lack of data for describing some of the units will preclude construction of maps for all study units.

Information to be used in this work element for the Puget Sound Lowland will be obtained from existing information in NWIS (National Water Information System) and from well logs on file in the U.S. Geological Survey Washington State office. Information to be used in this work element for the Willamette Valley will be obtained by reviewing about 5,000 Oregon well drillers reports, from which a small proportion will be selected for field location. Data bases for this part of the study include the U.S. Geological Survey's NWIS data base and separate lithology and hydrogeologic unit files.

The first step of this work element will be to construct a preliminary structure contour map of the top of the basement confining unit. For the Puget Sound Lowland, the map will be partly based on published and preliminary basement surfaces, (Banks, 1989; Hall and others, 1974; Pessl, 1982; Whetten and others, 1988; and Yount and Othburg, 1983). Maps from these sources show either the thickness of unconsolidated deposits or the depth to bedrock. Additionally, about 10,000 drillers' logs will be checked and appropriate data plotted to help identify the depth to bedrock. The configuration of the top of the basement confining unit for the Willamette Valley will first be estimated from the available information. This product will be conceptual in nature because of the paucity of information on the basement. Areas with no information will be delineated and, if time permits, studied in more detail in the later part of this study. Also, these areas would be target locations for the application of surface geophysical surveys during the second year of study. Thus, areas where the most information on bottom geometry could be gained from the surveys will be identified first. The early mapping of the top of the basement also will provide a guide for constructing the structure contours of the top of the other hydrogeologic units. In about January 1992, the basement configuration will be updated and finalized using any newly available information.

Concurrently, cross-sectional numerical models of ground-water flow will be constructed in selected areas. These models will be used to test the sensitivity of the simulated ground-water flow system to errors in the basement geometry. This process will help delineate those areas, or type of environments, where greater accuracy is needed in the basement geometry. This work also will enable identification of areas where geophysical surveys and exploration wells would provide the most beneficial data for future investigations. In selected areas, geophysical surveys will be used in the second year of the study to obtain better definition of the basement geometry.

Step 2 will be to describe the major, regional hydrogeologic units. This includes estimating their areal extent, their dominant sediment composition, and describing their relations to stratigraphic units. Regional correlation charts (one for each area) will be compiled during this step. The delineation of the hydrogeologic units for the Willamette Valley will parallel the division and the nomenclature established by the U.S. Geological Survey's Portland Basin investigation as much as possible.

Information from previous and ongoing studies will be assessed to assist in the definition of appropriate major hydrogeologic units for regional study. That information will include hydraulic conductivity, hydraulic heads, and stratigraphy. Because of their small extent, some local hydrogeologic units will be combined with other regional units based on common characteristics such as grain size. The reasoning for combining small units into a regional unit will be described.

The third step of this work element will be the construction of hydrogeologic sections. Existing sections will be identified. New sections will be added in selected areas using available control defined in the lithology and NWIS files or drillers' logs on file in each office. Where possible, the sections for the Willamette Valley will be linked together and extended to the boundaries of the aquifer system. This will provide for accuracy and error checks; some reassignments of hydrogeologic units might need to be revised at this point. In areas without well or geophysical information, the sections will be inferred. Areas with little or no control will be identified in order to define the areas where new data are needed and where the limited manpower resources will be expended.

Using prepared hydrogeologic sections, structure contours, and digitized land-surface altitudes, the last step will be to define the structure contours, thickness, and lateral extent of selected hydrogeologic units defined in step 2. For the Puget Sound Lowland, the available regional geologic maps (1:100,000 scale) first will be compiled on the basis of previous work (Frizzell and others, 1984; Logan, 1987a,b; Phillips, 1987; Roddick and others, 1979; Schasse, 1987a,b; Tabor and others, 1982; Walsh, 1987). The areas not included in the previous mapping will be identified. Available large scale maps for those areas will be compiled. Maps showing the areal extent of the hydrogeologic units will be constructed on the basis of correlations determined in step 2 and previously compiled geologic maps. The maps of areal extent, in conjunction with the constructed sections, and well and geophysical data will be used to construct structure contours for the top of selected units in the two areas. The thickness maps will be prepared, starting with the uppermost hydrogeologic unit, using land-surface altitudes, point elevation/thickness data interpreted from wells, and the structure contours.

Puget-Willamette Lowland project staff will integrate activities with ongoing U.S. Geological Survey projects to utilize project resources effectively. Additionally, hydrogeologic sections will be prepared and resources spent mainly in those areas where population growth is fastest and the need for water an increased understanding of the resources is greatest; these areas generally are on the east side of Puget Sound, in the northern Willamette Valley, and near Eugene, Oregon.

An attempt will be made to use marine seismic technology to obtain continuous seismic acoustic velocity profiles of basin-fill sediment along selected reaches of the Willamette River. The use of transient electromagnetic sounding techniques also may be tested at selected, favorable locations. This technique would be used to determine the depth to saline water and to profile, at pre-selected sites on the valley floor, the position of the top of shallow saline water discharging from the underlying, older Tertiary marine sediment. In the case where the saline water is nearly fully contained within the marine sediment, this technique would provide an estimate of the thickness of the basin-fill sediment.

The products from the above work will include a surficial unit map, structure contour maps of the top of selected units, a thickness map of each of these units, and a series of hydrogeologic sections.

Hydrologic Setting

Ground-water Flow System

The scope of the analysis of the ground-water flow system is to describe ground-water movement in the Puget-Willamette Lowland. This will include a description of the controls on the movement of ground-water, flow-path analysis, description of the lateral and vertical head distributions and differences, development of a conceptual ground-water flow model, and determining the feasibility for developing a method to delineate areas with the largest potential for ground-water development. In this analysis the saltwater-freshwater interface within the Puget

Sound Lowland and the upwelling of brackish waters in the Willamette Valley will be investigated. The quantity of flow will not be directly addressed in this work element. However, the information from this element will be integrated with ground-water flow modeling, estimation of hydraulic characteristics, and aquifer geometry to address the quantity aspect.

The description of the ground-water movement will proceed in discrete steps: (1) Analysis of existing water-level data, (2) testing of concepts of the movement of water in the aquifer system, (3) developing a conceptual model of ground-water flow, (4) assignment of hydrogeologic units to wells, (5) evaluation and possible development of an observation well network, (6) construction of preliminary water-level maps and (7) interpreting and summarizing the work completed above. Not all of the steps will be completed for each area and the order of the steps will be different for each area.

The first step for the Puget Sound Lowland will be a generalized regional analysis of the existing hydraulic-head information. This analysis will use most of the existing water-level information to construct water-level maps at a scale of 1:100,000 for the entire Puget Sound Lowland. Data will be segregated by well depth: shallow (less than 50 ft), medium (50 to 105 ft), and deep (greater than 105 ft) and maps will be constructed for either the latter two groups or the last group. The water levels in the shallow wells are closely related to land-surface altitude; that is, water levels are at least within 50 ft of land surface, a depth that is smaller than one-half of the land-surface contour interval on the 1:100,000 scale maps. A good regional representation of water levels in shallow wells can be constructed using land-surface altitudes and a regression relation between the altitude of water levels and land surface. These maps will be used to obtain an initial understanding of the lateral and vertical ground-water gradients, the direction of ground-water movement, and possible delineation of ground-water basins. The water-level data will then be examined to determine relations between well depth, land-surface altitude, and the locations of upward and downward vertical head gradients.

Previous analyses of the flow system will be compared with the above work. These previous analyses generally were restricted to small areas and included both descriptive and numerical-model analyses. Results of this effort may allow the project team to compare conceptual models of local and regional flow systems.

For the Willamette Valley, the hydrogeologic units that are open to a subset of the wells (selected for hydrogeologic interpretation in the previous work element) first will be determined. This step also will include an evaluation of the hydrogeologic units open in each well in the existing long-term observation well network operated by the Oregon Water Resources Department.

The areas with sparse or no water-level or well-inventory information will be identified during the above steps. That information will be combined with areas identified in the ongoing geologic work and work described in the next sections to delineate areas where inventories would provide the most information.

Cross-sectional flow models will be used to test differences among conceptual models of the aquifer system. The cross-sectional models also will be used to test concepts of vertical water movement and the hydrogeologic controls on that movement. The models will assist in the vertical discretization of the aquifer system into hydrogeologic units and in the understanding of the flow system.

The third step will use the results of the analysis of the water-level information, cross-sectional modeling, and previous studies to develop a final conceptual model or models of ground-water flow in the Puget Sound Lowland and Willamette Valley. During the study, eight to ten water samples will be collected and analyzed for tritium. These samples will, if possible, be collected along a flow path which would correspond to the flow path of one of the cross sections being modeled. This information would help to corroborate the conceptual model by delineating relative ages of ground water along a flow path.

The last step will synthesize the results of the above steps. The synthesis should enable the project staff to describe the movement of ground water in the Puget-Willamette Lowland.

Hydraulic Characteristics

The scope of this work element is to analyze existing information on the hydraulic characteristics and to describe these characteristics for the principal hydrogeologic units. The hydraulic characteristics will include, at a minimum, lateral and vertical hydraulic conductivity, and transmissivity. The storage coefficient, specific yield, and porosity also may be described if time permits. These characteristics will be related to geology, lithology, and depth in the aquifer system. The information compiled also will be analyzed to determine if geologic structures, such as folds and faults, affect hydraulic characteristics.

Aquifer test and specific capacity data will be assembled to calculate lateral hydraulic conductivity values, and hydraulic conductivity values derived through ground-water modeling will be compiled. Where possible, conductivity values calculated from aquifer- test and specific capacity data from identical wells will be compared; most aquifer tests are for municipal, fish hatchery, and ground-water exploration wells. The hydraulic conductivity values will be analyzed to obtain an understanding of the range, average, and frequency of occurrence of the values and to discern vertical and areal trends. Data that have already been segregated by hydrogeologic unit will be analyzed separately in a similar manner; resulting information from this analysis will be compared with all the data.

Wells that have specific capacity data, but have not been inventoried will be compiled; only those wells with either a well log or depth data will be included. The open intervals of any inventoried well will be assigned to a specific hydrogeologic unit. All inventoried wells and associated well data will be entered into the NWIS data base.

The hydraulic characteristics calculated for this work element will be used for preliminary estimates in ground-water flow models. Using water levels and the estimated hydraulic conductivities, flow nets may be constructed and analyzed.

For both areas, available information on vertical hydraulic conductivity will be compiled. Additionally, for the Puget Sound Lowland, widely distributed permeameter tests of glacial till will be conducted. These tests will be conducted because the vertical conductivity of the till is a major control on the quantity of ground-water recharge that the aquifer system receives. If time permits, permeameter tests also will be conducted on the more permeable glacial outwash materials in order to obtain an understanding of the variation in conductivity (control on recharge) between the till and outwash.

Storage coefficient, specific yield, and porosity information may be compiled. The porosity information would be used in estimating ground-water velocities in selected areas.

Stream-aquifer Relations

The purpose of this work element is to analyze ground-water movement to and from streams in the study area. The scope will include estimation of base flows of selected streams and, if time permits, estimating losing and gaining reaches of selected streams, and effects of lakes and reservoirs. This analysis would include a description of the control that each hydrogeologic unit has on the movement of ground water to and from the streams.

Locations of long-term streamflow gaging sites will be plotted and drainage basins (and surficial geology) delineated. Surface-water records for selected streams then will be analyzed. This analysis will encompass streamflow statistics, hypsometric relations, hydrograph separation (including baseflow separation), surface-water and ground-water drainage area, temporal and spatial distribution of precipitation, and the surficial distribution of hydrogeologic units. This information will be analyzed using several statistical methods (regression, correlation, time-series analysis) to determine if streams can be classified or grouped by selected characteristics. Once classified, then further study could be more narrowly directed toward selected streams within the more prevalent classifications. If they cannot be classified then representative streams for study will be selected based on common streamflow statistics (mean, standard deviation, skewness, coefficient of variation, and so forth).

In October 1991, one or more smaller perennial stream/s in the Puget Sound Lowland will be selected for study in conjunction with a district cooperative investigation during the period October 1991 through October 1992. It is tentatively planned that the stream would: (1) cross an area where a cross-sectional ground-water flow model is being constructed, and (2) traverse both glacial outwash and till materials in order to describe the difference in the stream-aquifer relations between those two geologic units.

At two or three locations along these selected stream/s, one of which will be located near a streamflow gaging station (at the other location(s) a staff gage would be installed), a shallow (about 20 ft) and a deeper (about 75 ft) piezometer will be installed close to the streams. These piezometers will be measured about twice a month and probably more often during sharply rising or falling stream stage. Alternatively, data loggers may be used to collect water-level stage information. Miscellaneous streamflow measurements may be made concurrently at the gaging station and staff gage sites. During relatively slow stage changes, only the staff gages would be read and discharge would be calculated from a derived stage-discharge relation. Also, streamflow and ground-water temperatures would be measured whenever the sites are visited.

During the year of monitoring, water samples may be collected at selected intervals from streams and piezometers. These samples would be analyzed for temperature, total dissolved solids, chloride, and oxygen and/or deuterium isotopes. Samples of precipitation also will be collected at selected sites that are currently equipped with rain gages and analyzed for chloride and the stable isotopes. One set of samples will be collected from the stream in about late January during high flow to determine if there are large variations in the stable isotope composition. The first comprehensive field sampling would be done during about April 1992, before, during, and after a period of precipitation. The next sets of samples would be collected in June and August 1992, during streamflow recession. Last, one set of samples will be collected in late October 1992 during a period of rising water levels. During each sample period, water samples also will be collected from existing wells near the streams. Preferably, the existing wells sampled will be spaced at increasing distances from the stream bank. If this sampling is undertaken, selected samples would be sent in for analysis to determine if concentrations are different enough to separate flow components.

The analysis of available streamflow data and the above constituent measurements will be used to study the hydraulic connection between the stream and aquifer and to estimate the probable range in the stream leakage coefficients. Last, these data will be used with the previously analyzed information and rainfall-runoff modeling results (R.S. Dinicola, U.S. Geological Survey, written commun., 1990; Dinicola, 1990) to assess whether stream-aquifer relations can be regionalized.

Application of Ground-water-flow Modeling Techniques

The scope of this work element encompasses the construction and use of ground-water flow models for integrating concepts on how the aquifer system operates, for estimating the various components of the water-budget and relating rates and distribution of recharge and discharge to hydraulic heads and regional ground-water movement. The U.S. Geological Survey's three-dimensional modular model (MM) by McDonald and Harbaugh (1984) will be used in most of this work element. For the Puget Sound Lowland, the two-dimensional (2D) model of Voss (1984), the three-dimensional (3D) model of Sapik (1988), and the 3D model of Essaid (1990) also may be used for assessing fresh-water saltwater relations.

The approach to this work element will be to first construct four to nine cross-sectional flow models. Each model will simulate a different hydrogeologic regime (a "type area"), generally delineated by the estimated total thickness of either the Puget Sound Lowland or the Willamette Valley and the configuration of bedrock. These models will be constructed during the first 3 years of the study. They will be constructed where previous and or ongoing studies provide an adequate data base. These models would be detailed owing to the local nature of the studies that they will be based on.

The models will be used to: (1) develop and test conceptual models of the regional flow system on the basis of the detailed local models, (2) test vertical discretization options for modeling the aquifer system, (3) estimate major controls on ground-water movement, (4) test effects of errors in estimating the depth to the top of the basement confining unit, (5) examine vertical head differences among units and lengths of flow paths, (6) estimate the probability of fresh ground-water movement in aquifers beneath saltwater bodies, (7) compare cross-sectional and 3D model results, (8) estimate effect of saltwater bodies on the freshwater-saltwater interface, (9) estimate hydraulic characteristics that might be appropriate for use in a regional 3D flow model (especially vertical hydraulic conductivity), 10) test ground-water-flow modeling techniques, and (11) estimate components of the ground-water budget.

As many as six models will be constructed along sections where the data are reliable and plentiful; this will allow the models to be calibrated or nearly so; lack of information on the deep system may preclude calibration. The results of the models will guide the development of later models in areas with less data and will assist in developing and testing concepts about the ground-water flow systems. These models also will be used to calculate flow paths and travel times; on the basis of those calculations, wells along one or two cross sections will be selected for sampling for isotopes (tritium and possibly chlorine-36). The results of the analysis will test the calculations and veracity of the conceptual model.

The SUTRA model (Voss, 1984), which simulates density-dependent ground-water movement, will be used to model flow along one of the cross sections in Puget Sound Lowland. However, it is time-consuming and difficult to use and the results of the SUTRA model are not directly transferable for use with the MM. The model will be used to test whether freshwater hydraulic heads and head-dependent boundary conditions are adequate to simulate the freshwater movement into saltwater bodies. Additionally, the SHARP model (Essaid, 1990) will be used to simulate flow along the Puget Sound cross section. This will allow for comparison of modeling techniques and for a comparison of estimates of location of the freshwater-saltwater interface.

Previously constructed ground-water flow models will be reviewed and evaluated. Initially, information from each model first will be compiled and compared. This information will include vertical discretization, type of model, hydraulic characteristics, boundary conditions, recharge, and, if applicable, approach to freshwater-saltwater interface problem. Major differences among the conceptual and numerical models will be identified. One or two models probably will be selected to study such aspects as regionalization of hydraulic characteristics and vertical discretization of the aquifer system.

The results of the above analyses, both modeling and the testing of concepts, will be studied to determine if a coarse-grid, 3D ground-water flow model of either aquifer system will be constructed. The simpler geometry of the hydrogeologic units in the Willamette Valley indicates that such a model may be feasible there. Preliminary work indicates that constructing a regional 3D model for the Puget Sound Lowland within the projects time constraints is probably not feasible. A model, if constructed, would be used only to integrate knowledge and gain better understanding of the flow system. No attempt would be made to calibrate the model outside of the context that calculated head distributions should generally have the same orientation as hand-drawn distributions, and known regional areas of upward and downward vertical head differences are reasonably simulated.

Water Budget

Water Use

The scope of this work element is to use available data to make an estimate of ground-water use within the Puget Sound Lowland and to use available data and data collected by the project team to estimate ground-water use within the Willamette Valley.

For the Puget Sound Lowland, water-use information from previous and ongoing hydrologic investigations and from the Washington State Department of Health will be compiled first, in fiscal year 1992. Next, municipal and industrial water-use information, based on surveys of individual utilities conducted by the U.S. Geological Survey, will be compiled.

Last, agricultural and rural-individual water use will be estimated. Agricultural-use estimates will be based solely on published water-use information, surveys of irrigation districts, and available maps and data on irrigated lands. The rural-individual water-use estimates will be based on population and per capita water use. The latter water use probably is least important because only about 150,000 people (less that about 2 percent of the population in the Puget Sound region) are in the rural-individual water-use category (Pacific Northwest River Basin Commission, 1970).

For the Willamette Valley, a review, compilation, and tabulation of water-rights data obtained from the Oregon Water Resources Department will be conducted in the first year of study. These data then will be compared with well records. In the second year, selected sites and areas will be visited to estimate irrigation water use, acreages irrigated, type of crops grown, and water application rates. For the period April 1990-October 1, 1990, selected synoptic irrigation-season Landsat scenes will be obtained in order to estimate crop types and acreages. This information will, in turn, be used to estimate ground-water withdrawals for irrigation use. The Oregon District Office Water-Use Specialist will obtain additional public-supply and industrial withdrawal information through direct query of these users; this work will be completed during fiscal years 1990 and 1991.

Recharge

The scope of this work element is to compile existing information on ground-water recharge and to estimate ground-water recharge in selected areas. Regional estimates of recharge will then be made using that information. The scope also will include an evaluation of estimation methods, comparison of results, and description of the major controls on ground-water recharge.

Four methods have been used to estimate recharge in the Puget-Willamette Lowland; these are the two monthly methods of Thornthwaite and Blaney-Criddle and two daily methods--the HSPF watershed model (in the Puget Sound Lowland) [Dinicola, 1990], and the DPM deep percolation model (in both the Puget Sound Lowland and Willamette Valley) [S.S. Sumioka, U.S. Geological Survey, written commun., 1990]. Only daily methods will be used in this study because they generally provide more accurate estimates of recharge than do the monthly methods.

The results from the existing HSPF and DPM modeling work will be compiled and analyzed. General relations between recharge and land use, vegetation cover, precipitation, soil characteristics, and geologic materials will be established. Morgan (U.S. Geological Survey, oral commun., 1990) has found that good relations exist, at least for the northern (Portland Basin) part of the Willamette Valley and Dion (U.S. Geological Survey, written commun., 1990) has found good relations for the southern Puget Sound Lowland.

Differences between results of the two models will be determined. These differences should relate to the factors that control ground-water recharge which, in turn, are dependent on each model's formulation of the physical processes (controls) involved. These differences will identify topics that need additional study or research.

One such topic already identified is evapotranspiration; currently, annual differences of up to 3 inches have been calculated by the two daily methods for coniferous forests. This quantity of water needs to be more accurately defined because it is an important factor in water-availability studies. The work of McNaughton and Black (1973), Black (1979), Black and others (1980), Giles and others (1984), and ongoing investigations (T.A. Black, University of British Columbia, written commun., 1989) will be reviewed and analyzed to determine if improved, functional relations can be developed for estimating forest evapotranspiration with modeling techniques. Formulations currently used to estimate potential evapotranspiration will be tested against actual values when soil water is a non-limiting condition. This information will also be used to assess the evapotranspiration values (both potential and actual) calculated by the two models.

Initial examination of some of the available information indicates that, when soil water is non-limiting, good relations exist between net radiation and evapotranspiration and between net radiation and solar radiation. It is recommended, therefore, that one of the Puget Sound Lowland basins currently being instrumented and monitored by the U.S. Geological Survey for rainfall-runoff modeling studies be selected and instrumented at one site with a net radiometer and pyranometer. Data collected with these instruments then could be used to estimate evapotranspiration and the relations between solar radiation and net radiation. This information could be compared with the modeling results of that basin to obtain a better understanding of the relation between various components of the water budget. This information would have transfer value throughout the Puget-Willamette Lowland.

The DPM model will be applied in selected basins which will include a broad range in land use and cover, climate, soils, drainage area, and streamflow; this work will be done in conjunction with other district projects in order to maximize efficient use of personnel. It is expected that one basin in the Puget Sound Lowland will be instrumented with time-domain reflectometry (TDR) equipment to monitor soil moisture changes with time; this will allow for checking modeling reliability against soil moisture. The Puget Sound Lowland basin may be the one where the net radiometer would be installed.

Results from these models and previous DPM work will be used to estimate regional relations between recharge and other important variables (soil types, precipitation, land use/cover, and topography) for both areas. These relations will be compared with the relations previously discussed to allow assessment of the value of additional information on recharge and on the reasonableness of the estimated relations. Major data bases that will need to be established for this effort (and other work elements) include: long-term daily climatological data, land-use information, soil characteristics, land-surface altitude, slope, and aspect, and average annual precipitation.

Discharge

The scope of this work element is to make estimates of ground-water discharge. Ground-water discharges naturally from the aquifer systems to streams, saltwater bodies, springs-seeps, and, to a much lesser degree, the atmosphere. This discharge quantity is about equal to recharge minus pumpage. Thus, the regional estimates of recharge and pumpage will provide an estimate of the total discharge, without regard to its distribution.

The regional analysis of streamflow records may provide some indication of the quantity that discharges to streams. This method probably will give better results for the Willamette Valley than for the Puget Sound Lowlands. Discharge quantities estimated by this method will be compared to the estimated distribution of recharge in order to investigate the reasonableness of the estimated discharge values. Most discharge from the Willamette Valley aquifer system is estimated to occur along the Willamette River and ultimately to the Columbia River. Previous work in the northern part of the Willamette Valley (D.S. Morgan, U.S. Geological Survey, written commun., 1989) has provided estimates of discharge for this area. Thus, using those values and recharge estimates, the reasonableness of the estimated values of the remainder of the valley can be checked.

For the Puget Sound Lowland, the numerous streams, variable topography, presence of extensive outcrop seepage faces along the Sound, and discharge to saltwater bodies makes estimating discharge by direct means very problematic. Thus, estimates of ground-water recharge and water-level maps mainly will be used to make preliminary estimates of discharge. Their values will be checked against existing estimates derived from local ground-water modeling studies.

Flow of Ground Water

The scope of this work element is to make estimates of the quantity of water moving in the aquifer systems. Water-level maps for the hydrogeologic units, estimates of hydraulic characteristics, and saturated thickness will be used to derive these estimates. Assuming that the aquifer systems are in equilibrium, the quantity of water estimated to be moving in the system will then be compared to the recharge estimates and to the estimates of the quantity and distribution of discharge.

Process-Oriented Studies

Topics described in the following sections may or may not be covered in this study, depending on the completion of the work elements previously described. The minimum scope of these topics will be to use the work completed and knowledge gained in this study to describe work elements needed in future investigations to obtain a better understanding of some physical processes, to suggest the more important regional hydrologic controls, and to describe interrelations among various climatic and hydrologic elements.

Watershed-hydrology Flow Paths

Watershed hydrology generally has been concerned with describing stream hydrographs in basins through modeling of such processes as overland runoff and infiltration; these processes were generally confined to the land surface, and subsurface processes were modeled in a simplistic manner. Correspondingly, ground-water hydrology in Puget-Willamette Lowland generally has been concerned with describing the flow of ground water through modeling of ground-water flow; generally, surface processes were analyzed separately or their effects (recharge-discharge) were estimated during the modeling work. However two important aspects are currently being recognized: (1) the importance of the variably saturated ground-water flow system for describing stream hydrographs, and (2) the need to account for the near-surface physical processes in ground-water hydrology.

Except for the overland runoff component for natural and slightly-developed watersheds in the Puget-Willamette Lowland during peak flows, most of the precipitation that is not used by evapotranspiration has traveled through the subsurface and is most of the volume of water represented in a stream hydrograph. Thus, understanding the mechanisms controlling the quantity of water in a stream requires a working knowledge (or at least a conceptual understanding) of the ground-water-flow system. In turn, the distribution of soil moisture, hydraulic conductivity of the geologic materials present, topography, configuration of the water table, plant community, and soil characteristics are all important for describing ground-water flow in the upper several hundred feet of the watershed.

Within the Puget-Willamette Lowland, Dinicola (1990) used hydrograph matching to obtain information to parameterize the physical processes simulated with the HSPF watershed/rainfall-runoff model. Results of the use of DPM in the Puget-Willamette Lowland were based on using the stream hydrograph as an input and a more detailed accounting of the soil and plant characteristics. Ground-water modeling studies in the Puget-Willamette Lowland have not included variably saturated ground-water flow and in only two cases (Sapik and others, 1989; E.A. Prych, U.S. Geological Survey, written commun., 1989) were results from more detailed watershed/water-balance type analyses incorporated. Generally, only water-level information was used to calibrate the model; streamflow hydrographs have not been used, but average streamflow has been used to check on the model-computed values of ground-water discharge.

It is evident that, for both cases, more information on other hydrologic variables is desirable to support, disprove, or generally check the modeling results. Ideally, this information would be available for several watersheds representative of different physical, climatological, and environmental regimes. This would better define the near-surface processes and provide additional checks on the work completed in this project.

After precipitation or snowmelt moves into the upper soil zone, the pathway it follows also needs to be defined better. This would provide additional information on the stream-aquifer connection, hydraulic characteristics, and quantities of water moving in the hydrologic system. A water-quality sampling network would help to describe the ground-water pathway and contributions to streams, however, more detailed sampling (including soil-water samples) over a long period of time is suggested. In conjunction with the sampling, natural gradient tracer tests would provide good information. Tests would consist of injection of some conservative tracer material in selected areas of a watershed. Streams, soils, and aquifer units would then be sampled with time. The results of the sampling, model applications, and improved conceptual models of the movement of water could then be used to define sample strategies and tracer placement/quantities in some selected watersheds for future investigations.

Use of HSPF, DPM, and TOPMODEL (Beven and Kirby, 1979) in conjunction with 2D cross-sectional and 3D ground-water-flow models would provide information for describing how watersheds in the Puget-Willamette Lowland operate. In addition, this work would provide information on which hydrologic variables need to be measured in order to provide improved closure in describing the regional hydrology. To that end, it is suggested that time-domain reflectometry equipment be installed in several basins, preferably in basins currently or previously instrumented. This would provide an important check on the results of using HSPF and DPM and thus ground-water recharge. The information gained by this additional data could be evaluated and its applicability tested.

Last, depending on the physical and climatological characteristics of a watershed, one or more physical processes probably control the hydrology of the watershed. Characterization of the watersheds in the Puget-Willamette Lowland would thus allow for a description of the hydrologic controls and their variations. Watersheds ranging in size from about 10 mi^2 to more than 1,000 mi^2 could be defined and rainfall-runoff models applied to various groupings of the watersheds; the models would only need to be roughly calibrated. This type of method has been shown to yield good results over large areas (D.M. Wolock, U.S. Geological Survey, oral commun., 1989). Wolock and Price (1989) used digital elevation models to develop topographic data bases, allied parameters (slope, aspect, flow direction, and upstream contributing area), and watershed boundaries. This information was used with TOPMODEL to derive characteristics of basins in order to classify them. This allowed for delineation of pertinent hydrologic controls for each type or group of basins classified. In addition, results of the classification would provide a means to address regional aspects of water availability. Dinicola (1990) has completed similar work with the Puget Sound Lowland for small (less than 10 mi^2), low altitude basins. However, potentially important hydrologic controls and larger basins were not studied in his work. The viability of applying Wolock's method will be studied in the second year of this project.

Climate

Some inclusion of climatic effects on the hydrology of the Puget-Willamette Lowland aquifer system will be done in this study. Climate variability within the study area can result in large year-to-year differences in precipitation recharge and thus can greatly limit the applicability of ground-water-model projections. This is especially true because stationary climate generally is assumed in model projections. Additionally, because of the extensive saltwater bodies in the Puget Sound Lowland, the potential for global warming and concurrent sea-level rises could detrimentally change the position of the freshwater-saltwater interface.

The scope of the work related to climate in this study will include two tasks. The first will incorporate some of the variability and uncertainty of climatic parameters into the estimation procedures for ground-water recharge (and perhaps into the watershed models). This will allow for a more realistic assessment of the current and potential range in water availability based on about the last 100 years. Proxy and (or) general circulation model information will then be used to assess the sensitivity of the ground-water system to potential future climatic regimes. In the second task, the potential effects of sea-level rise will be analyzed by changing boundary conditions in the constructed cross-sectional ground-water models, and comparing the new results with previous model results.

REPORTS

The results of this study will be published in the U.S. Geological Survey's Water-Resources Investigations Report (WRIR) and Professional Paper (PP) series. These publications will be both book-and-map-type reports. Because of the nature of the two distinct aquifer systems within the study area, there will generally be two volumes for most published reports.

Reports under consideration for publications are (does not include the two published bibliographies):

Topic	Series
Geologic framework of the Puget-Willamette Lowland regional aquifer-system analysis, Puget Sound Lowland, Washington	PP
Geologic framework of the Puget-Willamette Lowland regional aquifer-system analysis, Willamette Valley, Oregon and part of Washington	PP
Application of geophysical techniques for the Puget-Willamette Lowland regional aquifer-system analysis, Washington and Oregon	WRIR
Estimation of ground-water recharge for the Puget-Willamette Lowland regional aquifer-system analysis, Puget Sound Lowland, Washington	WRIR
Conceptual model of ground-water flow for the Puget-Willamette Lowland regional aquifer-system analysis, Puget Sound Lowland, Washington	WRIR
Estimates of water-use for the Puget-Willamette Lowland regional aquifer-system analysis, Willamette Valley, Oregon and part of Washington	WRIR
Hydrogeologic framework for the Puget-Willamette Lowland aquifer-system analysis, Willamette Valley, Oregon and part of Washington	PP
Hydrogeologic framework for the Puget-Willamette Lowland aquifer-system analysis, Puget Sound Lowland, Washington	PP
Summary of the Puget-Willamette Lowland regional aquifer-system analysis, Washington and Oregon	PP

WORK ELEMENTS

The major work elements for this study that have been previously described are summarized in the following outline. Time lines for the major work elements of the Puget-Willamette Lowland Regional Aquifer System Analysis are shown in figure 3.

I. Hydrogeologic framework

A. Compile available information
B. Collect new geophysical data
C. Construct structure contour map for the top of the basement confining unit
D. Describe regional hydrogeologic units and relate to geologic units
E. Prepare hydrogeologic sections
F. Construct structure contour maps of the tops of the units
G. Construct thickness maps of the units

II. Regional ground-water flow system

A. Analyze existing water-level information and observation well networks
B. Assign hydrogeologic units to open intervals of wells to be used in study
C. Map preliminary water-level surfaces
D. Develop conceptual model(s) of regional ground-water flow
E. Analyze water-level information
F. Construct regional water-level maps for selected hydrogeologic units

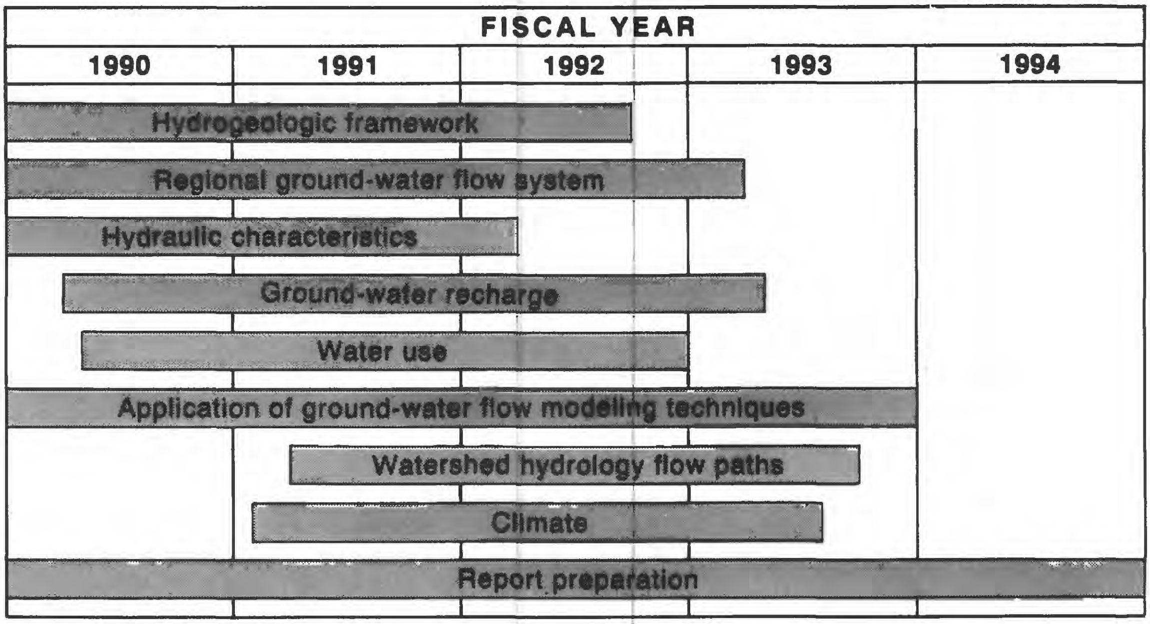

Figure 3.—Time lines for the major work elements of the Puget-Willamette Lowland Regional Aquifer-System Analysis.

III. Hydraulic characteristics

A. Compile and analyze existing data from pumping tests and specific capacity tests
B. Conduct permeameter tests

IV. Stream-aquifer relations

A. Analyze surface-water records
B. Monitor water levels of ground water and surface water in selected, small perennial stream drainages
C. Collect water-quality information

V. Water use

A. Compile available information
B. Inventory selected high-capacity wells
C. Update NWIS data base
D. Estimate irrigation water use through site visits and analysis of Landsat scenes

VI. Ground-water recharge

A. Compile and analyze existing results from the HSPF and DPM models
B. Analyze existing information on forest evapotranspiration and compare results from the HSPF and DPM models
C. Apply DPM to selected basins, one or two of which may have some instruments installed
D. Develop regional relations to estimate ground-water recharge
E. Estimate the distribution of average annual recharge

VII. Ground-water discharge

A. Compile existing information
B. Analyze surface-water records for estimating baseflows
C. Compare estimates of recharge to baseflow estimates in selected areas
D. Use water-level maps and recharge estimates to describe discharge areas

VIII. Flow of ground water

A. Digitize and grid water-level contours and thickness maps of selected hydrogeologic units
B. Use information in "A" above and estimates of hydraulic characteristics to describe the quantity of water potentially moving in the ground-water system
C. Compare values in "B" above with the recharge estimates
D. Use results in "B" above to refine estimates of quantity and distribution of discharge

IX. Application of ground-water flow modeling techniques

A. Compile information on previously constructed models
B. Construct two-dimensional cross-sectional flow models in several "type areas"
C. Compare results of two to three types of models in a selected area, one area each for the Puget Sound Lowland and the Willamette Valley
D. Construct coarse-grid regional three-dimensional ground-water flow model for the Willamette Valley (optional)

X. Watershed hydrology - flow paths

A. Apply, compare, and test different watershed modeling techniques in selected basins that have constructed, cross-sectional or areal ground-water flow models
B. Conduct watershed flow-path experiment
C. Characterize watersheds and their influence on the ground-water flow system

XI. Climate

A. Use 80- to 100-years of climatological data for estimating ground-water recharge to assess climate variability on recharge estimates
B. Use the above recharge estimates to test sensitivity of ground-water movement to climate variability
C. Test effects of potential sea-level rise on ground-water flow system using calibrated cross-sectional models

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