The Bridgeport Slide, North-Central Washington

RICHARD D. ECKERLIN
U.S. Army Corps of Engineers

LOCATION AND DESCRIPTION

The Bridgeport slide is located on the Columbia River in north-central Washington, approximately 2 mi upstream from the town of Bridgeport (Figures 1 and 2). The Bridgeport slide was first identified in 1968 during geologic investigation for raising the reservoir level behind Chief Joseph Dam. The landslide begins 0.5 mi upstream of the south abutment of the dam and continues upstream for 2.5 mi, encompassing an area slightly larger than 1.25 sq mi (U.S. Army Corps of Engineers, 1986) (Figure 3). The slide ranges in depth from 400 ft at the headscarp to approximately 100 ft at the toe. Approximately 50 vertical feet of the slide toe was inundated in 1954 during initial reservoir filling, and an additional 10 ft was inundated in 1981.

The climate in north-central Washington is arid. The slopes bordering the reservoir are covered with sagebrush and sparse grass. Orchard and grass crops are raised on some of the irrigated terraces upstream of the landslide, and locally small clusters of trees are present in gullies.

Between 1973 and 1984, a total of 16 borings were drilled through the slide mass into granitic bedrock. Inclinometers were installed in all borings for periodic monitoring of landslide movement. Recent displacement and cracking of a former county road near the shoreline show that parts of the slide are active.

GEOLOGIC SETTING

The Bridgeport slide is situated within a deeply eroded part of the Columbia River valley along a segment of the river that separates the Columbia Basalt Plateau on the south from the Okanogan Highlands on the north. Rocks in the lower part of the valley and in the Okanogan Highlands are a complex of metamorphic rocks intruded by Mesozoic granitic rocks. Miocene Columbia River basalts are exposed on the south side of the valley and locally on the north side. During the Miocene the ancestral Columbia River was crowded against the Okanogan Highlands by encroaching basalt flows. Silt and clay were deposited as the basalt flows periodically dammed the Columbia River and its tributaries. These lake sediments, known as the Latah Formation, were overridden by successive basalt flows. Subsequently, the Columbia River cut its present canyon about 1,000 ft below the plateau surface into the granitic rocks.

Pleistocene continental ice sheets advanced from the north into and across the canyon, depositing varied thicknesses of glacial outwash sand and gravel, lacustrine silts, and till atop the irregular granitic bedrock surface. Late-glacial lake sediments were deposited in the canyon by intermittent ice damming of the Columbia River. Glacial deposits also filled abandoned channels of the Columbia River and many of the abandoned tributary canyons. The present Columbia River has incised itself through the glacial sediments into the granitic bedrock, leaving a terraced inner valley within the larger ancient valley.

A notable feature of the Columbia River valley above Chief Joseph Dam is a steplike effect produced by recession of the basalt cliffs (Jones et al., 1961). Masses of disturbed material suggest that much of the retreat of the basalt cliffs was due to landsliding.

SITE GEOLOGY

Movement on the Bridgeport slide has occurred from Pliocene through Holocene time as the Columbia River initially established its course along the plateau margin and again as it re-established its course following Pleistocene glaciation. Incompetent sediments in the Latah Formation may have provided the slip surfaces for historic mass movement. Erosion at the toe of the riverbank slope, coupled with uplift pressure from ground water, likely led to the slope failure.

Beneath the Bridgeport slide the Latah Formation consists of near-horizontal beds of clay, sand, and poorly indurated siltstone and claystone (Figure 4). Recent slippage at the foot appears to be within a blue-green clayey granitic sand unit as much as 60 ft thick. The clayey sand grades downward into decomposed granite residuum that is about 10 to 15 ft thick and that overlies firm granitic rock.

Granodiorite and granodiorite gneiss are locally exposed at lake level both upstream and downstream of the slide. The slide mass itself consists of clay, silt, sand, gravel, boulders, rock rubble, and masses of rela-

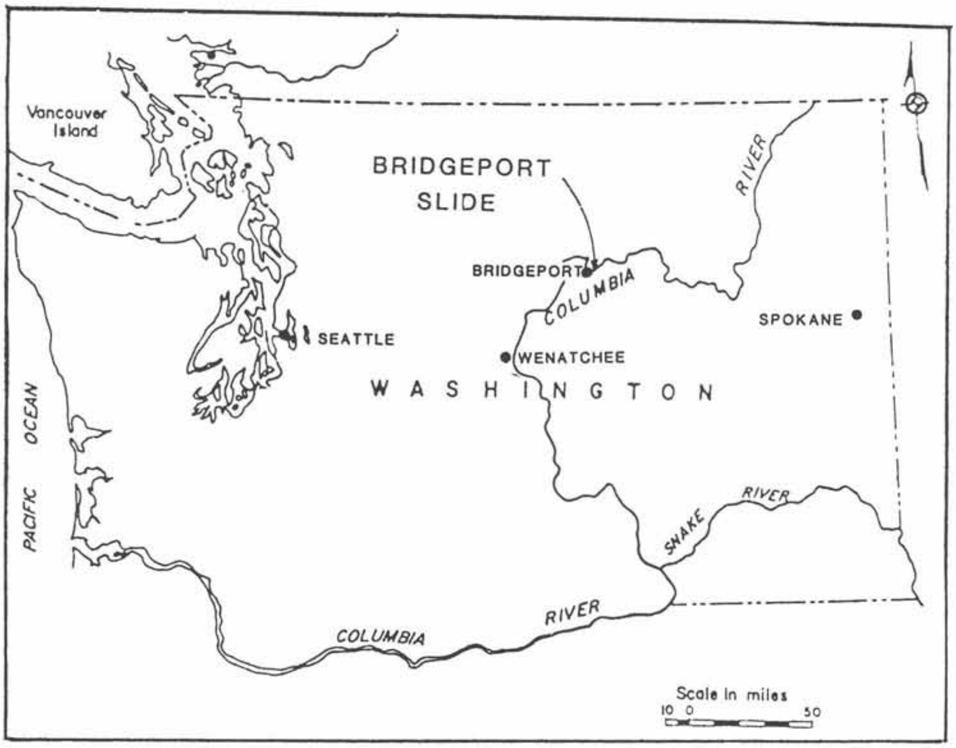


Figure 1. Location of Bridgeport landslide.

Figure 2. The Bridgeport slide viewed from the west above Chief Joseph Dam. The Columbia Plateau is at the top of the photo. See geologic map, Figure 3, for position and scale of the landslide. Photograph by the U.S. Army Corps of Engineers, October 20, 1978.

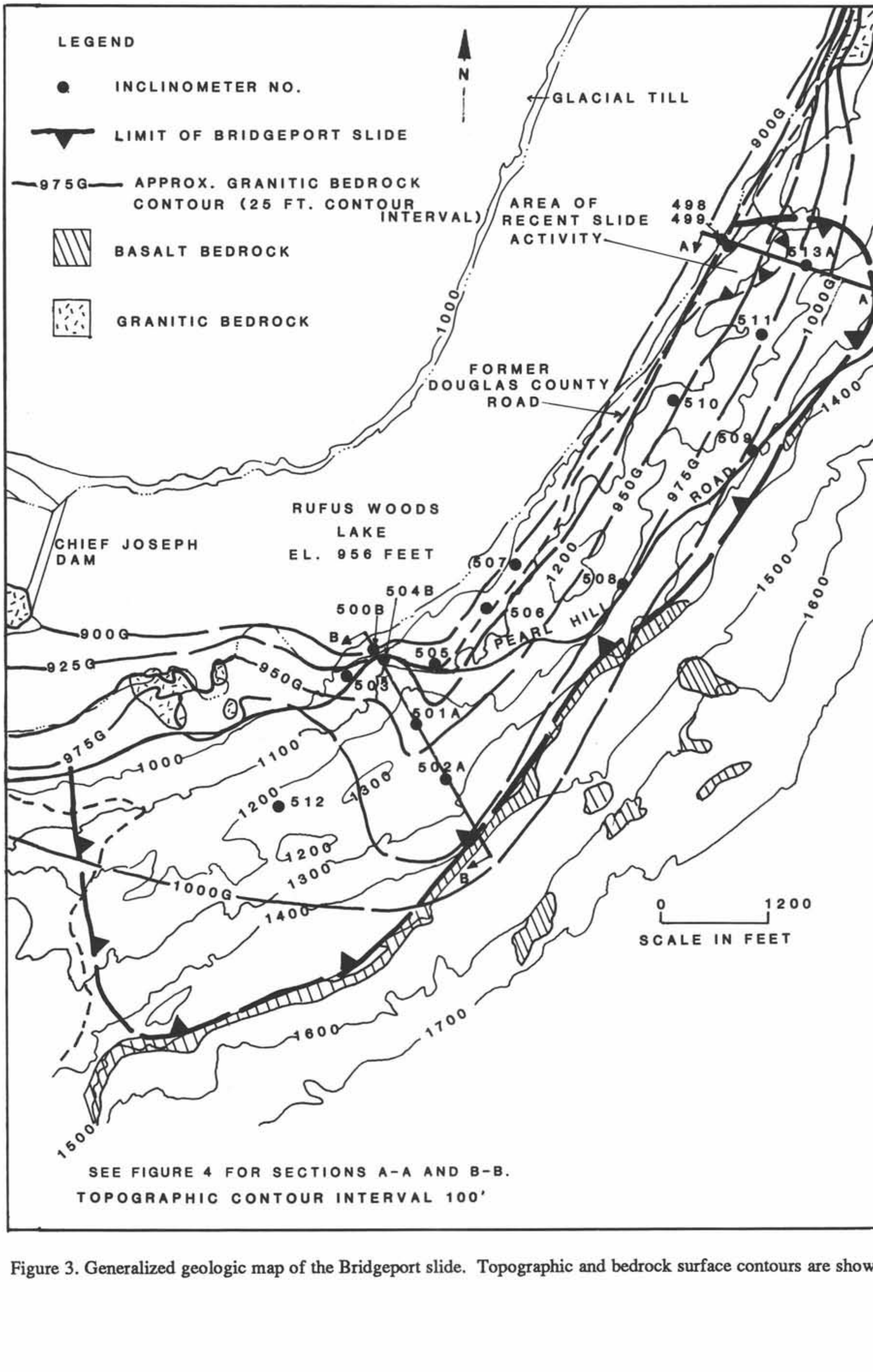


Figure 3. Generalized geologic map of the Bridgeport slide. Topographic and bedrock surface contours are shown.

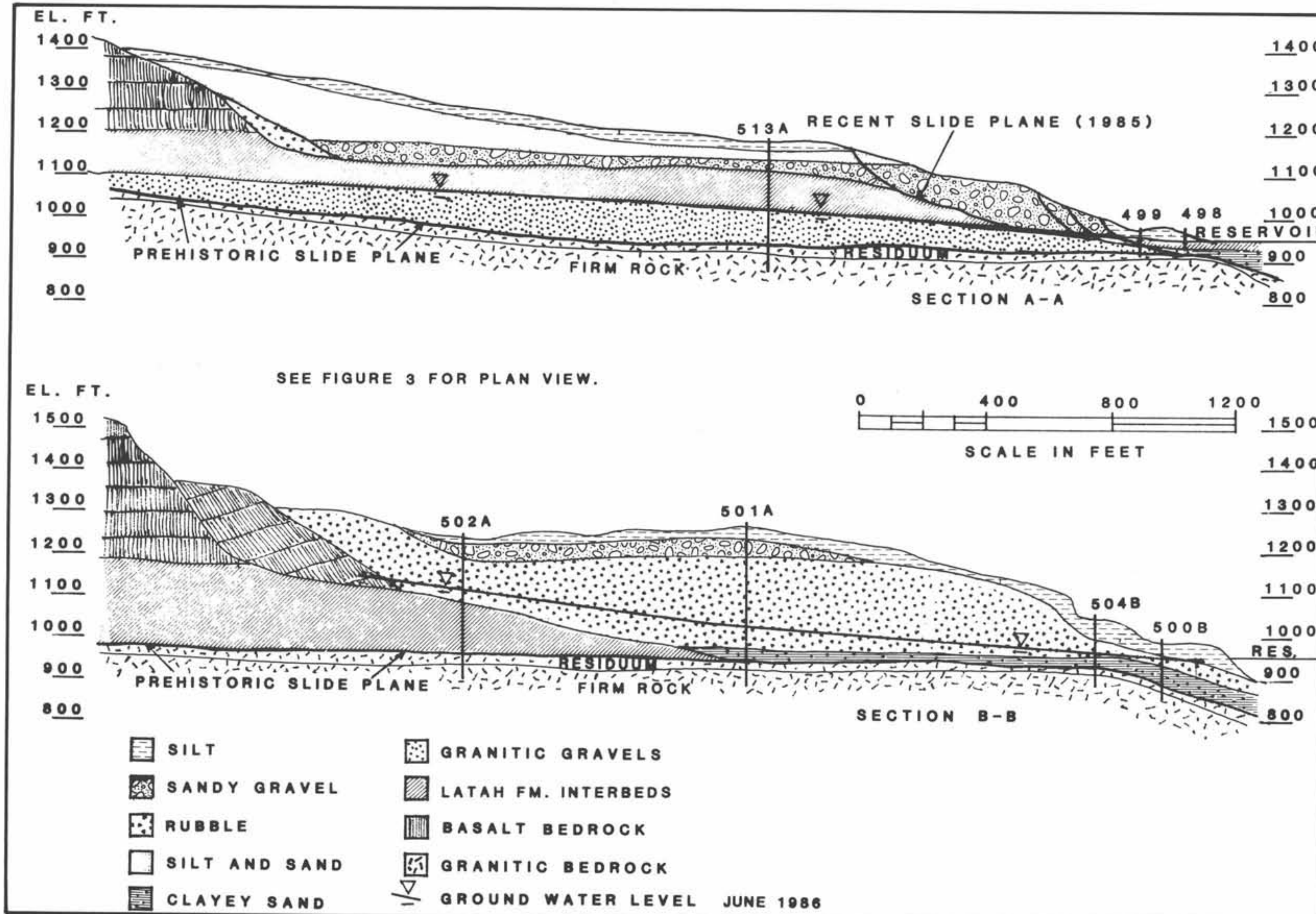


Figure 4. Geologic sections through the Bridgeport slide. Position of the prehistoric slide plane has been inferred from inclinometer data.

tively intact basalt. Geologic sections through the slide are shown on Figure 4.

Interflow zones in the Miocene basalts that form the slide's headscarp tend to store water that eventually drains into and through the slide mass. Recharge to the interflow zones is probably by precipitation and irrigation on the Columbia Plateau. Ground-water levels recorded in several inclinometer borings indicate that more than 150 ft of head above the reservoir level exists within the slide. Ground-water levels, together with inclinometer data, are recorded approximately every 3 months. Many localized damp and wet areas exist year-round at the slide surface. Most of those areas are above the ground-water table and probably represent seepage from perched water tables.

Of concern are the artificial perched water tables caused by irrigation and land development. These tend to alter ground-water conditions in the sensitive materials and contribute to slope failure. This mechanism combined with reservoir fluctuations causes a triggering effect resulting in localized slope failures. As the toe is unloaded, major sliding can be expected. Such sliding mechanisms were considered in the early 1970s during the slope stability studies for re-evaluation of the real estate guide acquisition line. This line defines the freeboard allowance above the full reservoir level and was established to include allowance for induced surcharge operations plus a reasonable additional freeboard for adverse effects of saturation, wave action, and bank erosion. The acquisition line encompasses the entire landslide. The acquired easements allow for private ownership, but prohibit permanent dwellings. Presently the land is used for dryland wheat farming and for cattle grazing, both of which have a negligible impact on ground water.

INSTRUMENTATION

In 1973, the U.S. Army Corps of Engineers began a mapping and drilling program to determine the form and condition of the slide, the location of the slippage surface(s), and slide lithology and to measure the rate of movement. Three inclinometers were installed in 1973, two in 1975, four in 1982, one in 1983, and six in 1984. The inclinometer locations are shown on Figure 3. The inclinometer borings range in depth from 60 ft on the foot of the slide to 385 ft near the slide headscarp. Inclinometers are read quarterly using a sensitive "digitilt" instrument with magnetic-tape field recorder.

Between October 1975 and June 1976 two inclinometers adjacent to former Douglas County Road 321 at the upstream (north) end of the slide became inoperable due to excessive movement at a depth of about 50 ft. As a result of this movement, which also resulted in surface disruption, the road had to be relocated around the active slide area. This work was completed in 1980. Localized landslide movement subsequent to raising the reservoir in 1981 has destroyed part of the abandoned segment of the county road, and cracking of the ground surface is now visible several hundred feet upslope. In the remainder of the slide area, cumulative movements measured for each of the inclinometers presently in service is less than 2 in. to date; however, there has been a noticeable acceleration of movement since the reservoir was raised 10 ft in 1981.

Since 1976, the slide has been monitored at least annually by aerial photogrammetric surveillance of approximately 60 targets on the slide's surface. Control targets are located on the ridge above the headscarp and on the opposite side of Rufus Woods Lake. The sensitivity of the aerial surveillance is such that movements of less than 0.5 ft are not detectable. Aerial surveillance of targets throughout the upstream active portion of the slide indicate a total cumulative movement of less than 1 ft between May 1976 and June 1981. From June 1981 to April 1988, a maximum movement of about 7 ft has been recorded.

CONCLUSION

The limits of sliding are not precisely known; however, a volume of material well in excess of 5 million cy appears to be involved, with sliding occurring on a relatively flat surface near the top of the granitic bedrock. The major cause of the ancient landslide was probably erosion of the toe of the slope by the Columbia River. After initial failure, a new set of geologic and hydrogeologic conditions was created, making the Bridgeport slide susceptible to further, but more localized movement. There are some indications of rising piezometric levels in the slide which are contributing to local instability. The reasons for this rise are presently unknown.

There is no apparent landslide threat to Chief Joseph Dam from the actively sliding area at the north end of the Bridgeport slide. Presently, failure is by slow creep and does not appear to be serious, although there are indications of an increased rate of movement since the 10-ft rise of reservoir level in 1981. There does not appear to be enough material in this active slide to block the river or significantly fill the reservoir. However, the possibility of a rapid failure resulting in a dangerous wave in the reservoir cannot be disregarded.

Pearl Hill Road is a well-traveled highway which crosses the slide and is considered of critical importance for upstream property owners. If progressive enlargement of the actively sliding areas along the landslide toe occurs, this road could be endangered.

Studies in the 1970s considered increasing the number of generating units at Chief Joseph Dam above the current 27 units. A reservoir slope stability evaluation was completed for the maximum proposed reservoir elevation of 970 ft. Stability trends determined for this reservoir elevation were applied to the current reservoir elevation of 956 ft. One result of the study was that the entire Bridgeport slide was included within the guide acquisition line. Locations of critical failure surfaces with respect to the reservoir were taken into consideration in establishing criteria for locating this acquisition line.

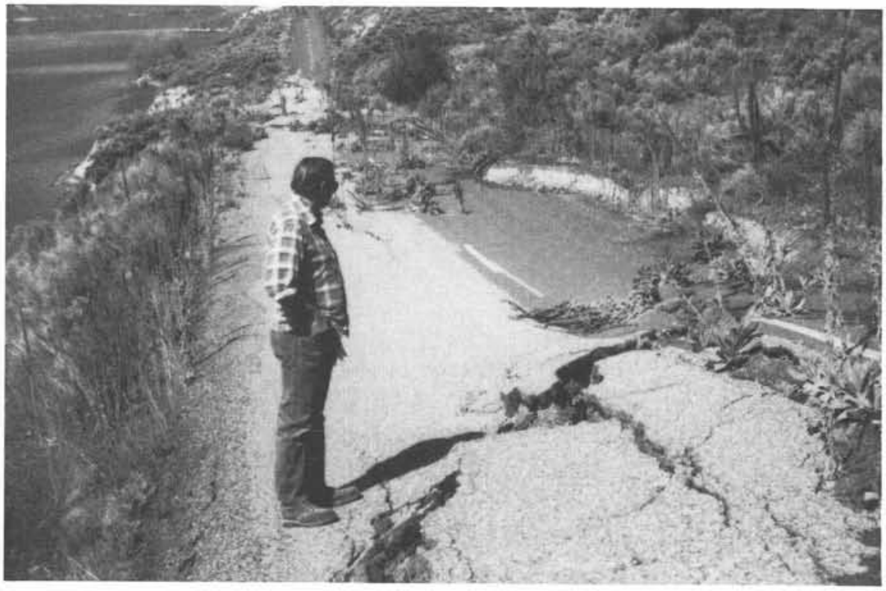
ACKNOWLEDGMENTS

I thank R. W. Galster, U.S. Army Corps of Engineers (retired), for originally stimulating my interest in the Bridgeport slide. Galster first identified the landslide in 1968 and provided valuable suggestions and encouragement for preparation of this paper. Also I acknowledge K. D. Graybeal and Monte Kaiser, Jr., Seattle District, U.S. Army Corps of Engineers, for their efforts during the periodic collection and interpretation of instrumentation data.

REFERENCES

Jones, F. O.; Embody, D. R.; and Peterson, W. L., 1961, *Landslides along the Columbia River Valley, Northeastern Washington*: U.S. Geological Survey Professional Paper 367, 97 p., 6 plates.

U.S. Army Corps of Engineers, 1986, *Periodic Inspection Report No. 8–Chief Joseph Dam, Columbia River, Washington*: U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 42 p., 15 plates.



Views of a failure on a Douglas County road near the toe of the Bridgeport landslide. Photographs by R. W. Galster, May 1984.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Slope Stability Analysis in Timber Harvest Planning; Smith Creek, Pacific County, Washington

STANLEY H. DUNCAN
Weyerhaeuser Company

INTRODUCTION

Forest managers responsible for timber harvest in steep watersheds of the Pacific Northwest are faced with a multiplicity of environmental concerns. As a first step in planning harvest operations, an assessment of the site's slope stability, other resources (such as fisheries), downstream property use, and domestic water supplies must be conducted. This assessment serves as the basis for deciding whether developing a detailed, site-specific harvest plan is warranted.

While the potential impact of logging and road construction activities on downslope or downstream resources has been well documented, most studies have reported worst-case situations. Few report the expected results of planning and plan execution based on both environmental and operational conditions. The result is a perception that all timber harvest operations in steep terrain have a potentially deleterious impact on downstream resources. This perception often leads to unwarranted engineering solutions that are economically unrealistic or, at a minimum, expend capital without significant beneficial results.

This paper discusses use of a slope-stability assessment technique in the development and successful execution of a harvest operation by a private corporation on a site adjacent to a sensitive fisheries resource. The plan was developed by a team consisting of a logging engineer, a geologist, and a hydrologist in 1977 and carried to completion in 1978 and 1979.

SITE HISTORY AND CHARACTERIZATION

In 1974 Weyerhaeuser Company acquired approximately 2,268 acres of timber along the lower reach of Smith Creek, a tributary to Willapa Bay on the coast of Washington (Figure 1). Other than the previous owner's salvage of wind-thrown timber resulting from hurricane-force winds in the Columbus Day storm of 1962, the timber stand had not been logged, and, except for a few spur roads, there were essentially no roads in the area.

The timber stand bordered Smith Creek on slopes in excess of 70 percent. Many landslides associated with spur roads that had been constructed for the timber salvage operations had entered Smith Creek, and an active natural landslide was present at the extreme downstream edge of the timber stand.

Smith Creek drains a watershed of about 27.9 sq mi and is dominated by thick, fine-textured soils developing from deeply weathered siltstone, sandstone, and basalt (Gower and Pease, 1965; Wagner, 1967). The stream is estuarine upstream to river mile 1.0 and is subject to tidal influence to about river mile 1.5 (1/2 mi below the lower portion of the plan site). The stream has a low gradient and maintains significant runs of chum (*Oncorhynchus keta*), chinook (*O. tshawytscha*), and coho (*O. kisutch*) salmon. Sea-run cutthroat (*Salmo clarki*) and steelhead (*S. gairdneri*) trout are also abundant. Spawning of these species is known to occur within the stream reach bordering the proposed harvest unit. The Washington Department of Fisheries reports that the limiting factor for salmon production in Smith Creek is a lack of suitable spawning gravel (Phinney et al., 1975). Most of the gravel of suitable quality occurs within the plan area. Two small tributaries used by young salmon and trout as wintering areas enter Smith Creek in the proposed harvest area.

Water quality was not examined, but natural turbidity and suspended sediment levels were expected to be high during periods of high stream flow due to the fine, easily transported sediment derived from the soils and rocks of the basin.

ASSESSING POTENTIAL INSTABILITY

Landslides associated with spur roads during the timber salvage operations, the apparently natural instability of parts of the site, and the vulnerability of the fisheries resource in this segment of Smith Creek combined to cause the area to be by-passed during conventional logging operations. Weyerhaeuser field personnel recognized that if this site were to be harvested, the value of the standing timber realized, and the fisheries resource given adequate protection, it would require extraordinary practices. A geologist and a forest hydrologist were asked to evaluate the site and assist in development of a harvest plan.

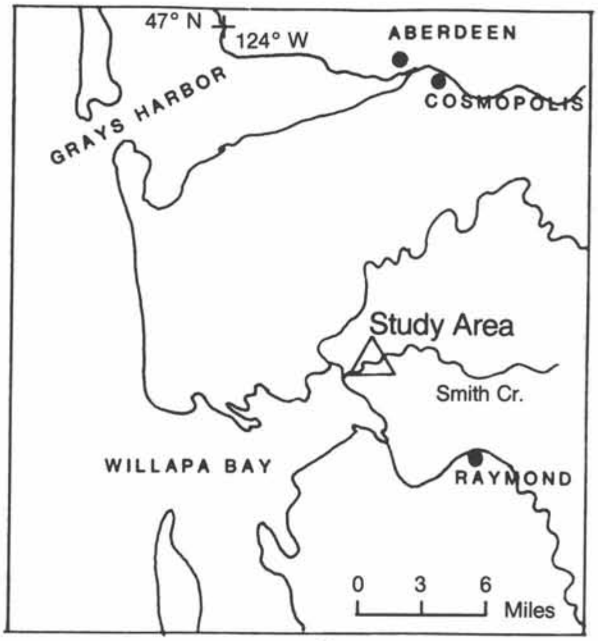


Figure 1. Location of the Smith Creek project, Pacific County, Washington.

A site evaluation was made by the team, and a terrain classification map was prepared to display the landslide potential of the site for use in harvest-plan development. This assessment of potential slope stability used soil and geologic data from a soil survey of the area (Duncan and Steinbrenner, 1969), onsite investigation, and analysis of aerial photos. The completed map was similar to that developed by Rickert et al. (1978) to assess potential land management impacts in Oregon. The terrain classification map identifies those sites having the highest potential for natural landslide activity and sites of previous slides. To be of practical benefit to onsite planning, a more specific delineation of potential problem sites, as well as those that are stable, was required.

To further quantify slope stability, specific sites identified on the qualitative terrain classification map were assigned an average index of slope stability using a technique developed by Duncan et al. (1987). With this indexing system, specific terrain characteristics such as slope angle, position, form, soils, and climatic factors were evaluated and assigned specific values relating to potential landslide risk associated with standard logging

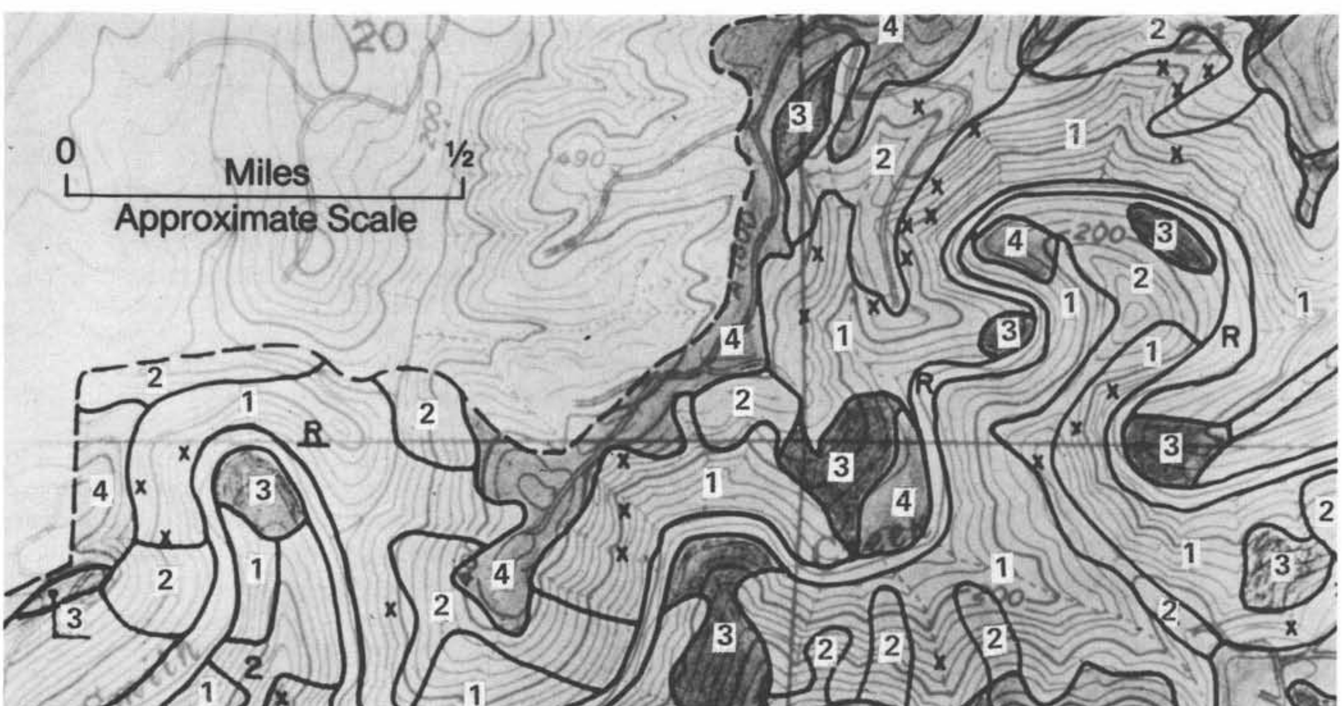


Figure 2. Portion of an engineering requirement classification map of part of the lower Smith Creek site. Numbers refer to the engineering requirement classes (Table1). x, existing landslide. Roads shown on the topographic base were constructed to access wind-thrown timber during the late 1960s.

road and landing construction. These data were combined with the terrain classification map to produce a map that depicts landscape units classified by the relative risk of slope failure from roads and landings and by the level of engineering required to minimize landslides that might result. This engineering requirement classification map (Figure 2) and its interpretation are similar to that described by Bourgeois (1978). Four engineering requirement classes are identified: Class 1 referring to those terrain units expected to present the greatest difficulty to logging and roading operations, through Class 4, which represents area offering the least difficulty (Table 1).

The relations among the four engineering requirement classes and the empirically developed slope stability index (Duncan et al., 1987) are shown on Figure 3. Each engineering requirement class is based on the relative level of difficulty anticipated to construct a stable road or landing on sites whose failure potential is represented by the failure risk distribution curve. Using this concept, areas requiring extraordinary design and construction are identified, allowing plan and cost adjustment.

Table 1. Engineering requirement classes

Class	Description
1	Extreme Failure Potential
	These sites should be avoided since significant stability problems could result from road construction. Maximum design, construction and maintenance is required.
2	High Failure Potential
	Soil and geologic conditions make these sites susceptible to stability problems requiring a high level of engineering and careful construction practices to minimize slope disruption. These sites commonly have high maintenance requirements.
3	Moderate Failure Potential
	Generally stable. Special engineering and careful construction may be required on microsites.
4	Low Failure Potential
	No significant stability problems; standard engineering practices are usually adequate.

The assessment of erosion potential and engineering requirements anticipated in site development that was compiled for the lower Smith Creek project integrated existing soil and geologic information with regional slope stability research and onsite geotechnical reconnaissance. The product developed in this process depicts average conditions. A more detailed characterization of the potential stability of microsites was developed during the siting of specific roads and landing locations.

THE HARVEST PLAN

The harvest plan was developed using the slope stability map overlaid on a topographic base as the primary planning medium. About 61 percent of the area was classified in engineering requirement classes 1 and 2, sites that would present extreme engineering difficulty and risk to the stream should a slope failure occur. While environmentally acceptable roads could be constructed on these sites, initial cost and future maintenance were determined to be uneconomical. An alternative approach was to locate landings on the ridges and to log across the stream, fully suspending the logs over the stream and the streamside management zone. Slash and woody debris entering the stream were to be removed at the time of logging.

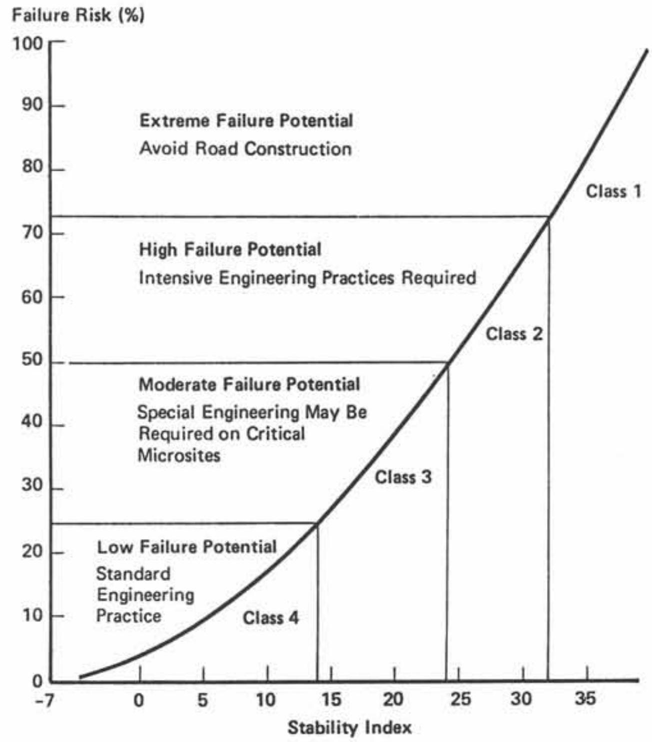


Figure 3. Relations of four engineering requirement classes to the stability index and associated failure risk curve where: Failure risk (%) = 3.6236 + 1.0787 (Index) + 0.03428 $(\text{Index})^2$ (Duncan et al., 1987)

Figure 4. The lower Smith Creek area showing a typical knife-edged ridge and landing and the streamside management zone. The only landslide occurring within the plan area is in the center of the photo; its relation to logging is unknown.

Roads were confined to ridge tops (Figure 4), but because of the knife-edge ridges and steep slopes, excess soil material was removed to disposal sites located in engineering requirement Class 4 areas. The disposal sites were to be reforested at the same time as the harvest units.

Planning and evaluation of harvest alternatives was done by treating individual timber blocks as separate units. A cost analysis was performed for individual timber units. In this analysis, each of the various harvest alternatives was compared to conventional harvest methods for similar terrain conditions, in compliance with Washington forest practice regulations and company environmental guidelines.

Logging in two units in the Smith Creek area required crossing the stream. To gain access to these units while causing the least disturbance to the stream, portable E-Z bridges (Oregon Bridge Engineering Company) were used and were to be removed upon completion of harvest and regeneration.

In order to maintain streamside integrity and provide shade along east-west-trending stream reaches, the plan called for a buffer strip a minimum of 50 ft wide to be left along both sides of the stream (Figure 4). Within this zone, all hardwood, principally red alder (*Alnus rubra*), and conifers leaning over the stream were to be left uncut. On steep slopes where falling trees could enter the stream, directional falling and jacking practices were to be employed. Those trees leaning such that directional falling techniques would not be effective were to remain until they could be felled by cable assist during logging. Merchantable conifers within the streamside zone that could be harvested without disturbing the stream bank were to be removed.

RESULTS

Cost/risk analyses showed that skyline logging (a method of fully suspending logs above the ground from an overhead cable system attached at two higher areas) from ridges was more economical and presented less environmental risk than conventional non-suspended systems. Conventional logging methods would require construction of mid-slope roads, and because of slope steepness and apparent instability, excess soil material would have to be removed to stable disposal sites.

The plan was executed and the area harvested in 1978 and 1979. Upon completion, those roads considered most vulnerable to erosion were provided with waterbars (small closely spaced ditch and ridge systems that cross the road at an angle, allowing interception and removal of runoff water) and closed to vehicular traffic.

The area was planted with 2-yr-old Douglas fir *(Pseudotsuga menziesii)* seedlings within a year following logging. Site visits were made annually for 3 yr; a final visit was made after 8 yr. On each visit, inspections for erosion and mass wasting that could be attributed to logging activities were conducted.

In the 8 yr since harvest, only one landslide has occurred. The slide was a shallow debris avalanche (estimated volume of 500 cy) that took place high on the slope and did not reach the stream (Figure 4). Examination of roads has shown that storm-water runoff is distributed onto the forest floor and that no significant or measurable erosion of road surfaces or ditches has occurred. There are no points where runoff from the road can directly enter Smith Creek.

Through the use of an interdisciplinary team that incorporated environmental considerations in a cost-effective framework throughout the planning and implementation process, the unstable and highly sensitive lower Smith Creek site was successfully and economically harvested with no identifiable impact on the stream system. In discussing road location in sensitive watersheds, Duncan (1984) states that geomorphic mapping, planning, and geological interpretation is of little value unless that technology is implemented. Successful implementation, however, requires the expertise of local field personnel throughout plan development and execution.

The successful experience at lower Smith Creek shows that a team comprising the necessary disciplines, local personnel, use of available technology, and site specific prescriptions can provide operationally and environmentally desirable results.

ACKNOWLEDGMENTS

The author thanks D. H. Jordan and R. L. Wenham, forest engineers with the Weyerhaeuser Company, Twin Harbors Region, and D. J. McGreer, currently forest hydrologist for the Potlatch Corporation, Lewiston, Idaho, for their contribution to the successful development of the lower Smith Creek logging plan. A special acknowledgement is given to R. S. Claunch, raw materials operations superintendent, Twin Harbors Region, for initiation and successful operational execution of the project.

REFERENCES

Bourgeois, W. A., 1978, Timber harvesting activities on steep Vancouver Island terrain. In Youngberg, C. T. (editor), *Proceedings Fifth North American Forest Soils Conference*: Colorado State University, Ft. Collins, CO, pp. 393-409.

Duncan, S. H., 1985, Road location in sensitive watersheds–An industry perspective. In Swanston, D. N. (editor), *Proceedings for a Workshop on Slope Stability; Problems and Solutions in Forest Management*, Seattle, WA, U.S. Forest Service General Technical Report PNW-180, pp. 78-80.

Duncan, S. H. and Steinbrenner, E. C., 1969, *Soil Survey of the Clemons Tree Farm*: Weyerhaeuser Company Forestry Research Center, Centralia, WA, 66 p.

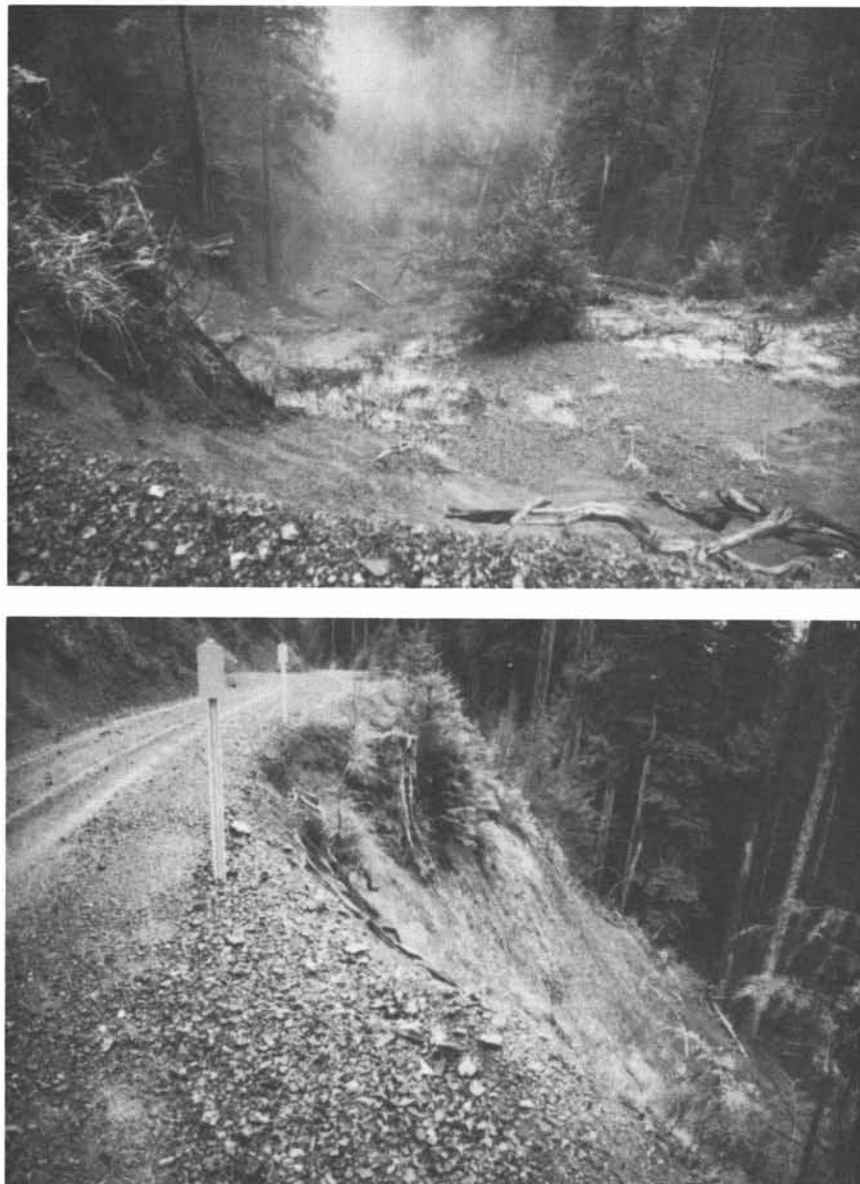
Duncan, S. H.; Ward, J. W.; and Anderson, R. W., 1987, A method for assessing landslide potential as an aid in forest road placement: *Northwest Science*, Vol. 61, No. 3, pp. 152-159.

Gower, H. C. and Pease, M. H., Jr., 1965, *Geology of the Montesano Quadrangle, Washington*: U.S. Geological Survey Geologic Quadrangle Map GQ-374, 1 sheet, scale 1:62,500.

Phinney, L. A. and Bucknell, P., 1975, *A Catalog of Washington Streams and Salmon Utilization*: Coastal Region, Vol. 2, Washington Department of Fisheries, Olympia, WA, 301 p.

Rickert, D. A.; Beach, G. L.; Jackson, J. E.; Anderson, D. M.; Hazen, H. H.; and Suwijn, E., 1978, *Oregon's Procedure for Assessing the Impacts of Land Management Activities on Erosion Related Nonpoint Source Problems*: State of Oregon Department of Environmental Quality, Portland, OR, 219 p.

Wagner, H. C., 1967, *Preliminary Geologic Map of the South Bend Quadrangle, Pacific County, Washington*: U.S. Geological Survey Open-File Report 67-266, 1 sheet, scale 1:62,500.



Two views of a debris flow originating from the outside edge of a forest road. Use of the U.S. Forest Service three-level planning system allows potential failure sites such as this to be identified so that correction or mitigation can be planned before environmental damage occurs. Photographs courtesy of the U.S. Forest Service.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Chestershire and Backdrop Timber Sales: Case Histories of the Practice of Engineering Geology in the Olympic National Forest

THOMAS E. KOLER and KENNETH G. NEAL
U.S. Forest Service

INTRODUCTION

Background

The practice of engineering geology in the Olympic National Forest (Figure 1), as in other national forests, is a recent development resulting from environmental policy legislation enacted in the late 1960s and early 1970s. These laws include the National Environmental Policy Act of 1969 (NEPA), the Federal Water Pollution Control Act Amendments of 1972, the Endangered Species Act of 1973, the Safe Drinking Water Act of 1974, the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA), and the National Forest Management Act of 1976 (NFMA). Prior to this suite of legislation, the application of earth sciences in the Olympic and most other national forests was primarily the concern of soil scientists. Geologists were involved almost solely with economic mineral deposits. By 1974, engineering geologists, along with geotechnical engineers, technicians, and drill crews, were employed full-time as members of geotechnical teams in many national forests, including the Olympic. Initially, the practice of engineering geology was limited to solving problems related to road design and construction. However, it soon became apparent that the practice of engineering geology had much broader applications, particularly as related to timber sale project planning. The two case histories presented in this paper, Chestershire and Backdrop timber sales, are examples of how our profession has contributed to project work in the Olympic National Forest and how the "state of the art" has progressed since 1975.

Levels of Project Investigation and Application

Since 1975, a majority of project work completed by engineering geologists in the Olympic National Forest has been directed toward planning, locating, designing, and constructing low-volume, single-lane logging roads. Most of this work involves both evaluation and analysis of slope and foundation stability and evaluation of the suitability of rock and aggregate materials for use in construction.

Engineering geology projects in the Olympic National Forest are three-tiered and scale dependent. The theory behind this system is that each tier forms a base on which the next higher tier is built. Level 1, the lowest tier, consists of reconnaissance mapping for area planning purposes, at a scale of 1 in. = 2,000 ft (1:24,000). Level 2, the intermediate tier, consists of reconnaissance mapping for transportation planning, or road or facilities location, at a scale of 1 in. = 300 ft (1:3,600). Level 3, the highest tier, consists of site-specific investigation, usually for design of roads or other facilities, with data collected at a scale of 1 in. = 50 ft (1:600) or less.

The level of data collected is scale dependent. The number of data points and the accuracy and reliability of data collected increase in direct proportion to the square of the percent increase in scale; for example, a section developed at 1 in. = 10 ft has 25 times as many data points as one developed at 1 in. = 50 ft. In like fashion, the type of decision that can be based on a specific set of data is also scale dependent, from Level 1 decisions regarding the suitability of a parcel of land for management, modification, or use, to Level 2 decisions regarding impacts along alternative corridors through that parcel, to Level 3 decisions regarding designs to fit terrain characteristics at a specific site along the selected route (Figure 2).

Geologic Resources and Conditions Database

All project data collected, regardless of level, are entered into the Olympic National Forest Geologic Resources and Conditions Database, a 1:24,000-scale map-based system consisting of project location, rock, soil, and landform overlays. Data collected from Level 2 and 3 investigations are reduced to Level 1-scale accuracy and plotted on the database maps for use on future projects. The form of this database is planned to evolve from the current manual system into an integral part of a computerized Geographic Information System over the next several years.

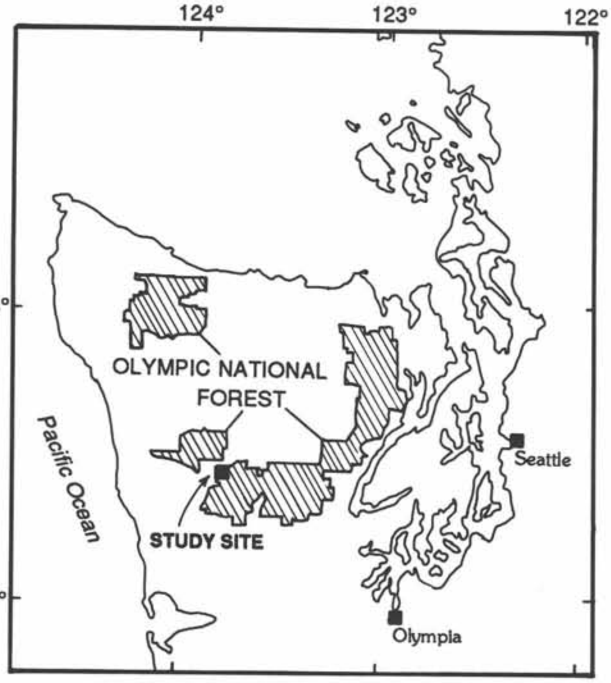


Figure 1. Study site location, Olympic National Forest.

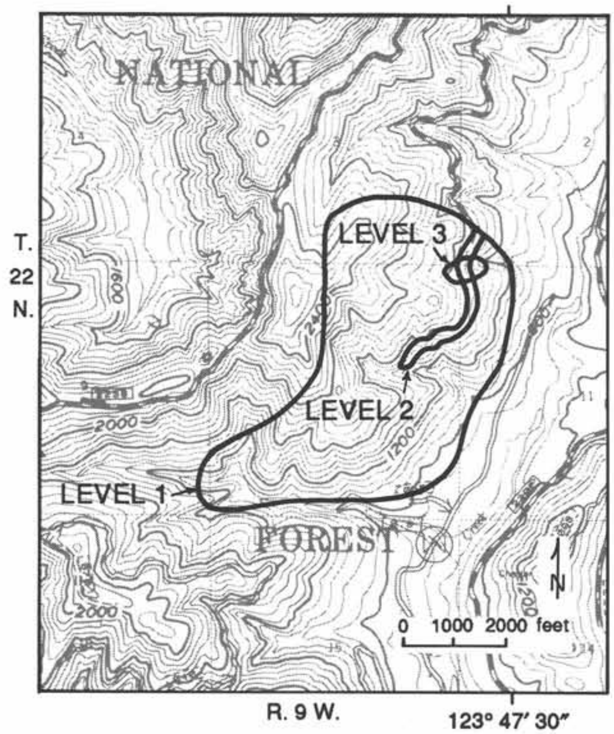


Figure 2. Diagram of the Forest Service three-level analysis system.

Investigative Standards

Since the inception of the full-time practice of engineering geology in the Olympic National Forest, all project work has followed a set of standards. Rock and soil units designations are based on stratigraphic relations and physical charcteristics. Soil units are classified in the field using the Unified Soil Classification System (Casagrande, 1948; American Society for Testing and Materials [ASTM], 1987). Rock units are classified in the field using the Unified Rock Classification System (Williamson, 1984). Designation of rock and soil units is completed at a scale appropriate for the investigative level.

For Level 1 and 2 investigations, a topographic map at the pertinent scale is used for plotting of field data, and specific conditions and interpretations relative to a given location are recorded in a field notebook. Site-specific (Level 3) investigative work follows the Field-Developed Cross-Section Method (Williamson et al., 1981). This method involves the measurement to scale, in section, of the distribution of terrain features and related subsurface characteristics of rock, soil, and ground water interpreted by the engineering geologist. Field-developed cross-sections are constructed using the Brunton Compass, hand clinometer, and cloth tape.

Level 3 investigations are commonly tied to engineering site surveys for reference. Subsurface exploration is conducted on Level 3 investigations as needed to confirm interpreted subsurface relations, to obtain soil and rock samples, and to conduct tests at specified locations and depths. The payoff for using these standards is a consistent methodology used by the project engineering geologist; this is essential to providing consistently high quality and reliable services to the client.

For specific project applications (usually during Level 3), representative samples of soil and rock units are tested in the materials laboratory for engineering quality and strength parameters following the testing procedures set by ASTM (1987) and the American Association of State Highway and Transportation Officials (1986). Laboratory testing is completed to confirm field testing and to provide more accurate data on materials characteristics and strength.

Analytical Standards

The goal of slope stability analysis is assessment of risk of failure. Prior to 1984, calculation of factor of safety for these involved "hand cranking" of values using hand-held calculators, or even slide rules. Slope stability analyses were completed only for site-specific investigations of slope movement features. Evaluations of broad areas for risk of failure were usually done subjectively; infrequently, the infinite slope equation was used for area analyses. (Methods of slope stability analysis are outlined in Morgenstern and Sangrey, 1978.)

With our acquisition of programmable hand calculators and personal computers, the speed and sophistication of analysis increased several orders of magnitude. Prellwitz (1985, 1988; Prellwitz et al., 1985) employed these new tools and refined the three-level method of completing project work. Using the infinite slope equation as part of an algorithm for Levels 1 and 2, Prellwitz wrote the programs Slope Stability Infinite Slope (SSIS) and Slope Stability Infinite Slope for Critical Height (SSISCH) for use on the Hewlett-Packard 41 (HP 41) hand-held programmable calculator. (Critical height refers to the maximum height of an excavated road cutslope that can be constructed without slope failure.) Prellwitz (1985) also developed the program Slope Stability Method of Slices (SSMOS) for the HP 41 for use in site-specific (Level 3) analyses; it uses three methods of analysis: Fellenius or Ordinary Method of Slices, Modified Bishop, and Simplified Janbu. Armed with these three programs and the HP 41, the engineering geologist could now finish a major portion of his/her analysis in the field utilizing a field-developed cross-section. Hammond et al. (1988) have taken this work a step further with their program Level I Stability Analysis (LISA) for IBM and other compatible personal computers. The major differences between Prellwitz's calculator-based programs and Hammond's LISA are that the latter uses probability statistics and as many as 1,000 iterations of the infinite slope equation to determine failure probabilities by area.

The Forest Service engineering geologist has transitioned through the adoption of these programs from use of a mostly subjective process for planning (Levels 1 and 2) and a somewhat cumbersome but sophisticated slope stability analyses for site-specific (Level 3) projects, to use of easily applied, highly sophisticated computer programs for slope stability analyses for all project phases, from planning (Levels 1 and 2) through design and construction (Level 3). This has significantly increased project and program efficiency and effectiveness.

Analyses of rock and aggregate sources are also three-tiered. During Level 1, the quality of each designated rock or soil unit is evaluated to determine potential suitability for use, with the end-product being identification of new prospects to be investigated. During Level 2, rock and soil units are designated and evaluated for each proposed site. Suitability of each unit is evaluated, on the basis of the results of field tests, for the proposed use. The suitability and estimated quantity of rock and aggregate materials must be evaluated along with terrain characteristics and local environmental conditions and the distance of the site from the proposed application to determine whether any further investigative work is warranted. Level 3 analyses consist of synthesis of data developed during measurement of field-developed cross-sections, results of lab testing, and confirmational drilling; separation of materials into suitability use zones; and, where appropriate, slope stability analyses using the previously Level 3 methods for soils, plus Hoek and Bray's methods (1981) for analyzing wedge and planar rock failures.

To demonstrate how engineering geologists assigned to the Olympic National Forest completed project work before and after the advent of the "computer age", two case histories are discussed below.

CHESTERSHIRE AND BACKDROP TIMBER SALE CASE HISTORIES

Located within the Quinault Ranger District of the Olympic National Forest, the Chestershire and Backdrop Timber Sale planning areas overlap each other along Quinault Ridge and the upper reach of Chester Creek (Figure 3). Both are discussed here because they give a historical perspective of how a Level 1 project was completed in the late 1970s (Chestershire) and the mid- to late 1980s (Backdrop). Because of the overlap, data used for both areas are the same or similar.

Level 1

Chestershire Timber Sale Planning Area

An investigation of the Chestershire Timber Sale planning area was requested by the Quinault Ranger District in 1978. The stated purposes for the investigation were to:

(1) Determine the probability of reactivating the Chester Creek landslide by reopening a segment of Forest Service Road 2261 that crosses the toe of the slide;

(2) Locate corridors that would be suitable road location alternatives to the existing road crossing the toe of the slide; and

(3) Determine effects of road development and timber harvest on Chester Creek and other potential slide areas.

The District Ranger was concerned that a potential increase in sedimentation into Chester Creek would occur as a result of harvesting timber and constructing roads in this planning area. Since Chester Creek was identified as an anadromous fishery, any increase in sedimentation would have a potential for causing both short- and long-term adverse effects. Because of these concerns, the District Ranger requested two investigations, one (Level 1) of the Chestershire planning area, and a second (Level 3) of the Chester Creek landslide. Two teams of engineering geologists were mobilized to conduct both investigations concurrently.

Aerial photographic interpretation and field mapping of the Chestershire Planning Area were completed in 1978. Field mapping was completed according to standards discussed in the introduction of this paper. Soil and rock units were designated and classified. Areas of saturated soils and slope movement features in soil and rock were identified and mapped. Slope percent was measured in the field or derived from existing

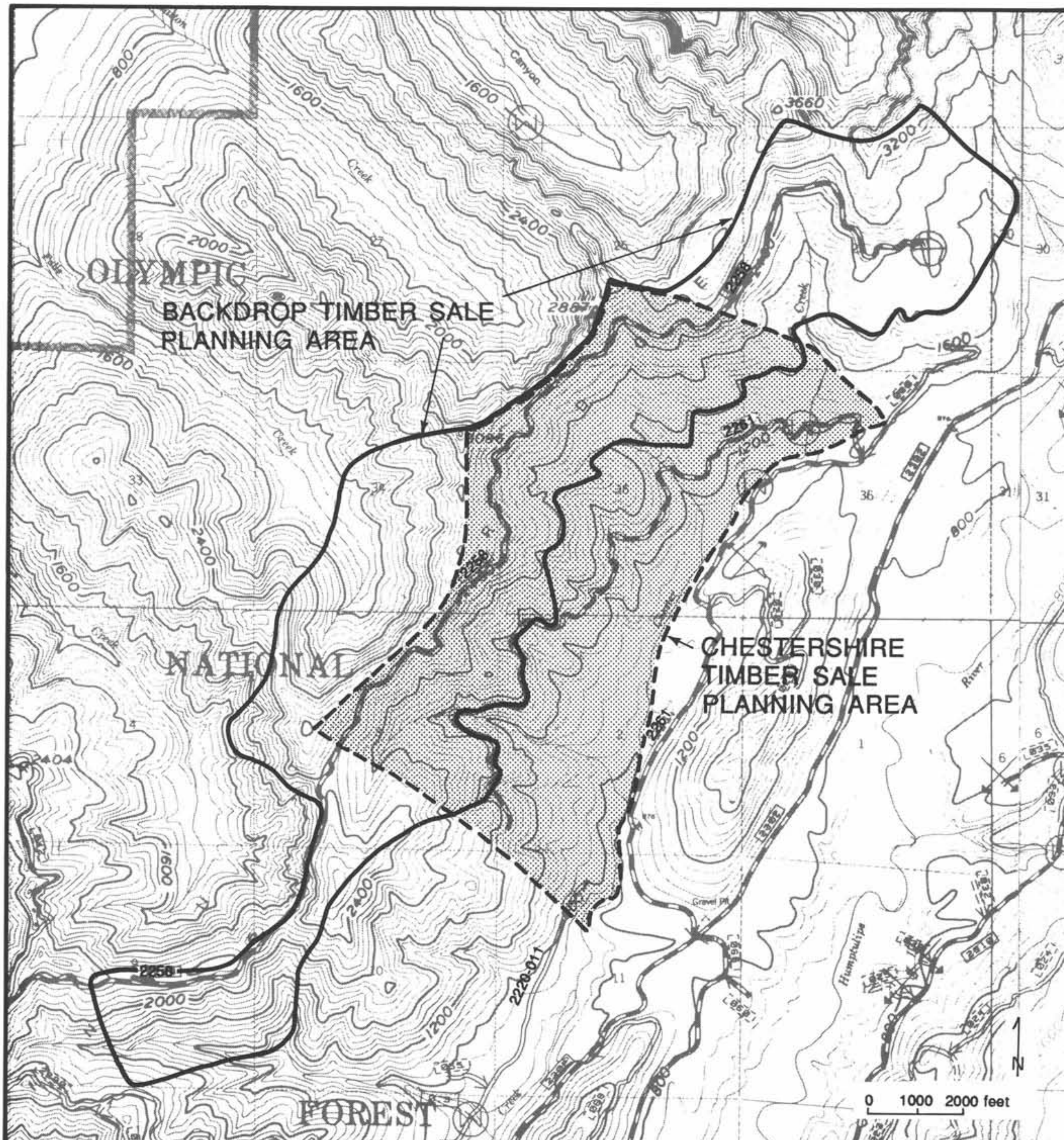


Figure 3. Locations of the Chestershire and Backdrop Timber Sale Planning Areas.

topographic maps. The map scale used for this study was 4 in. = 1 mi (1:15,840). Analyses of rock structures were completed to identify portions of slopes where the potential existed for slope movement due to road excavation.

Office analyses and documentation included the development of a series of overlays to relate physical characteristics of soil and rock materials and the distribution of ground and surface water to existing slope movement features. This formed a union/intersection of data sets, which allowed the identification of critical factors related to slope stability and erosion. These critical factors are:

- Slopes greater than 70 percent;
- Hard rock units covered by shallow soil;
- Adversely oriented mass planar features in rock; and
- Saturated soils.

A slope stability/erosion zonation map was then compiled from these data (Figure 4). Zone 1 has stable slopes; Zone 2 has potentially unstable rock slopes; Zone 3 has slopes that have a low to moderate probability of slope movement; Zone 4 has stable slopes but a high potential for soil erosion; and Zone 5 has unstable soil slopes. Subjective estimates were then made of the potential of initiating slope movements from road construction and timber harvest activities; the scope of predicted effects was also estimated.

A short report (Neal, 1979) outlining predicted impacts in each slope stability/erosion zone was submitted to the Quinault Ranger District interdisciplinary timber sale planning team (ID team) as a reference for the timber sale environmental analysis report (EAR) as required under the NFMA. This report included a geotechnical assessment of transportation and logging alternatives and an evaluation of alternative rock sources in the area.

To answer the question regarding the probability of reactivating the Chester Creek landslide by reconstruction of the existing road, a Level 3 study of the slide area was made concurrently with the Level 1 study of the Chestershire planning area, using standards specified for Level 3 (site-specific investigations) outlined in the introduction. Interpretations of subsurface conditions were confirmed by drill exploration. On the basis of analysis of the slide data, Savage and Neal (1979) recommended that no timber harvesting, road reconstruction, or new road construction be conducted adjacent to or within the landslide area. Results of this investigation were also utilized in the Chestershire Sale EAR.

It should be noted here that while the the level of investigation conducted on the Chester Creek landslide was appropriate for the scope and nature of the problem, it is unusual for Level 3 standards to be applied to project planning and environmental assessment. This example shows, however, that the three-tiered system is a flexible standard that can fit most circumstances.

Backdrop Timber Sale Planning Area

Since the Chestershire planning area overlaps the Backdrop Timber Sale planning area (Figure 2), pre-existing data collected for the former were utilized for the latter as much as possible. Additional fieldwork to cover areas not previously mapped was completed during the 1986 field season. The objectives for this project were the same as those stated for Chestershire.

A series of overlay maps was compiled to augment those used for the Chestershire area. Included as a new overlay was a map of all proposed timber sale clearcut units (Figure 5). Each unit was analyzed to determine the probability of slope movement using the LISA computer program. The following data were used for these analyses: physical characteristics and depth of soil, slope percent, the ratio of ground-water depth to soil depth (dw/d), root shear strength, and tree surcharge.

As noted in the introduction, LISA analyses are completed using probability statistics; LISA generates as many as 1,000 iterations of the infinite slope equation. By using LISA, the engineering geologist provides more statistically meaningful results than those provided by the older subjective methods. Table 1 shows the probability of the occurrence of slope movements for each proposed timber sale clearcut unit under existing natural conditions (base level), after a 50 percent partial cut, and after clear cutting. From the data developed, it is apparent that many of the units are potentially unstable; slope movements are predicted to occur in some even without logging. Aerial photographic interpretation and field reconnaissance of existing clearcuts in the area indicate that the locations of slope movement features appear to correlate well with predictions generated with LISA. Although there are no large slope movement features in the area other than the Chester Creek landslide, there are a number of small features within each timber sale unit.

Calculations of safety factor for the Chester Creek landslide (Savage, 1979) indicated a high probability of failure. Koler (1988) synthesized the Chester Creek landslide data into a format suitable for LISA by using SSIS to back-calculate the physical parameters for input. Results from the LISA analysis for the Chester Creek landslide showed that under natural conditions 68 percent of the area would continue to fail without any timber harvest, as compared to 72 percent after a 50-percent partial timber cut, and 77 percent after clear cutting. These analyses provided a statistical probability for potential management alternatives that clearly shows that the earlier "no go" decision was valid.

Results of these analyses were compiled and documented (Koler, 1988) in a report for use in timber sale area environmental analysis.

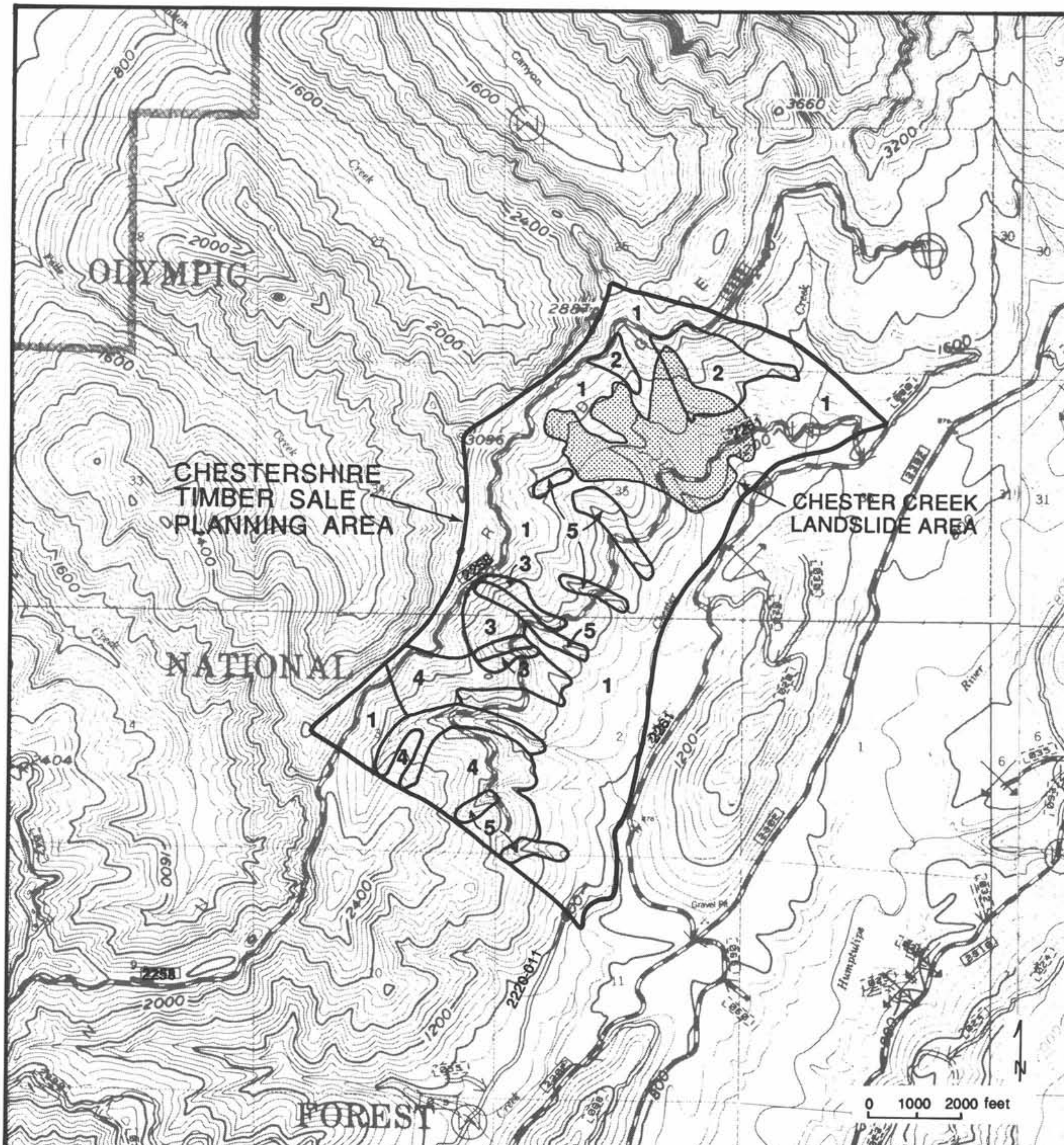


Figure 4. Slope stability/erosion zone map for the Chestershire Timber Sale Planning Area.

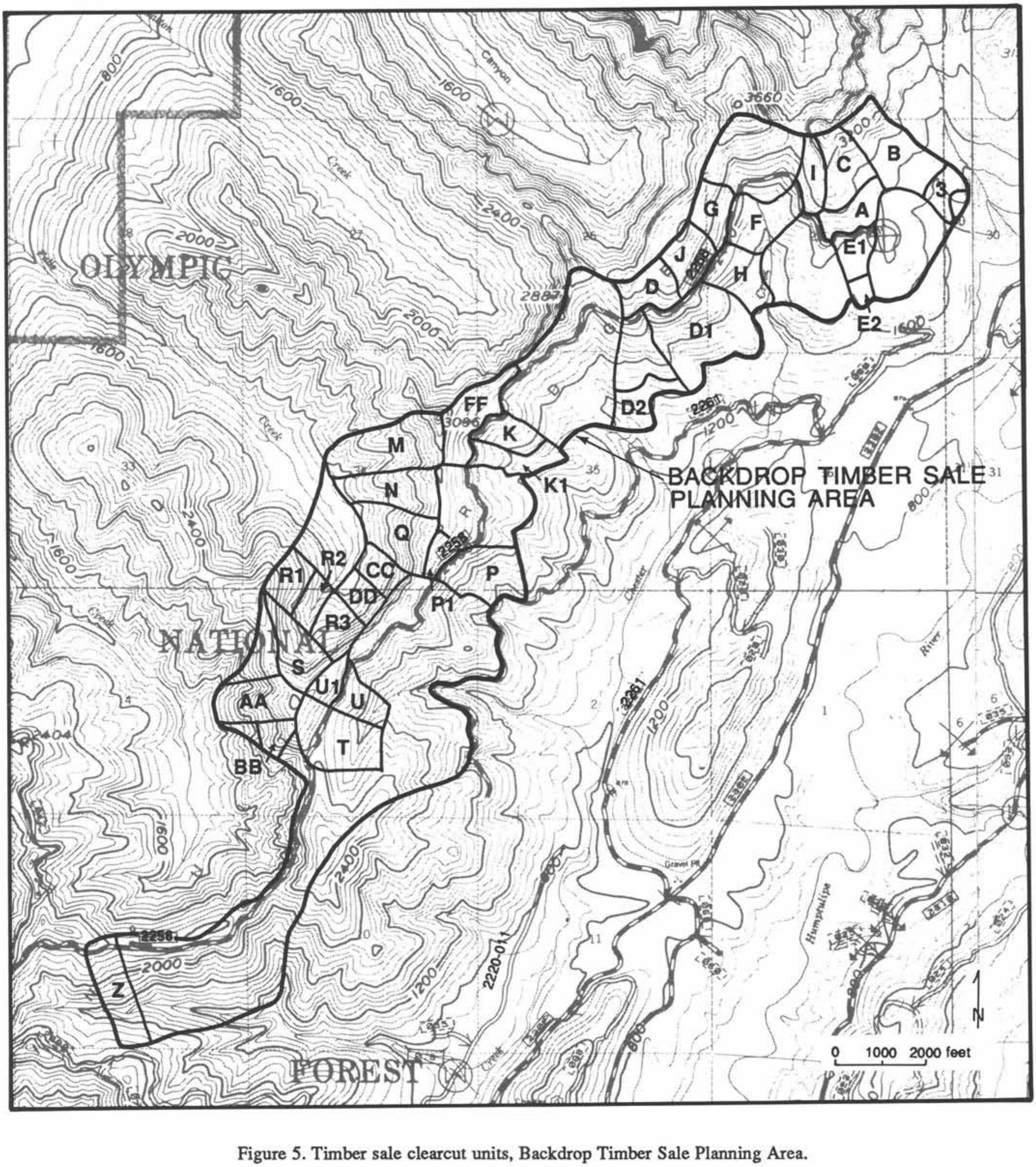


Figure 5. Timber sale clearcut units, Backdrop Timber Sale Planning Area.

Table 1. Level 1 Stability Analysis for Backdrop Timber Sale Planning Area; see Figure 5.

Timber sale unit	Natural conditions	50% partial cut	Clear cut
A	16%	26%	35%
B	53%	70%	78%
C	32%	49%	60%
D	18%	37%	46%
D1/D2	68%	72%	77%
E1	17%	26%	40%
E2	26%	45%	61%
F	36%	49%	61%
G	57%	74%	78%
H	59%	71%	80%
I	55%	76%	84%
J	50%	58%	66%
K	52%	61%	66%
K1	52%	61%	66%
M,N,Q	68%	81%	84%
P	52%	75%	85%
P1	20%	39%	52%
R1	71%	86%	92%
R2	21%	30%	36%
R3	54%	65%	71%
S	58%	72%	80%
T	17%	26%	35%
U	46%	67%	77%
U1	16%	25%	32%
Z	20%	25%	31%
AA	54%	69%	65%
BB	63%	73%	80%
CC-DD	46%	58%	65%
FF	31%	44%	53%
3	71%	86%	93%

Level 2

Chestershire Timber Sale Planning Area

The Quinault District Ranger decided, on the basis of reports by Neal (1979) and Savage and Neal (1979), to abandon the segment of Road 2261 that crossed the toe of the Chester Creek landslide. In 1981, the District Transportation Planner proposed two corridors for possible road construction (Figure 6). The first corridor was planned to provide access to slopes west of the Chester Creek landslide, upslope from Road 2261. The second corridor involved the extension of Forest Service Road 2220-011 along a broad glaciofluvial terrace above the west bank of Chester Creek. This extension was planned to provide access to slopes west of Chester Creek and to tie back into Road 2261 southwest of the Chester Creek landslide. A third corridor would provide temporary access across the middle part of the Chester Creek landslide to access timber northeast of the slide, and a fourth was planned (after the third was dropped) to access that same timber from the east. Level 2 geotechnical work along these corridors consisted of interpretation of aerial photographs and reconnaissance mapping along proposed alignments at 1 in. = 300 ft (1:3,600) to substantiate Level 1 interpretations and to supplement the detail of available data. During this process, each corridor was divided into terrain segments, and typical ground conditions were sketched in cross-section. Data and information were synthesized and evaluated, and several short reports were written (McBane, 1981a, 1981b; Neal, 1982a, 1982b). The Quinault District Ranger's decisions, formed on the basis of these reports, included constructing a road along the second corridor, dropping the first and third corridors, and, tentatively, planning to construct a road along the fourth corridor at a later time.

In December 1983, Neal conducted a Level 2 investigation of an area at the toe of the Chester Creek landslide to evaluate the potential for increased slide activity that might result from logging there. As a result of his report (Neal, 1983a), a follow-up memo (Neal, 1983b) and subsequent meetings with District and Supervisor's Office staffs, the Chester Creek landslide was removed from further consideration for timber harvesting.

As with the Level 1 analyses, this Level 2 assessment predated Prellwitz's computer programs. Field and office analyses at that time were still "hand cranked". Since many of the recommendations were based on subjective conclusions, considerably more communications were necessary to reach the recommended decision than have been necessary since probability analyses using LISA have been completed on similar slopes.

Backdrop Timber Sale Planning Area

When the Backdrop area was first designated for timber sale planning, a great deal of attention was focused on the Quinault Ridge Road (Forest Service Road 2258, Figure 5). Prior to any planning of timber sale units or boundaries, the Quinault District Ranger requested a geotechnical report for transportation planning along this road because it is the only access along Quinault Ridge and numerous road-associated slope movements have closed it. A geotechnical reconnaissance for reconstruction of the road was conducted by McBane (1981). As of early 1988, no transportation planning for the Backdrop Timber Sale has been finalized. To complete transportation planning, the 1981 geotechnical work by McBane would need updating because of more recent slope movements. Future slope stability analyses will be conducted using Prellwitz's SSISCH and rock slope analysis methods developed by Hoek and Bray (1981).

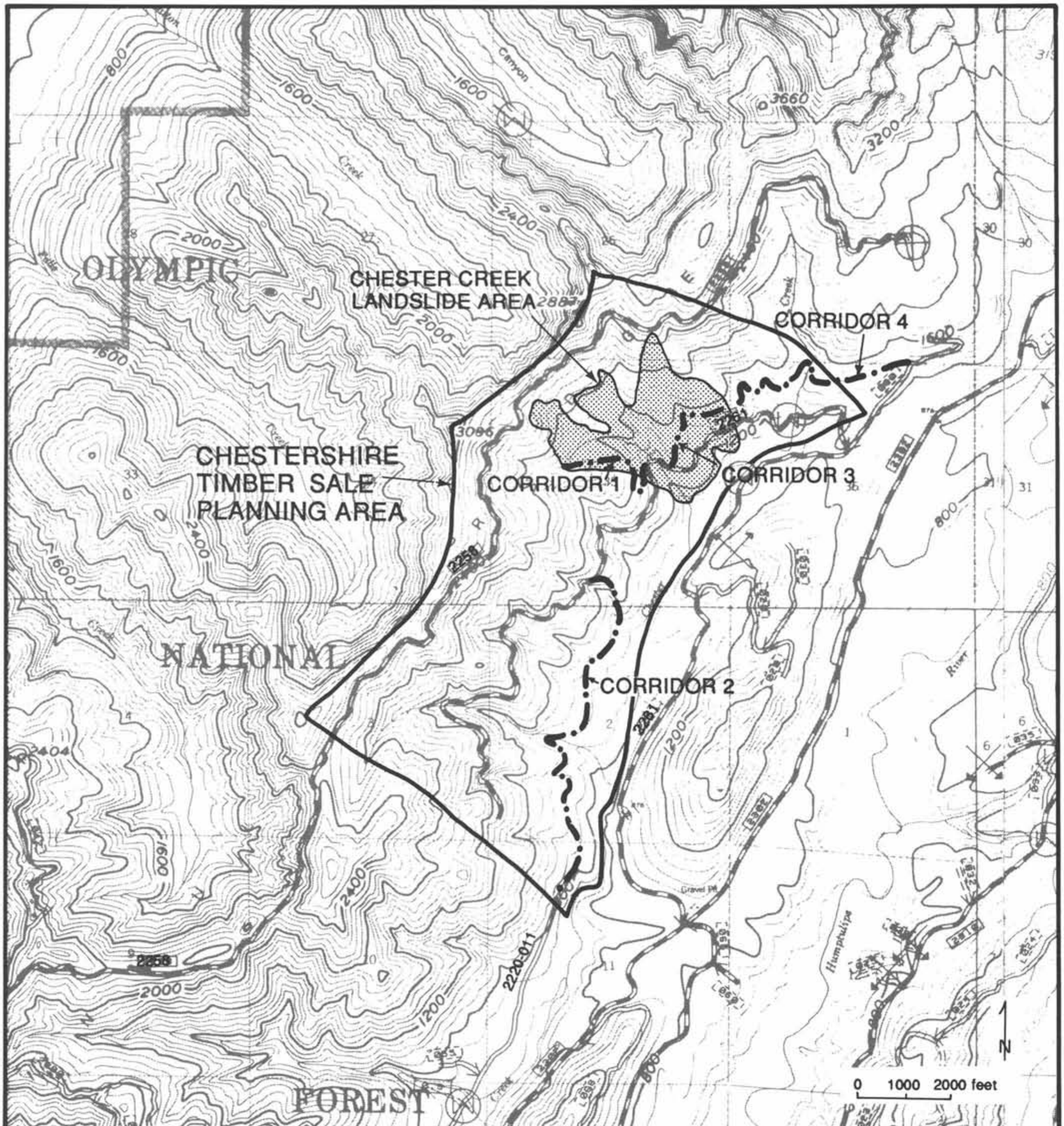


Figure 6. Alternative road corridor locations for the Chestershire Timber Sale Planning Area.

Level 3

Chestershire Timber Sale - Extension of Forest Service Road 2220-011

A site-specific geotechnical investigation was conducted in 1982 along the preliminary survey line (P-line) for design of the 2220-011 tie road along Corridor 2 (Figure 5). This investigation built upon data collected during Levels 1 and 2 project work. The project engineering geologist divided the P-line into terrain segments. Soil, rock, topographic, and ground- and surface-water conditions were used as criteria for delineating segments. The purpose of segmentation was to provide data and portray conditions that represented typical terrain characteristics, and, in turn, to enable the development engineer to select a design that was appropriate for ground conditions encountered for each segment. The project engineering geologist completed slope stability analyses for areas of existing slope movement features, or which appeared to have the potential for slope movement to be initiated by road construction. In addition to small slope movement features, conditions encountered included steep slopes with saturated soils and spring lines, plastic soils with low shear strength values, and rock slopes with inherent adverse discontinuities.

The Modified Bishop Method of Slices (Bishop, 1955) was used to analyze features with ongoing or predicted rotational movement. The infinite slope equation was used to analyze features with ongoing or predicted translational movement. Different design alternatives were evaluated for conditions in each segment. The project engineering geologist presented analyses of alternatives and recommendations in his report (Koler, 1982).

The Wineglass pit, located roughly 6 mi northeast of the project, was selected for production of pit-run aggregate. This pit had been investigated previously; the last phase of drill exploration there prior to the Chestershire road construction was completed in 1981. The Geotechnical Section provided a rock source operating plan to be included in the timber sale contract package (Blair, 1982).

The extension of Forest Service Road 2220-011 has been completed. The construction phase involved considerable consultation with an engineering geologist, primarily dealing with the suitability of subgrade materials for use at constructed grade level (Neal, 1985; Jordan, 1988). To date, no new logging has been conducted in the area because of decreased demand. Resale of some of the old Chestershire timber sale units is contemplated.

Backdrop Timber Sale - Road 2258000, Station 67+76 to 67+90

In 1983, subsequent to McBane's Level 2 investigation of Road 2258000 for transportation planning, a site-specific (Level 3) investigation was conducted of the segment of Road 2258000 between Stations 67+76 and 67+90 to evaluate alternative ways to regain adequate width for log haul. Road 2258000 was needed for log haul for the Binder timber sale area, located on the west slopes of Quinault Ridge. A team comprised of engineering geologists and a geotechnical engineer investigated the site using the field developed cross-section method, Unified Rock Classification System, and Unified Soil Classification System, as outlined in the introduction. Subsurface conditions were confirmed and foundation strength characteristics were measured during drill exploration (refer to Figure 7, Geotechnical Cross Section 30 for Binder Timber Sale). Road alignment alternatives were analyzed using a yarder simulator. Construction of a Hilfiker retaining wall to support the roadway was selected as the preferred alternative. Design analyses were completed using the Region 6 retaining wall design guide (Driscoll, 1979). Conclusions and recommendations were documented in a report written for design (Blair and Scheible, 1983).

Binder timber sale was dropped from the program because of environmental and economic considerations, so the retaining wall was not constructed. However, with upcoming planned logging of the Backdrop timber sale area, a contract was prepared in 1987 for wall construction in 1988. After award of the contract (and after the snow had melted), additional slope movement, which resulted in loss of all remaining soil in the foundation area, was discovered. The project engineering geologist remeasured site conditions and is currently working on modifying the wall design (Jordan, 1988).

CONCLUSIONS

Employment of engineering geologists in the U.S. Forest Service increased significantly in the mid-1970s after enactment of federal environmental legislation. The Olympic National Forest began employing engineering geologists as part of its geotechnical staff in 1974. Engineering geologic services have greatly expanded from those early years, from investigation of rock and aggregate sources and road corridors to investigations for area planning, water well and drainfield location and design, and, most recently, review of small hydroelectric project applications. Since the mid-1970s, the geotechnical staff employed by the Olympic National Forest have been assigned to the Supervisor's Office, with their duty station at Ft. Lewis, Washington. The Geotechnical Section is comprised of a team of engineering geologists, geotechnical engineers, civil engineering and lab technicians, and a drill crew. While each of these fields is essential to the production of complete geotechnical services, none can operate independently of the others. Having all skills in a centralized location fosters teamwork.

Engineering geologists on the Olympic National Forest staff complete work within a scale-dependent, three-tiered system. Level 1, the lowest tier, comprises

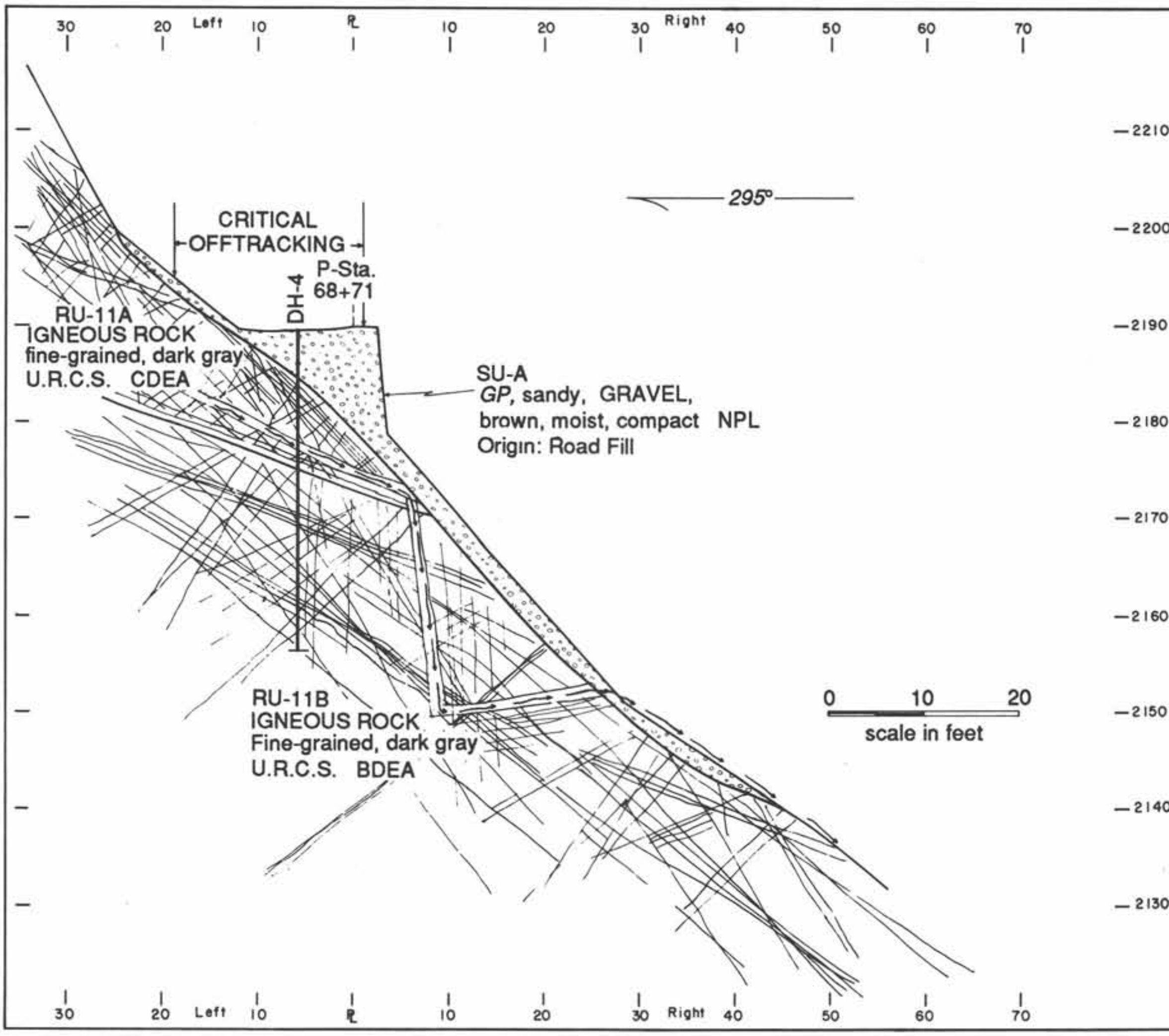


Figure 7. Geotechnical cross-section 30 for the Binder Timber Sale.

the area and project planning stage; data are collected and mapped to a minimum 1:24,000 scale. Level 2 involves reconnaissance mapping of corridors for transportation planning or road or facilities location, at a scale of 1:3,600. Level 3 is site-specific, and mapping is completed to a scale of 1:600 or greater. This paper traces the evolution of this three-tiered method of work over the past 10 yr by examining two overlapping projects, the Chestershire and Backdrop Timber Sale areas, located on the Quinault Ranger District of the Olympic National Forest. During this period, the "computer age" has come into being for engineering geologists in the Forest Service. The Chestershire Timber Sale examples demonstrate past methods, which included subjective evaluations of broad areas and analyses of mathematical models developed for specific sites. The Backdrop Timber Sale examples demonstrate current methods, with expanded use of mathematical models to predict probabilities of slope movements over broad areas, with assistance from programmable calculators and personal computers. The net effect of this computerized analysis is a statistical probability of slope movement for each proposed activity during each project phase, from planning through design and construction. This adds credibility to geotechnical conclusions and recommendations and facilitates more objective management decisions regarding resource management and use.

REFERENCES

American Association of State Highway and Transportation Officials, 1986, Standard Specifications for Transportation Materials and Methods of Sampling and Testing–Part II, Methods of Sampling and Testing: *American Association of State Highway and Transportation Officials*, Washington, DC, 14th ed., 1,275 p.

American Society for Testing and Materials, 1987, Description and Identification of Soils (Visual Manual Procedure): *Annual Book of ASTM Standards*, Vol. 04.08, pp. 409-423.

Bishop, A. W., 1955, The use of the slip circle in the stability analysis of slopes: *Geotechnique*, Vol. 5, No. 1, pp. 7-17.

Blair, M. R., 1982, *Rock Source Operating Plan, Pit No. 2302196-0.4 (Wineglass Pit), Chestershire Timber Sale*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 1 p.

Blair, M. R. and Scheible, A. A., 1983, *Geotechnical Investigation for Design, Road 2258000, Station 67+76 to 67+90, Binder Timber Sale, Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 39 p.

Casagrande, A., 1948, *Classification of soils*: American Society of Civil Engineers Transactions, Vol. 113, pp. 901-930.

Driscoll, D. D., 1979, *Retaining Wall Design Guide, U.S. Forest Service Region 6*: Foundation Sciences, Inc., Portland, OR, 428 p.

Hammond, C. J.; Miller, S. M.; and Prellwitz, R. W., 1988, Estimating probability of landslides by Monte Carlo simulation. In *24th Symposium on Engineering Geology and Soils Engineering*: University of Idaho and Washington State University, Coeur d' Alene, ID, pp. 319-331.

Hoek, E. and Bray, J. W., 1981, *Rock Slope Engineering*: The Institute of Mining and Metallurgy, London, UK, 358 p.

Jordan, J. R., 1988, Personal communications, Engineering Geologist, U.S. Forest Service, Olympic National Forest, Ft. Lewis, WA.

Koler, T. E., 1982, *Geotechnical Investigation for the Reconstruction of 2220-011 Road, and the Design of the Proposed Extension of 2220-011 Road, Chestershire Timber Sale, Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 15 p.

Koler, T. E., 1988, *Geotechnical Report for the Environmental Assessment of the Backdrop Timber Sale Planning Area in the Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 9 p.

McBane, J. A., 1981a, *Geotechnical Report for Transportation Planning; Road Location Alternatives to Control Point I, Impacts of Extension _ Road 2220-011, Chestershire Timber Sale, Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 21 p.

McBane, J. A., 1981b, *Proposed Road Location, Chestershire Timber Sale, Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, memo, 1 p.

Morgenstern, N. R. and Sangrey, D. A., 1978, Methods of Stability Analysis. In Schuster, R. L. and Krizek, R. J. (editors), *Landslides–Analysis and Control*: Transportation Research Board, Commission on Sociotechnical Systems, National Research Council Special Report 176, p. 155-171.

Neal, K. G., 1979, *Geological Report for Environmental Assessment, Chestershire Timber Sale, Quinault Ranger District:* U.S.Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 13 p.

Neal, K. G., 1982a, *Trip Report; Proposed Unspecified Road Location across Chester Creek Landslide for Chestershire T.S., February 18, 1982*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 2 p.

Neal, K. G., 1982a, *Geotechnical Report for Road Location; Road Alternative 2 to Unit 4, Chestershire Timber Sale, Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 5 p.

Neal, K. G., 1983a, *Slope Stability Evaluation; Proposed Clearcut Unit P, Worchester T.S., Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 3 p.

Neal, K. G., 1983b, *Slope Stability Evaluation; Slopes Adjacent to Chester Creek Landslide*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 4 p.

Neal, K. G., 1985, *Request by Contractor to Cross Chester Creek Landslide*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 1 p.

Prellwitz, R. W., 1985, *Slope Stability Analyses by Three Methods of Slices with the HP 41 Programmable Calculator*: U.S.Forest Service Publication EM 7170-7, 66 p.

Prellwitz, R. W., 1988, *Preliminary Slope Stability Analysis with Hewlett-Packard HP 41 Programmable Calculator*: U.S. Forest Service Publication EM 7170-9, 77 p.

Prellwitz, R. W.; Howard, T. R.; and Wilson, W. D., 1985, Landslide analysis concepts for management of forest lands on residual and colluvial soils. In *U.S. Forest Service Geotechnical Workshop Proceedings*: U.S. Forest Service Publication EM 7170-6, pp. 146-162.

Savage, W. L. and Neal, K. G., 1979, *Geotechnical Report, Road Location Alternatives–Chester Creek Landslide, Quinault Ranger District*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 18 p.

Williamson, D. A., 1984, *Unified Rock Classification System*: Bulletin of the Association of Engineering Geologists, Vol. 21, No. 3, pp. 345-354.

Williamson, D. A.; Neal, K. G.; and Larson, D. A., 1981, *The Field-Developed Cross-Section–A Systematic Method of Presenting Dimensional Subsurface Information*: U.S. Forest Service, Olympic National Forest Geotechnical Section, Ft. Lewis, WA, 35 p.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

A Method for Application of Geologic Information in Management of the Gifford Pinchot National Forest

THOMAS K. REILLY
U.S. Forest Service

INTRODUCTION

The Management Situation

The geologic history, origin, and processes of a forest landscape have fundamental influences on the capabilities and limitations of the land. The geologic characteristics of an area influence landform formation, soil profile development and soil characteristics, and ground-water occurrence; they consequently influence vegetative types and patterns. Areal geology affects the ability to manage a forest without causing adverse environmental effects or impairing future land productivity. The geology of an area also provides opportunities for recreation, education, and scientific research. Knowledge of the geologic capabilities and limitations of a national forest should result in a better understanding of the trade-offs and "opportunity cost" of alternative management strategies.

Comprehensive geologic information is not easily available to planners at most national forests. This is because the U.S. Forest Service lacks a uniform system to store and display basic geologic information. A system does not exist for a variety of reasons, including a lack of a clearly demonstrated need, overestimation of the costs of acquiring such information, and the misconception that the information is already available from other resource inventories.

Recognition of the Need for a Geologic Information System

Several problems that occurred on the Gifford Pinchot National Forest (GPNF) underscored the need for a geologic information system.

- Availability of information was people-dependent. It was recognized that information became lost, stored in project files, or worse, stored in people's minds. If employees left the GPNF, they took with them information gathered at considerable expense.
- The quality of information was varied. With no consistent terminology, decisions about how to compile, save, and apply information were subjective and depended on the level of experience of the individuals involved.
- Involvement was often late and costly. Geologists working on the GPNF are assigned to the Engineering Branch, due to the traditional role of geologists in project design. Because of the lack of a geologic information system and time to gather planning-level information on a project basis, geologic expertise was usually sought only after planning decisions had been made. Many decisions involved road building or timber harvest in an area where, because needed geologic resources were lacking or the geologic conditions were adverse, difficulties were later encountered.
- Involvement in planning was recognized as being valuable. If basic geologic information was available at even a small scale, the consistencies (or inconsistencies) of geologic resources, conditions, and processes might be projected across an area between locations for which some information was available. If such projected information was readily available, planners and land managers would become aware that geologists could be involved in planning efforts on a cost-effective basis. Informed decisions pay off in reduced costs and improved resource protection.

While the above factors were recognized by geologists, it was not until late 1979 that the GPNF Forest Management Team became aware of the usefulness of a geologic information system. The Forest Planning Interdisciplinary Team was then being formed to develop a Land and Resource Management Plan in compliance with the National Forest Management Act. The Forest Geologist was selected to be a team member. A proposal for formulation of a system to support the planning effort was soon accepted. The intent of the proposal was not only to comply with the needs of the GPNF planning effort, but also to break out of the project mode and use the system in areal analysis. It was predicted that if a well-planned, long-term comprehensive geologic information system was developed, it would result in better management decisions based on better information.

Development of a System

Careful thought was given to format, structure, classification systems, and terminology for the new system. Considerable effort was required to ensure that the system would be technically valid and internally consistent, use nontechnical terminology, and be easily used by geologists and non-geologists alike. Also, organizational commitment was gained to ensure that the accuracy of the system would be maintained and improved through regular updating. Coordination was required to ensure that duplication and overlap with other resource systems (such as soils, hydrology, and minerals) did not occur. The system was tailored to satisfy management needs not already being met.

This paper reviews the geologic information system and some actual and potential general applications. The final sections describe some examples of system information use.

OVERVIEW OF THE GEOLOGIC RESOURCES AND CONDITIONS SUBSYSTEM

The initial geologic information system was developed after formulating standards and guidelines for information collection. In response to user needs, the format evolved to the present configuration. At the urging of forest managers, the system was included as one component of an overall comprehensive multi-resource information system, and it was designated the Geologic Resources and Conditions (GRC) subsystem. The overall system, known as the Total Resource Information (TRI) system, divides the entire GPNF into more than 200 distinct geographic areas (referred to as compartments) averaging about 6,000 acres each.

The name Geologic Resources and Conditions recognizes the basic division of geologic factors into resource development opportunities and potential constraints to certain land-management activities. The map scale used is 4 in. = 1 mi, which matches that of the larger TRI system. A user Subsystem Guide (U.S. Department of Agriculture, Forest Service, 1986b [hereafter U.S. Forest Service]) describes the subsystem, terms, systems, and methods used and possible applications of the GRC subsystem information. Federal regulations, derived from Acts of Congress, and Forest Service manual descriptions derived from those regulations refer to geologic factors as opportunities and constraints to land-management activities. Geologic opportunities include potential development and use of geologic resources. Geologic constraints are factors which affect cost, safety, or feasibility of management activities.

The GRC map system is designed to display basic geologic information in a simple, flexible format. Any land manager can have such a system developed at no major cost, if data and information gathered for site-specific project work are routinely plotted on system map overlays. GRC maps were developed in a three-step process.

- Office preparation: All available information was compiled on the 4 in. = 1 mi system base map overlays. Sources of information included project files and reports, published geologic information, and results of air photo interpretation.
- Field verification: Whenever possible, this step was accomplished in conjunction with other priority fieldwork. On the whole, only a slight increase in field time was required for verification, which greatly enhanced the product.
- Compilation: Boundaries were reconciled, the final map prepared, and a folder developed to store all available maps, photos, and records.

The Forest Service has established a national Geographic Information Systems (GIS) steering committee with a mandate to monitor, evaluate, and recommend ways to implement technologies and develop a national GIS strategy. Looking ahead to future GIS technology, GRC maps were developed on a controlled (spatial) base map referenced to geographic coordinates to allow accurate digitizing of geologic material unit boundaries and the location of landforms and geologic resources. The GRC subsystem is fully compatible with GIS concepts and software and can be readily digitized.

DETAILED SUBSYSTEM DESCRIPTION

Philosophy of the Subsystem

The GRC subsystem is user-friendly by design: it is a straightforward, single-sheet product that uses clear symbols and nontechnical terms. It is intended for general understanding by planners, resource specialists, and land managers.

GRC Subsystem Components

Components of the GRC subsystem are the map, the Legend, Materials Sources Information, and Special Considerations information block. Figure 1 is a representation of a GRC map.

All GRC maps are drawn on 24 in. x 36 in. reproducible mylar sheets. Transparent adhesive-backed pattern film is used to distinguish the various geologic materials units on the map sheet and on the left margin of the descriptive block. The user can locate the descriptive information in the information block keyed by the same film pattern.

A simplified representation of a GRC map sheet is given in Figure 2. On an actual map, the local road network is shown to help the user locate a feature or project. Annotations surrounding the map describe various features typical of GRC maps. If new information is obtained that results in a changed interpretation of materials unit boundaries, the map can easily be changed. The pattern film on the master copy GRC map

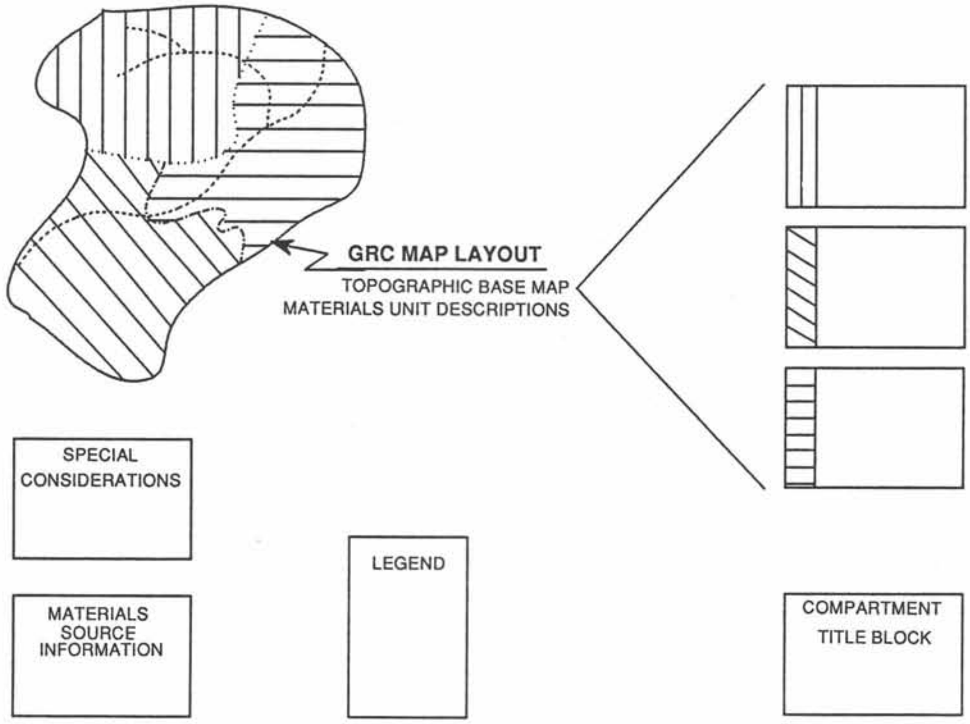


Figure 1. Sample Geologic Resources and Conditions (CRC) map layout.

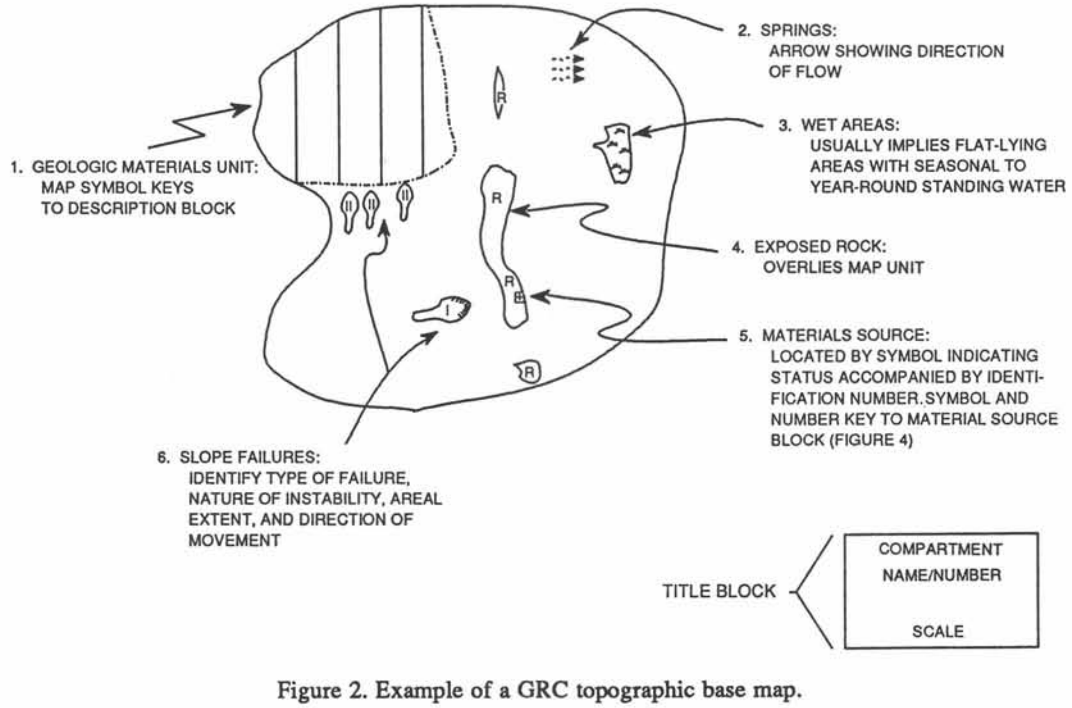


Figure 2. Example of a GRC topographic base map.

is removed, the boundary redrawn, new pattern film attached, and a new (updated) mylar copy is made from the master copy.

An enlargement of a typical geologic materials unit descriptions is shown in Figure 3. The left portion of the description displays the same pattern film as those materials units shown on the base map. Geologic conditions that may affect current or planned land management are outlined under "Significant Conditions".

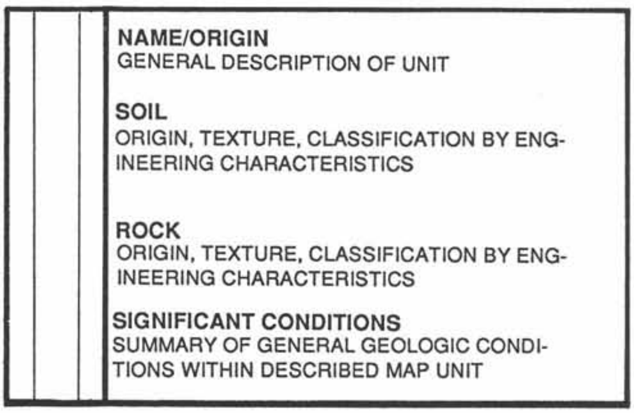


Figure 3. Typical Geologic Materials Unit (GMU) descriptions.

Figure 4 is the Materials Source Information for a typical GRC map. Each known usable source of construction materials is located on the GRC map by symbol and described in the map margin information block shown. The symbol on the map indicates the status (for example, developed or closed). If the information block is left blank, the absence of a known source is pointed out in the Special Considerations information block.

Some other types of information blocks are not shown in the figures. These are:

(1) GRC map Special Considerations: This space is used to summarize the significant geologic resources and conditions for the entire TRI compartment.

(2) GRC map legend: The legend displays and describes the symbols that locate geologic resources and conditions and identify geologic materials units. Confidence level of materials unit boundaries is indicated by either a solid (ground verified) or dashed (inferred) line.

Elements of the GRC Subsystem

Minimum elements of the GRC subsystem are:

- A display of geologic resources, usually located at an individual site, identified by symbol. *Geologic resources* include construction materials sources, ground water, caves, and geologic points of interest.

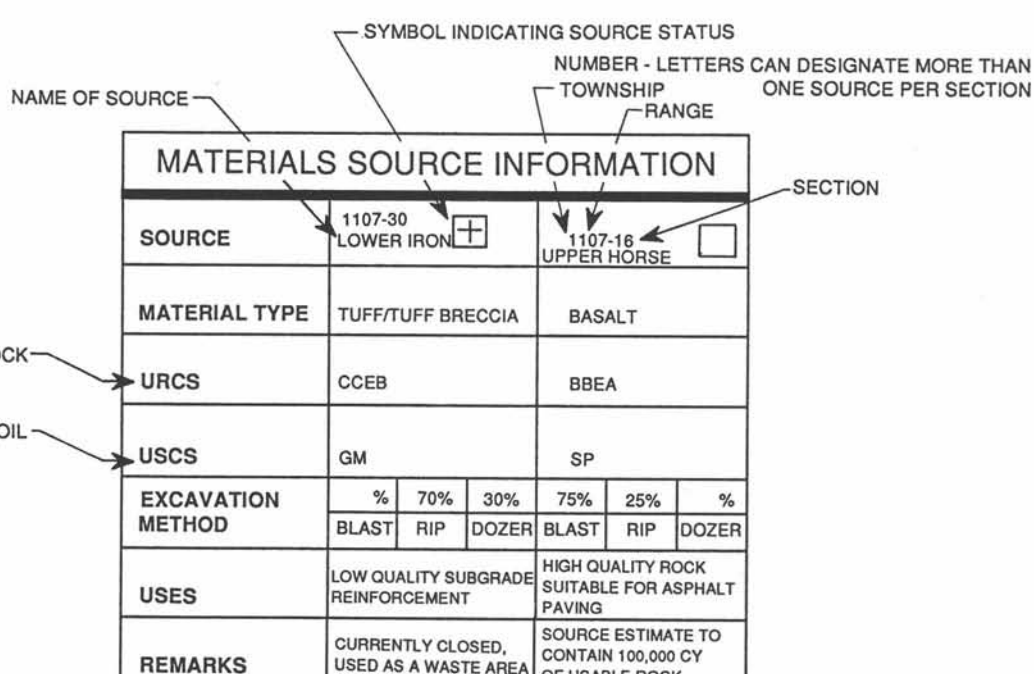


Figure 4. Typical GRC map materials source information block.

- A map display of geologic materials units (GMUs) distinguished by symbol. These units are designated by soil and/or rock type based on stratigraphy, physical characteristics, and associated processes. Certain soil types or landforms of a particular origin such as till or slope movement deposits may be designated as GMUs.
- A display of landforms, identified by symbol. Landforms displayed include rock outcrops and talus areas, wet areas, and slope features. The combination of geologic materials units and landforms is used to define *geologic conditions*.

Descriptive information concerning *geologic resources and conditions* is given in the map margin. It includes descriptions of the GMUs, an explanation of map symbols, a summary of information about construction materials sources, and a summary of special considerations such as significant geologic resources in the area.

Geologic Resources

The definition of geologic factors is found, in part, in planning regulations and the Forest Service Manual, Chapters 1910, 2550, and 2880 (U.S. Forest Service, 1985a). Energy and mineral resources were not added to this subsystem because they are already shown on the TRI Minerals subsystem maps.

The geologic resources shown on GRC maps reflect known occurrences. However, the fact that a resource is not displayed may reflect only a lack of past need or site-specific work to locate the resource.

Earth Construction Materials

This resource consists of deposits of rock, gravel, cinders, and mixtures of sand, silt, and clay that are of sufficient quality to be used as construction materials, such as fill, road base or surfacing rock, or armor for erosion protection. Since the overwhelming proportion of earth construction materials used on the GPNF is natural or crushed rock, the geologic resource is generalized as "rock resource".

Materials sources are inventoried and categorized as active or inactive. The status of the source is determined by the District Ranger after interdisciplinary analysis of the effects of source development. Management direction provided by the District Ranger consists of written criteria on size, period of operation, means of access, and ultimate rehabilitation of the site. Forest engineering geologists prepare a long-term source development and rehabilitation plan consistent with this direction. A contract operating plan is prepared, consistent with the development plan, designating that portion of the source to be used for each project.

By using the comprehensive process described above, impacts to GPNF resources are minimized, and each rock source is developed and used in an efficient manner.

Ground Water

This resource consists of known or inferred occurrence of subsurface water that can be developed for a potable water supply or other purposes. The groundwater resource in the GPNF has not been systematically assessed by geologists or hydrologists. The occurrence of ground water and associated aquifer recharge systems is generally evaluated by GPNF geologists on an area or project basis. To date, this resource has been developed to supply recreation and administrative sites with potable water and for irrigation at the Wind River Nursery.

GRC maps show water well locations. GMU descriptions may also identify potential for ground-water extraction.

Caves

This resource consists of natural or developable underground spaces (caves). In the GPNF, numerous natural cave systems were formed by lava flows. The location of these caves is an important consideration for resource management activities because many contain significant geologic, cultural, or biological resources. Several caves provide recreational opportunities; however, some present hazards. Except for caves well known to the public that do not contain sensitive geologic or biological resources, cave entrances are not shown on GRC maps. Forest policy is to conduct an analysis to develop a management plan for any caves that might affect or be affected by management activities.

Geologic Points of Interest

This resource consists of examples of unique or spectacular features depicting geologic processes or phenomena of the Earth's evolution, including volcanic or glacial landforms and effects, academically significant contacts between soil and/or rock units, sedimentary structures, landforms, or fossil locations. Some geologic points of interest are regionally or nationally significant; all features inventoried may have value for scientific study, public education, and for recreation and interpretive programs.

As part of the forest planning process, all inventoried Geologic Points of Interest have been rated for significance using Forest Service criteria. The most significant features were considered for nomination as Special Interest Areas in the Forest Plan. The sensitivity to disturbance of sites was also rated to identify those features more likely to be damaged or destroyed by management activities. All sites will be analyzed to deal with the effects of adjacent management activities.

Geologic Conditions

This information category is defined to include features or processes that affect the safety, cost, or feasibility of resource management activities and development.

Geologic Materials Units

The GMU is a basic component of the GRC subsystem and is defined as an area characterized by a mappable distinctive geologic condition. Each GRC map area has been divided into one or more GMUs on the basis of soil and rock materials origin and characteristics (such as thickness, strength, and permeability), ground- and surface-water distribution, ground slope, dominant geologic processes (such as slope movement in the viscous fluid state), and characteristic landforms (such as benches or cliffs).

All materials unit descriptions follow the same format. To reduce subjectivity and increase reliability and reproducibility, standard soil and rock unit classification systems are used: the Unified Soil Classification System (USCS) (American Society of Testing and Materials, 1987), and the Unified Rock Classification System (URCS) (Williamson, 1984).

GMUs are differentiated on the GRC map by symbol and keyed to a description in the map margin. The description contains information about both the soil and rock materials, such as their thickness and physical properties. The description also contains a summary of the significant geologic condition for the GMU, such as the presence of the numerous slope movement features or high potential for slope movement (compared to adjacent GMUs), rock outcrop areas, and wet areas. In addition, the GMU description may contain information about the suitability of the materials for use in construction. In some instances, the description may recommend further site-specific work to evaluate areas in the GMU pertaining to potential management activities.

Information used to define GMUs is derived from a variety of sources of varied accuracy and reliability. The overall accuracy is suitable for general, preliminary management decisions. The two types of lines separating GMUs (solid and dashed) represent ground-verified and inferred boundaries, respectively.

Rock Outcrop

Rock outcrops affect the cost and feasibility of road construction and alternative timber harvest methods. This condition must be further analyzed because many of these areas have been inferred from air photo interpretation. Depending on physical characteristics, rock outcrop areas may exhibit different stability characteristics, may respond differently to management activities, and may have potential for use as construction materials.

Talus Deposits

Talus deposits are significant to timber harvest and transportation planning because of potential slope instability and difficulty in reforestation. Some talus deposits may be suitable for use as construction materials, depending on factors such as particle size, rock quality, ground slope, and deposit thickness. The value as a potential rock resource must be compared to other resource values, such as wildlife habitat.

Significant "Wet Areas"

This condition is defined as areas of elevated or seasonally high ground-water table or seep/spring areas. Since many of these wet areas are inferred from air photo interpretation, their location requires field confirmation, site-specific mapping of feature size, and determination of water quality. Wet area conditions affect road drainage and pavement design, the cost of road construction, and slope stability. Intensive field investigation prior to road design and construction is the basis for evaluating alternative design and construction techniques and mitigating slope stability concerns.

Slope Stability

Seven categories of slope movement forms and processes, distinguished by Roman numeral, appear on GRC maps. These seven categories represent three basic mechanisms (slide, flow, and fall) and four subcategories. Many features exhibit combinations of mechanisms. In those instances, the predominant mechanism is used as the basic descriptor.

The seven categories of mechanisms and associated symbols are a shorthand method of cataloging slope movement features. General guidelines for managing within GMUs cannot be applied to individual slope movement features. Management and resulting location and design alternatives must be based on site-specific field investigation and evaluation of conditions for each feature.

Subsystem Updating

As new information is acquired, geologists will make necessary changes to the appropriate GRC map. The revision date in the title block reflects new information, and a revised map is provided to the ranger district.

USE OF GEOLOGIC RESOURCES AND CONDITIONS MAPS

Potential Use of the GRC Subsystem by Resource Area Managers

Although the information displayed and described may relate most directly to engineering and slope stability concerns, GRC subsystem information is adaptable to many other national forest resource management needs.

The following examples are some potential applications of the GRC Subsystem information by resource area managers.

- Recreation management: Uses include interpretation for the public of geologic points of interest, development of caves suitable for public use, evaluation of potable ground-water potential, and consideration of effects of geologic processes on recreation developments.

- Fish and wildlife management: Slope failures contributing sediment to streams can be identified on GRC maps and stabilization alternatives developed.
- Range management: GRC maps may indicate potential for development of ground-water supplies for grazing allotments and wildlife improvement projects.
- Timber management: GRC maps, when used with other resource inventories, are useful in identifying nonproductive land areas or areas potentially not suitable for timber harvest. GRC maps are also useful for timber sale planning. By identifying areas of potentially adverse geologic conditions early in the planning process, time can be allowed for more thorough evaluation. Recommendations concerning potential mitigation can also be requested from Forest Service geoscientists. Slope stability may affect specific sale location, layout, and viability. Since, at this stage, timelines are established for various disciplines to provide further input to the planning process, the GRC map and summary can effectively convey significance of soil and rock factors at a preliminary resolution level.

During timber sale layout, the sale and transportation planners can use the GRC map to locate construction materials sources. The map is also useful for preliminary evaluation of geologic conditions prior to approval of spur road and landing locations. Identification of rock outcrop areas may suggest a viable opportunity to use rock bolts as logging system cable anchors (with appropriate verification).

GRC maps do not eliminate the need for further geospecialist involvement prior to project planning or design. The time involved in providing additional input is greatly reduced by concentrating on known problem areas recognized earlier in the planning process.

- Water and soil management: GRC maps are useful to soil and water specialists in evaluating site productivity, existing stability, soil parent material, and geologic factors relating to the production, transportation, and deposition of sediments affecting water quality. The GRC subsystem complements other resource subsystems such as soil and water, as conflicting information is identified and conflicts resolved.
- Minerals and geology management: GRC maps show the location of material sources. They may be used for preliminary evalution of geologic conditions which may affect proposals to prospect, explore, or develop minerals or energy resources.
- Facilities engineering management: During initial transportation route planning, the GRC map provides a general estimate of how area slope stability may affect potential routes, as well as a basis for making a general estimate of cost of construction, by considering factors such as location of earth construction materials sources, location of potentially expensive rock outcrop or talus areas, location of recommended special construction areas, and materials properties such as ease of excavation. The GRC map is also useful in establishing preliminary estimates of feasibility of constructing associated transportation structures, such as bridges.

Examples of GRC Subsystem Use

Although the initial incentive for development of the GRC was support of forest planning, geologists tried to ensure that the information and format would be useful in the future. An example of the use of GRC information for three types of management needs is provided below.

Area Analysis

The Dry Burton Planning Area, in the northern part of the GPNF, is adjacent to private land in a scenic area. The steep slopes in the area have a history of natural slope movement, and the public expressed concern that any management activity in the area would increase the risk of a future catastrophic event. With the GRC map as a starting point, preliminary slope stability analyses were conducted using techniques developed to predict areas of high risk for slope movement from road construction and timber harvest. This allowed the District Ranger to be fully aware of the risk of management activities and allowed interdisciplinary analysis of the possibility of recommending certain portions of the area as unsuitable for timber harvest. The GRC map was also used to identify other geologic factors within the planning area. The resulting report (U.S. Forest Service, 1984) is an example of system application.

Environmental Assessment for a Proposed Road

Due to public responses during review of the draft Mount St. Helens National Volcanic Monument Comprehensive Management Plan (U.S. Forest Service, 1985b), the feasibility and environmental impacts of reconstructing Road 51 (a key route for access to the monument from the south and east) were assessed (U.S. Forest Service, 1986a). One of the management concerns identified in initial office evaluation for the project was the effect of road reconstruction. The area GRC maps were examined to estimate any adverse effects to geologic resources and conditions.

The following geologic information was obtained directly from the GRC maps for the project area.

Geologic Resources

- No inventoried geologic points of interest exist in the project area.

- Three caves marked on the area GRC maps are near the existing Road 51 and would not be affected by any proposed management alternative.
- All alternatives would use construction materials in varying amounts. Three materials sources are located on the GRC maps; one is within the project area.

Geologic Conditions

All route alternatives could potentially affect area slope stability. Alternative routes were evaluated for material suitability, natural and modified stability, and investigative complexity as estimated from the area GRC maps.

- Material suitability: The measure of suitability predicts the effect of the materials present on the timing, feasibility, and cost of construction of the alternative routes on the basis of the physical characteristics (permeability, foundation suitability and strength, excavation characteristics, and use of the material) of the earth materials present. The properties of those materials were estimated from the GMU descriptions. Material suitabilities were rated as high, moderate, or low on the basis of these characteristics. Alternative routes traversing a majority of high-suitability earth materials were rated as of good suitability; routes traversing a majority of low-suitability materials were rated as of poor suitability.
- Natural stability: Some GMUs in the project area exhibit evidence of recent or past slope movement. Some portions of the area may be marginally stable due to materials characteristics and ground slope; other portions of the area are stable. Ratings ranged from good (no existing features; materials inherently stable) to poor (some slope movement features; inherently unstable material, especially on steep slopes).
- Modified stability: On the basis of material suitability, terrain, and alternative road prism designs, some areas have a higher probability of slope movement during or after road construction than do other areas. This measure predicts the effects of each alternative on the stability of excavations and embankments. Ratings range from good to poor on the basis of the estimated ability to eliminate slope stability problems along each alternative route. Areas in which there is a high probability of slope movement will require more stabilization measures in project design than those areas in which slope movements are unlikely.
- Investigative complexity: Field investigations may reveal conditions requiring special design or construction methods to insure safety and feasibility or to mitigate adverse impacts to other resources. An effect of each route alternative is the consequent variable degree of investigative complexity, which also carries a variable degree of uncertainty or risk to route safety, feasibility, cost, or performance. The complexity of the routes ranged from low (little or no steep terrain, no special structures or construction methods proposed) to high (steep, unstable or potentially unstable terrain, low-suitability earth materials, or one or more special structures proposed).

It is worth noting that this analysis began in the fall of 1985, and within a month the area began receiving snowfall. The environmental assessment was completed in early spring. Had the GRC maps for the planning area not been available, it would not have been possible to estimate the effects of alternatives on the geologic resources and conditions due to snow cover.

Project Design

Ideally, GRC maps are used in the initial planning stages of a project. If this is done, consideration of geologic factors would lead to a recognition of the potential impacts of a project on area geologic resources and conditions. After interdisciplinary analysis and management decision for the project alternative, an assessment can be made of the need for and degree of involvement for geoscientist personnel to participate in the predesign phase. Comparison of a proposed project location with the area GRC map will reveal areas where more intensive site-specific investigation is warranted. After project completion, any additional information on area geologic resources and conditions gained during project area investigations is added to the GRC map to improve its overall accuracy.

SUMMARY AND CONCLUSIONS

Prior to 1980, the GPNF, like most national forests, did not have a means to store and display geologic information. Consequently, involvement of the geoscientist did not occur until the project design stage, when changes or mitigation of adverse impacts were difficult or prohibitively expensive and time consuming. If a geologic information system that was easy to use, readily updated, and technically valid could be developed, use of geologic information would increase. With greater information availability, involvement would shift from project design to forest-wide planning and area analysis. If such a shift could occur, it was predicted that cost of project investigation and design would be reduced, and unforseen environmental consequences would also diminish.

In late 1979, the opportunity arose to develop such a system with the appointment of the Forest Geologist to the Forest Planning Interdisciplinary Team. A proposal was accepted to develop a long-term geologic information system. This system evolved and was named the Geologic Resources and Conditions Map Subsystem, in recognition of the types of geologic factors (opportunities and constraints) that may affect management activities. The GRC is one of several subsystems in the overall TRI system.

The GRC system is based on information projected from field data collected at specific sites. The information has been interpreted and described in nontechnical terms and is structured for ease of use. Because of its simple format, the system can be easily updated, and its accuracy increases as new information is acquired. Forest Service planners, engineers, and foresters have been trained in use of the system, and, due to availability and simplicity of the system, geologist involvement has broadened from project design into planning.

Since development of the GRC, the following benefits have been observed:

- Geologists have had full involvement in the identification of potentially unsuitable lands during the forest planning process. Forest Service managers have recognized the extent and status of geologic resources and conditions as they may affect future management activities.
- The GRC map system has proved useful as a tool from which to estimate both the general effects of proposed projects on the area's geologic resources and conditions and the effect of those geologic factors on the safety, cost, and feasibility on the proposed projects.
- The GRC map system has been shown to be useful in estimating project complexity and hence timing and scope of involvement of geoscientist personnel.
- The GRC provides the basic data to perform and verify area slope stability analyses for the GPNF cumulative effects assessment process.
- Data extracted from the GRC will be used in the future for planning the use of substitute earth anchor systems for use as logging tower tailholds.
- Using GRC maps, engineering geology staff can prioritize their involvement in planning for various projects.
- GRC maps provide data to share with other state and federal agencies, researchers, and schools. For example, the State of Washington Department of Natural Resources Division of Geology and Earth Resources used the GRC extensively in producing the geologic map of the southwest quadrant of Washington (Walsh et al., 1987).

The GRC system was built on accurate topographic maps, making spatial location of features and digitizing of the location of materials boundaries and geologic resources and conditions a possibility in the future. This makes the GRC system fully compatible with Geographic Information System concepts and software.

The GRC map system is easy to construct. Once agreement was reached on format and materials classification systems (fully documented in a User Guide), the system was implemented by starting with project file information, published geologic reports, and air photo interpretation. As opportunities arise, GRC maps can be field verified and supplemented with additional information. With time, the maps will increase in accuracy.

REFERENCES

American Society of Testing and Materials, 1987, *Description and Identification of Soils (Visual-Manual Procedure)*: Annual Book of ASTM Standards, Vol. 04-08, pp. 409-423.

U.S. Bureau of Reclamation, 1974, *Earth Manual* [2d edition]: U.S. Bureau of Reclamation, Washington, DC, 316 p.

U.S. Department of Agriculture, Forest Service, 1984, *Dry Burton Planning Area Land Suitability Evaluation–Geotechnical Recommendations*: Gifford Pinchot National Forest, Vancouver, WA, 31 p.

U.S. Department of Agriculture, Forest Service, 1985a, *Directives Manual–Chapter 1920*: U.S. Forest Service, Washington, DC, 186 p.

U.S. Department of Agriculture, Forest Service, 1985b, *Mount St. Helens National Volcanic Monument Comprehensive Management Plan (FEIS)*: Gifford Pinchot National Forest, Vancouver, WA, 214 p.

U.S. Department of Agriculture, Forest Service, 1986a, *Road 51 Reconstruction–Environmental Assessment*: Gifford Pinchot National Forest, Vancouver, WA, 36 p.

U.S. Department of Agriculture, Forest Service, 1986b, *Geologic Resources and Conditions Subsystem Guide*: Gifford Pinchot National Forest, Vancouver, WA, 112 p.

U.S. Department of Agriculture, Forest Service, 1987, *Draft Environmental Impact Statement–Proposed Land and Resource Management Plan*: Gifford Pinchot National Forest, Vancouver, WA, 258 p.

Walsh, T. J.; Korosec, M. A.; Phillips, W. M.; Logan, R. L.; and Schasse, H. W., 1987, *Geologic Map of Washington–Southwest Quadrant*: Washington Division of Geology and Earth Resources Geologic Map GM-34, 28 p., 2 plates, scale 1:250,000.

Williamson, D. A., 1984, *Unified Rock Classification System*: Bulletin of the Association of Engineering Geologists, Vol. 21, No. 3, pp. 345-354.

In some areas, such as the Dog Hair Timber Sale Area, Quilcene Ranger District, Olympic National Forest, it is not economical to build new roads and harvest timber because the source of rock road material is far from the site and the mature timber is not large enough for the saw mill. One solution to this problem is the use of wood chip as road base course material. By processing wood chips onsite, this material can be transported ready for a pulp mill and the remainder can be used in road construction. In this U.S. Forest Service photograph, the bulldozer is moving woody debris before spreading more wood chips. A small volume of crushed rock aggregate can be used to cap the woody base course. Photograph courtesy of the U.S. Forest Service.

One means of stabilizing a logging road that has failed is the earth-reinforced structure. In this Forest Service photograph, a load of rock aggregate is about to be unloaded on top of steel "ribbons", visible behind the truck. The ribbons are "nailed" in place and serve as anchors for the wall. After several lifts are placed, the road will be reestablished at its former elevation, (uphill of the truck).

Ground-Water Resource Evaluation and Management

Michael R. Warfel, Chapter Editor

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Ground-Water Evaluation and Management: Introduction

MICHAEL R. WARFEL
CH2M Hill, Inc.

CHAPTER OBJECTIVE AND CONTENTS

Objective

This chapter provides a collection of papers representative of the diversity of ground-water resource evaluation and management problems encountered in Washington. Because ground water is a factor in most subsurface exploration and construction projects, assessment of ground-water occurrence and movement is a common component of such projects. The multidisciplinary aspect of engineering geology projects is illustrated by the diversity of papers contained in these volumes; many of the Part II case histories include a ground-water component. However, this chapter presents papers describing projects or assessments which have ground water as their primary focus.

One of the authors represented in this chapter, James R. (Bob) Jensen, died suddenly on December 9, 1988. In honor of his years of contributions to geohydrology, we respectfully dedicate this chapter to his memory.

Overview of Ground-Water Problems and Project Types

In order to place this chapter into perspective, a brief discussion of ground-water problems and projects potentially encountered in engineering geology practice is appropriate. Table 1 illustrates the range of problems and project elements which arise from man's interaction with ground water; it was compiled based on topics discussed in Freeze and Cherry (1979). The major ground-water study topics outlined in Table 1 generally fall into one or more of three categories: (1) exploration, exploitation, and management of ground water for beneficial use; (2) control of ground water associated with contaminant sources and construction projects; and (3) assessment of the role of ground water in natural geologic processes which continue to change the complexion of our Earth. All these ground-water problems and project elements have been encountered in Washington in the time since pioneers settled here and pursued their need for water supplies, structures, and acquisition of knowledge to facilitate coexistence with the surrounding and underlying earth materials.

Chapter Contents

With the range of problems and project elements in Table 1 representing the universe of potential ground-water topics, a subset of papers was sought for this chapter to provide an interesting "cross section" of ground-water work and conditions in Washington. The seven papers included in this chapter represent the general topics of ground-water resource evaluation (Jensen and Eckart; West and Noble; Drost), ground-water resource management (Olson; Brown and Randall), and construction and geotechnical problems (Noble; Herman). Ground-water contamination problems are not within the scope of this chapter; they are addressed in the Waste Disposal and Ground-Water Contamination chapter of this volume.

OVERVIEW OF GROUND-WATER LAWS IN WASHINGTON

A general understanding of ground-water laws of the State of Washington provides insight into the issues and concerns described by the case histories of this chapter. The following elements of the Revised Code of Washington (RCW) and amendments to the Code constitute the major laws which govern ground water in this state (Washington Department of Ecology, 1986):

Chapter 90.44 RCW, Regulation of Public Groundwaters, 1945: Extends application of surface-water statutes (Chapter 90.03 RCW) to appropriation and beneficial use of ground waters; addresses ground-water management.

Chapter 90.48 RCW, Water Pollution Control Act, 1945: Mandates maintenance of highest possible water-quality standards consistent with public health and enjoyment, and requires use of best available methods to prevent and control pollution of waters of the state.

Chapter 90.54 RCW, Water Resources Act, 1971: Establishes state water-resources policy fundamentals to ensure resource protection and full beneficial utilization; defines beneficial uses of waters of the state.

Table 1. General categories of ground-water problems and corresponding project elements

Category of Problem	Project Elements
Ground-Water Resource Evaluation	
System definition	Ground-water occurrence, movement, water budgets
Water-supply production	Well and well-field design/construction
Artificial recharge	Resource replenishment/non-consumptive use
Ground-Water Resource Management	
Withdrawal regulation	State water rights and diversion permits
Water-quality regulations	Drinking water standards and criteria
Aquifer protection zones	Local and regional planning; zoning restrictions
System modeling	Predictive tools for management of water quantity and quality
Other Beneficial Uses	
Irrigation	Water supply for seasonal agricultural use
Heat Pumps (heating and cooling)	Shallow, fresh water aquifers; water temperature <25° C
Geothermal heating	Deep, saline aquifers; water temperature >180° C
Ground-Water Contamination Problems	
Man-induced problems	Effects of waste disposal and hazardous materials spills
Nature-induced problems	Elevated mineral and radionuclide concentrations
Pollutant discharge regulations	State waste disposal facility permits
Construction and Geotechnical Problems	
Slope stability	Pore pressure relationships in soil and rock
Dams and reservoirs	Ground-water seepage control/grouting
Tunnels and excavations	Ground-water seepage control/dewatering
Structure and agricultural	Foundation drains in buildings, tile and ditch drains in fields
Evaluation of Natural Geologic Processes	
Faulting and earthquakes	Pore pressure relationships, prediction of events
Petroleum and mineral deposits	Influence of ground water on deposition and movement of deposits
Genesis of land forms	Slopes, river valleys, caves, etc.
Geothermal systems	Convection mechanisms, water-steam equilibria

Amendments to Chapter 90.54 RCW, 1984: Requires local governments to consider ground-water quality and quantity during development of comprehensive plans.

Amendments to Chapter 90.44 RCW, 1985: Provides for establishment of ground-water management areas to address ground-water quantity and quality issues; requires the Department of Ecology to develop procedural regulations and guidelines.

A more complete listing of state laws relating to ground water, and of regulations promulgated pursuant to these laws, is included in State of Washington Ground Water Quality Management Strategy (Washington Department of Ecology, 1986).

GROUND-WATER INFORMATION AND REFERENCE MATERIALS

For the reader who is interested in obtaining additional information regarding the principles of ground-water occurrence and movement, drilling and water well technologies, current ground-water management activities in Washington, and ground-water resource data, additional references are included in the reference section of this introduction.

REFERENCES CITED* AND ADDITIONAL REFERENCES

*Freeze, R. A. and Cherry, J. A., 1979, *Groundwater*: Prentice Hall, Englewood Cliffs, NJ, 604 p.

Johnson Division, 1986, *Groundwater and Wells* [F. G. Driscoll, principal author and editor, second edition]: Johnson Division, St. Paul, MN, 1,089 p.

King County Planning Division, 1986, *Ground Water Resource Protection, A Handbook for Local Planners and Decision Makers in Washington State*: King County Resource Planning, Seattle, WA, 105 p., 4 appendices.

Martin, L. J., 1971, *Ground Water in Washington*: Report No. 40, Washington Water Research Center, Pullman, WA, 40 p.

Molenaar, D.; Grimstad, P.; and Walters, K. L., 1980, *Principal Aquifers and Well Yields in Washington*: Washington Department of Ecology Geohydrologic Monograph 5, Olympia, WA, 1 sheet, scale 1:1,000,000.

*Washington Department of Ecology, 1986, *State of Washington Ground Water Quality Management Strategy* [T. Barrett, principal author]: Washington Department of Ecology, Office of Water Quality, Olympia, WA, 62 p.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Hydrostratigraphy of the Clover/Chambers Creek Basin, Pierce County, Washington

LARRY WEST
Sweet, Edwards/EMCON, Inc.

and

JOHN B. NOBLE
Robinson & Noble, Inc.

INTRODUCTION

The growing awareness that our traditionally pure and plentiful ground-water supplies are neither infinite nor invulnerable to contamination has spawned a considerable interest in ground-water management. This is particularly true in areas heavily dependent on ground water, such as the Clover/Chambers Creek Basin in central Pierce County, Washington (Figure 1). The Clover/Chambers Creek basin covers approximately 150 sq mi and includes a population of 232,000. For three-fourths of the year 90 percent of the water for Washington's second largest metropolitan area comes from the ground. During summer and droughts when the city of Tacoma is restricted from drawing on the Green River, the entire basin is even more dependent on ground water.

Inherent in effective ground-water management are comprehensive understanding of the ground-water regime to be managed and application of a conceptual ground-water model that facilitates the planning process. This paper presents the hydrostratigraphy of the Clover/Chambers Creek basin, which in turn provides the basic geologic/structural framework for the conceptual ground-water model used by the Tacoma-Pierce County Health Department in long-term management of the Clover/Chamber Creek basin's ground-water resources.

A hydrostratigraphic unit is a body of rock having considerable lateral extent and composing "a geologic framework for a reasonably distinct hydrologic system" (Maxey, 1964). Hydrostratigraphic definition of water resources has proven particularly applicable for Pierce County and the Clover/Chambers Creek basin because:

(1) It closely parallels glacial and time-stratigraphic geologic units already established in the area.

(2) It focuses attention on, and allows discrimination of past, present, and future ground-water production zones.

(3) It readily identifies areas of aquifer interconnection as well as distinguishing areas most vulnerable to ground-water contamination.

Consequently, hydrostratigraphic definition of the Clover/Chambers Creek basin provides resource managers with a relatively simple tool directly applicable to the planning process. This has proven particularly useful in Pierce County where effective ground-water management has been hampered by continued debate over the significance of complex aquifer and aquitard relationships under relatively localized conditions. Although a clear understanding of local hydrogeologic conditions is essential in site-specific situations, it does little in support of regional ground-water planning in terms of assessing the quantities of available resource and the vulnerability of resource quality to basin- or county-wide planning decisions.

While the hydrostratigraphy of the Clover/Chambers Creek basin was developed from interpretation of more than 500 water well reports on file with the Washington Department of Ecology (Figure 2), the Pleistocene stratigraphy developed by numerous investigators over the last 30 yr greatly facilitated the process. Therefore, we present a brief summary of this previous work, the difference between glacial and interglacial lithologies, and their influence on the basin's hydrostratigraphy.

PLEISTOCENE STRATIGRAPHY

During the Pleistocene Epoch, several Cordilleran glaciers advanced into the Puget Sound lowland. The most recent of these (Vashon) was about 5,000 ft thick at the latitude of Seattle and probably 1,500 ft thick over the Clover/Chambers Creek basin; its terminus was about 12 mi south of Olympia. Each glacier was responsible for depositing varied assortments of till, outwash sand and gravel, and glacial lake sediments.

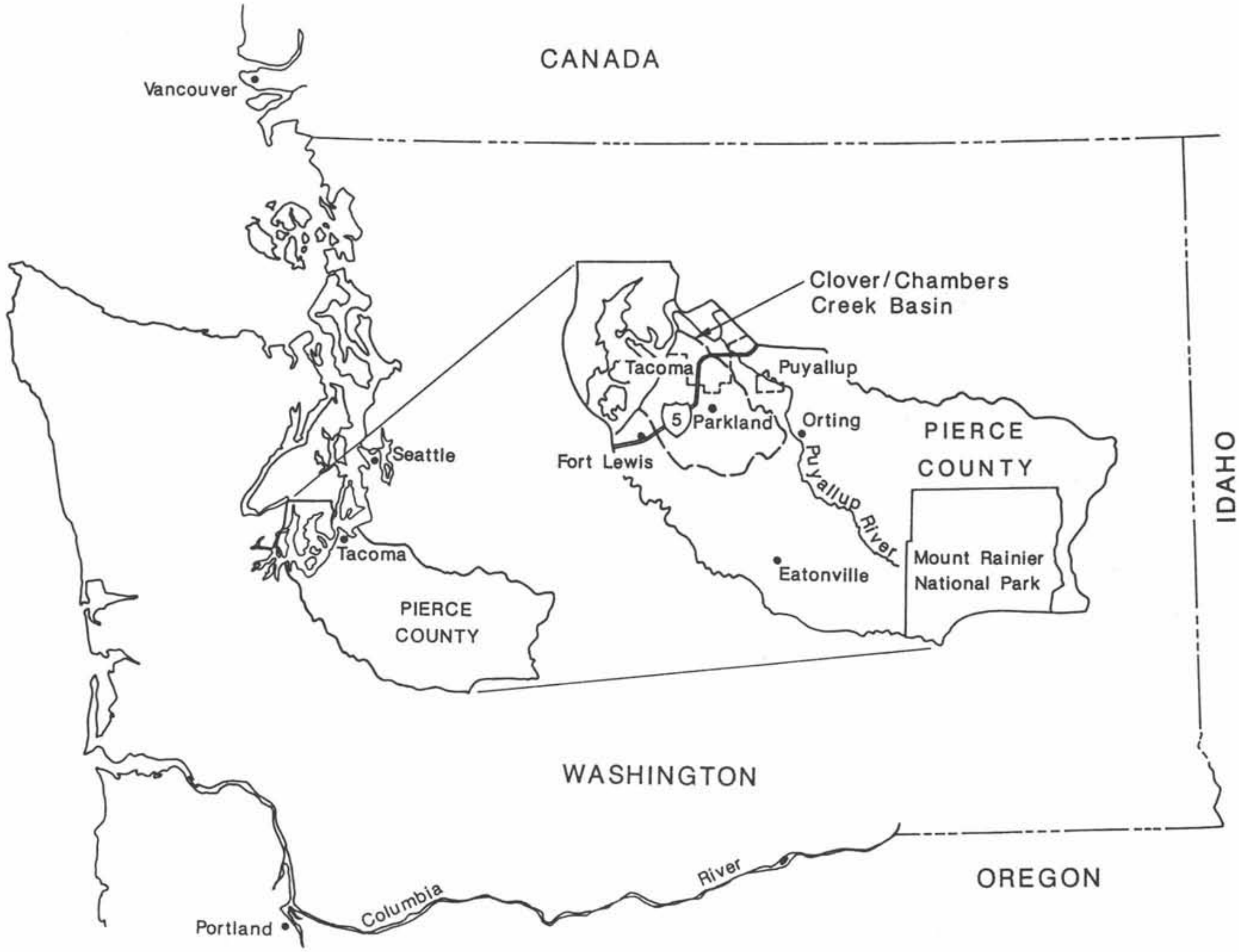


Figure 1. Location of the Clover/Chambers Creek basin

Pleistocene Deposits

The origin and types of sediments occurring in the Clover/Chambers Creek ground-water basin are a direct reflection of the glacial activity during the Pleistocene Epoch. Only unconsolidated sediments (clay, silt, sand, and gravel) deposited by the glaciers during glacial periods or by streams and rivers during interglacial periods are exposed at the surface within the Clover/Chambers Creek basin. The nearest bedrock exposures are about 4 mi east of the study area near the Puyallup River. Unconsolidated sediments also dominate the subsurface geology and the underlying ground-water basin to considerable depth. The deepest wells in the area (more than 2,000 ft deep) did not encounter bedrock (Walters and Kimmel, 1968). Geophysical investigations (including gravity, aeromagnetic, and seismic surveys) indicate that the study area is located over a deep structural basin, the Tacoma Low, filled with more than 2,000 ft of unconsolidated materials (Rogers, 1970).

For the purpose of the Clover/Chambers Creek geohydrologic study (Brown and Caldwell, 1985), the area's unconsolidated deposits were divided into several major types on the basis of environment of deposition and of permeability. The fundamental criterion for this division by environment of deposition was glacial versus nonglacial.

Glacial Deposits

Outwash sand and gravel was deposited by meltwater streams in front of the glaciers during their advances. Advance outwash deposits consist of all sizes of sand and gravel, as well as scattered cobbles and boulders. Near the glacier front, poorly sorted sand and gravel was deposited by high-energy streams. At greater distances these materials usually are more stratified and better sorted. These outwash gravels are generally the most permeable of glacial deposits. Even farther from the glacier, the gravel content is less and sand content greater. And most distally from the glacier front, or in

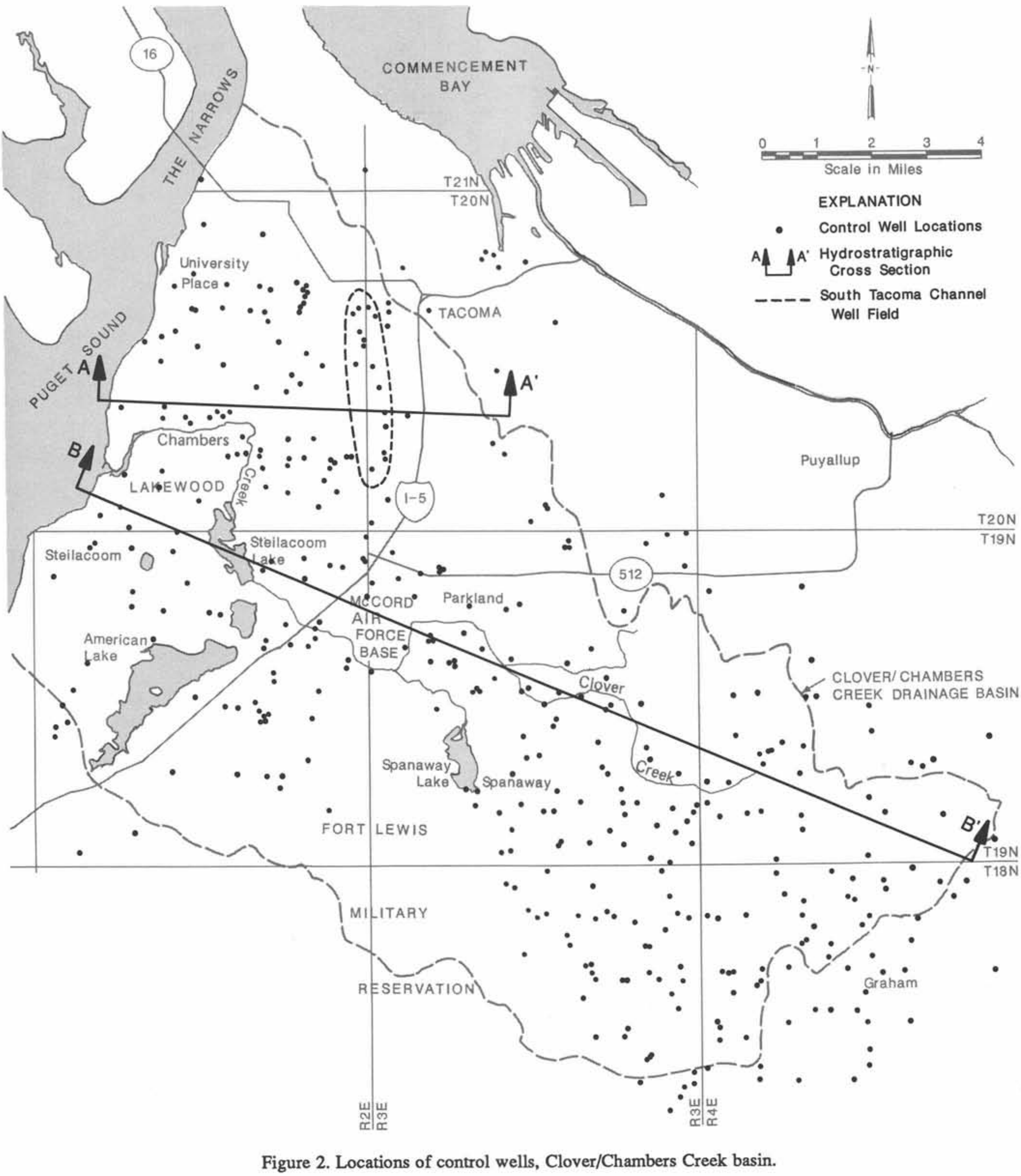


Figure 2. Locations of control wells, Clover/Chambers Creek basin.

valleys remaining after glacial retreat, the deposits can be silt and clay which filled glacial lakes. These lake deposits have low permeability.

Till is an unsorted to poorly sorted glacier-generated mixture ranging from clay-size particles through boulders. It is dense and has the general appearance of concrete. Till resulted from the compaction of a slurry of granular materials worked by the advancing and overriding glacier. Consequently, till tends to consist of reworked material at the face of the ice. As a result of the crushing and compaction, till commonly exhibits low permeabilities. However, within the Clover/Chambers Creek basin the till is not everywhere impermeable and does not uniformly serve as a barrier to the transport of water and pollutants. Some wells in the area have obtained moderate yields from till deposits. The typical till of the area has a far lower clay content than the classic tills of the midwestern United States.

As the glaciers receded, meltwater streams again deposited coarse sand and gravel over the previously compacted till. This recessional outwash is similar in character to advance outwash in that it is finer grained and less permeable with increasing distance from the glacier. There is a tendency for more cobbles and boulders to be present in the recessional outwash than in the advance outwash.

Sands and gravels of the glacial deposits in the basin tend to be relatively light-colored, containing considerable quartz and feldspar in the sand fraction, whereas the gravels contain notable amounts of granitic and metamorphic rocks. Source areas included the northern Cascades and the coast range of Canada; both regions are dominated by large areas of relatively acidic rocks.

Chronology studies of the Vashon deposits by Mullineaux et al. (1965) indicate the Vashon ice occupancy of the Seattle area may have lasted only 1,000 to 1,500 yr. The previous glacial occupancies may have been of similar durations.

Nonglacial Deposits

Nonglacial materials were deposited during intervals between glaciations. They are also accumulating today as bottom sediments in Puget Sound, floodplain sediment in the valleys, and both mineral and organic filling of lakes and bogs. In general, the nonglacial sediments are finer grained than the glacial sediments, and they commonly contain vegetal material.

Sand, silt, and gravel of the nonglacial deposits tend to be darker colored than glacial deposits and commonly lack granitic or metamorphic rock types. They are rich in andesite fragments. Silts commonly have a pinkish to lavender cast, which is typical of modern deposits originating from Mount Rainier, a major source of detritus in the present-day Puyallup and Nisqually rivers which border the study area.

Stratigraphic Chronology

The nonglacial climatic episodes lasted far longer than the glacial. No reliable dates bracketing these interglacial periods are known, but magnitudes of 50,000 to 100,000 yr are likely.

Crandell et al. (1958) were first to describe and name a multiple sequence of glaciations and nonglacial episodes in Pierce County. Their sequence from youngest to oldest was:

Vashon glaciation

Unnamed nonglacial interval

Salmon Springs glaciation (a nonglacial interval suspected within)

Puyallup interglaciation

Stuck glaciation

Alderton interglaciation

Orting glaciation

Later, Armstrong et al. (1965) described the Vashon as a stade within a broader glaciation designated Fraser. In this report, the term Fraser need not be further used because only Vashon-stade deposits of the Fraser are present in the area. Armstrong et al. (1965) also applied the term Olympia Interglaciation to the "unnamed nonglacial interval" of Crandell et al. (1958).

Where possible, geologists assign "rock units" (or identifiable and mappable geologic formations) to the separate time periods. The combination defines the stratigraphy. Thus, Vashon Drift is assigned to the Vashon Stade and the Puyallup Formation is assigned to the Puyallup interglaciation. However, no named and identified unit has been definitively applied to the Olympia interglacial period. It has been common practice to assign the Kitsap Formation to this time period. However, that relation has been seriously questioned by Noble and numerous other investigators in recent years.

Noble, during prior work in the area and during performance of the 1985 Brown and Caldwell study, suspected the existence of two glaciations above the Kitsap, plus an intervening nonglacial episode. Thus, with the Olympia interglacial interval firmly defined as that period preceding the Vashon, the Kitsap Formation would not represent that time. Table 1 presents the relations between climatic units and stratigraphic units as developed for the central Pierce County area.

GROUND-WATER OCCURRENCE

Distinguishing between glacial and nonglacial environments of deposition has been critical to the definition in this study of several distinct hydrostratigraphic layers. This layering is believed to have a major impact on the occurrence, availability, and contamination/protection of the ground-water resource.

Table 1. Time-stratigraphic chart, central Pierce County, from Brown and Caldwell, 1985

Climatic Unit	Mapped stratigraphic unit in study area
Vashon glaciation	Vashon Drift
Olympia interglaciation	None (Evans Creek to east--alpine drift)
Unnamed glaciation (upper Salmon Springs?)	Uncertain
Unnamed interglaciation	Kitsap Formation
Salmon Springs glaciation	Salmon Springs Drift
Puyallup interglaciation	Puyallup Formation (to the east)
Stuck glaciation	Stuck Drift (to the east)
Alderton interglaciation	Alderton Formation (to the east)
Orting glaciation	Orting Drift (to the east)
Earlier Pleistocene glacial episodes	None

The glacial layers, tending to be coarse grained and more permeable, serve as the major aquifers of the area. However, because of their high-energy and rapidly changing depositional setting, the glacial deposits tend to be heterogeneous and discontinuous. Many local drillers have had the experience of obtaining an excellent well yield at a particular depth, then drilling a "dry hole" to the same depth at a nearby location.

The nonglacial layers, tending to be finer grained and less permeable, are also much more uniform over their areal extent than the glacial layers. Furthermore, as they do not commonly contain materials suitable for yielding water to wells, they tend to be regional aquitards, which means they act as confining layers and create a regional impedance to the movement of ground water.

HYDROSTRATIGRAPHY

As the preceding sections illustrate, the area's geologic history and the variety of depositional processes which have been active provide for an extremely complex distribution of sediments which control the local ground-water flow. The complex subsurface geology of the Clover/Chambers Creek basin must be represented in a simplified, interpretive geohydrologic model if the model is to serve as a practical tool for protecting the area's ground-water resource. Yet the model must be sophisticated enough to approximate local geohydrologic conditions which might be involved in the relation between land-use activities and ground-water quality.

The first step toward defining the relations has been to define the study area's subsurface in terms of hydrostratigraphic layers. For purposes of the 1985 Brown and Caldwell investigation, a hydrostratigraphic layer is a grouping, both vertically and horizontally, of sediments that were deposited at approximately the same time under the same environmental conditions and that exhibit, in general, the same physical and hydrologic characteristics. As a general caution, it is important to recognize that these layers are quite heterogeneous within their own narrowly defined limits and that variations in physical and hydrologic character are common, in places to the extreme. Nevertheless, taking the geohydrologic model as a whole, extreme conditions are rare. Where possible, notable variations in physical and hydrologic character are identified.

Table 2 lists the hydrostratigraphic layers defined and the geologic names commonly applied to them. Eight layers have been identified, extending from ground surface to a depth of about 750 ft. The major water-transmitting or producing zones are glacial layers A, C, E, and G. Interglacial layers A_1, B, D, and F generally retard or inhibit the flow of ground water. (See Figure 3.)

Layer A

This layer, principally glacial in origin, includes all materials stratigraphically above the Kitsap Formation of Walters and Kimmel (1968). The top of this layer is represented by the surface topography and geology of the area.

Table 2. Correlation of stratigraphic and hydrostratigraphic units for the Clover/Chambers Creek basin

Mapped stratigraphic unit in study area	Probable hydrostratigraphic layers defined in 1985 Brown and Caldwell study
Vashon Drift	A
None (Evans Creek to the east--alpine drift)	A_1
Uncertain	Below A_1 or A undifferentiated
Kitsap Formation	B
Salmon Springs Drift(?)	C
Puyallup Formation (to the east)	D
Stuck Drift (to the east)	E
Alderton Formation (to the east)	F
Orting Drift (to the east)	G
None	H, I

The youngest deposits included in layer A are peat and alluvium. Peat deposits are scattered across the surface of the study area and consist of partly decayed organic matter. They are associated with swamps and marshes, and their average thickness is about 24 ft (Walters and Kimmel, 1968). Alluvium consists of recently deposited sand, gravel, silt, and clay in the bottoms of creeks and streams.

Within the Clover/Chambers Creek basin, layer A ranges from less than 1 ft to about 350 ft thick and is typically 100 to 200 ft thick. The areal configuration of the base of layer A is shown on Figure 4.

Vashon Drift comprises most of this unit. Due to its widespread distribution and abundant surface exposures, the Vashon Drift is the best defined of all the local Pleistocene glacial sequences and has been subdivided into five parts:

(1) Vashon recessional outwash

(2) Steilacoom Gravel

(3) Vashon till

(4) Vashon advance outwash

(5) Colvos or Esperance Sand

Locally, the Steilacoom Gravel is a special type of recessional outwash deposit. It is composed of a consistently coarse gravel with interstitial sand and covers much of the study area. This unit was deposited by high-energy streams and rivers which rapidly drained a large proglacial lake in the Puyallup River valley. These rivers cut massive outwash channels (Kirby, Clover Creek, and South Tacoma channels) and spread the gravels out over the southern and western parts of the study area.

Other deposits of recessional outwash that consist of coarse sand and gravel are also scattered throughout the study area. Recessional outwash deposits, including the Steilacoom Gravel, rarely exceed a few tens of feet in thickness and are commonly underlain by Vashon till.

Vashon till is also a locally important unit in that in many places it represents the first barrier to the downward migration of contaminants. However, the presence of till does not always mean a barrier exists. The till of central Pierce County is present in two forms, lodgment till and ablation till. Lodgment till, locally referred to as hardpan, is a compact mixture of sand and gravel in a matrix of silt and clay which has a very low permeability. Ablation till is a loose deposit of

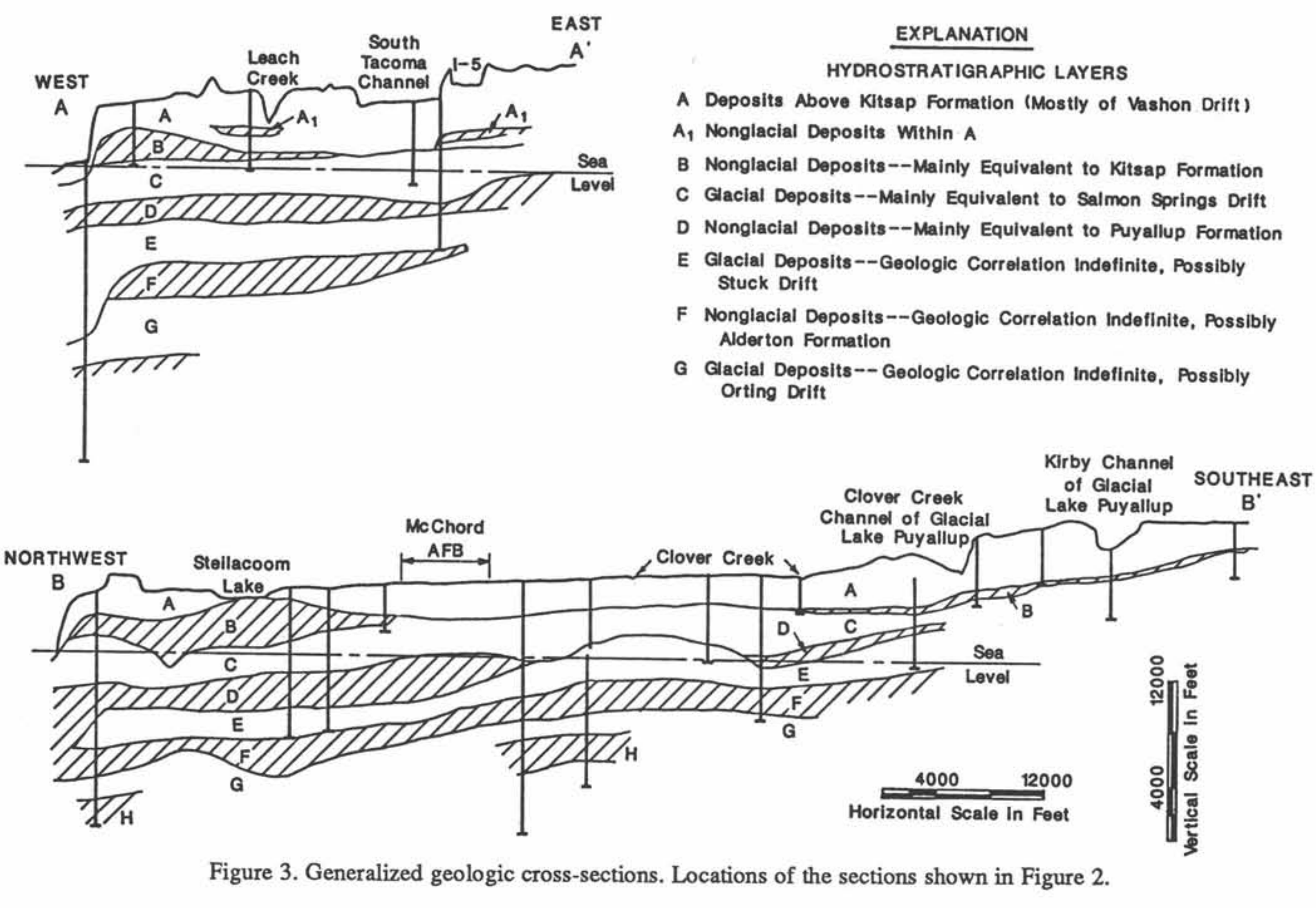


Figure 3. Generalized geologic cross-sections. Locations of the sections shown in Figure 2.

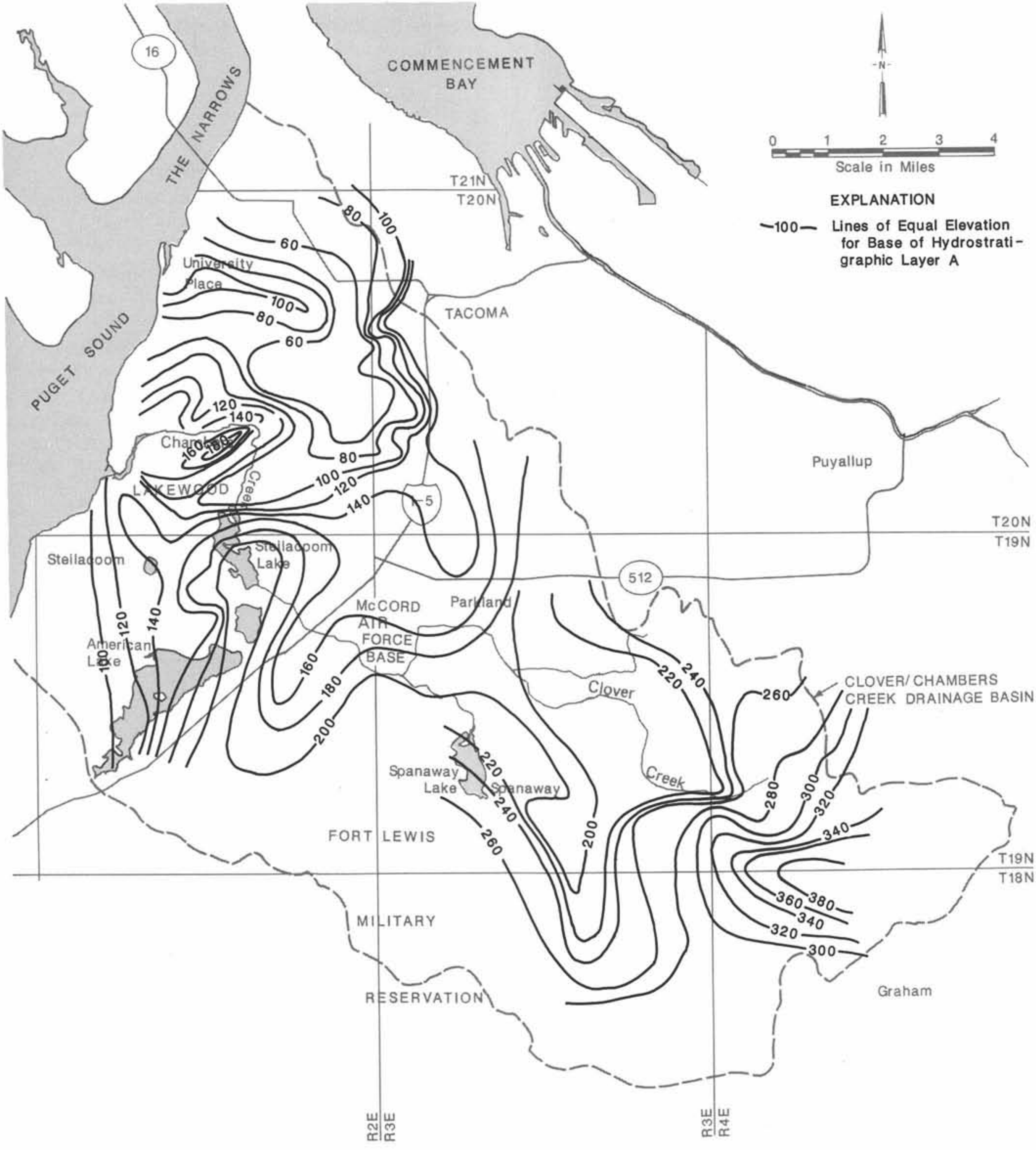


Figure 4. Contour map of the base of hydrostratigraphic layer A.

moderately permeable, unstratified gravel, sand, and silt. Generally, the till is about 5 to 30 ft thick; however, Walters and Kimmel (1968) have noted some well logs which indicate till sheets more than 100 ft thick. The till is present at the surface throughout much of the study area, particularly in the northern part. In the southern part of the study area, it occurs as scattered outcrops.

Underlying the till is the Vashon advance outwash, which consists of predominantly stratified, well-sorted, pebble-to-cobble gravel. The advance outwash is present beneath most of the study area in varied thicknesses, generally 25 to 50 ft. Surface exposures are limited to the northwest part of the study area and consist of numerous small outcrops in bluffs and stream cuts. The advance outwash is important as a principal aquifer for the Tacoma area.

The Colvos Sand, also called the Esperance Sand, can be considered an advance outwash deposit. However, due to its unique character, the Colvos Sand is generally mapped and discussed as a separate unit. The Colvos Sand consists of loose, well-sorted sand with scattered gravel beds and, in some areas, a distinctive basal clay. The clay was deposited in a proglacial lake formed when the advancing glacier dammed the north end of the Puget Sound lowland. The Colvos Sand is well exposed in bluffs along the Tacoma Narrows and in steep canyons draining into Commencement Bay. The Colvos Sand is as much as 150 ft thick and overlain by the Vashon advance outwash.

During the evaluation of layer A, it became evident that a distinct nonglacial unit was present within layer A. This relatively thin layer has been designated Layer A_1. Layer A_1 was recognized in 17 well logs, all from wells north of Chambers Creek (Figure 5). The A_1 layer is underlain by heterogeneous gravelly deposits of glacial origin. The implication of A_1 is that there are deposits of two glaciations above the Kitsap Formation. The age of A_1 may be equivalent to that of the nonglacial sediments below the Lawton Clay described by Mullineaux et al. (1965). Dates on the sediments below the Lawton Clay are in the range of 15,000 to 20,000 yr or more, whereas there are no finite dates less than 38,000 yr for any samples from the Kitsap Formation.

With the exception of regional upwell, nearly all ground-water recharge to the study area is contained in or ultimately penetrates layer A. Vertical and horizontal movement of ground water is highly influenced by subsurface Vashon till, local pods or lenses of silt and clay, and deposits of layer A_1, all of which tend to have low permeability. Most water drawn from wells completed in layer A should be considered susceptible to direct surface contamination. This statement is particularly true for areas not mantled by Vashon till. In areas with a thick till mantle, contaminant transit to water-bearing zones is less direct.

Layer B

Layer B in the western part of the area is equivalent to the Kitsap Formation as mapped by Walters and Kimmel (1968). The Kitsap Formation crops out along the Puget Sound bluffs near the southern boundary of the study area and in the lower reaches of the Chambers Creek Canyon near Chambers Bay. It is also the oldest sedimentary unit exposed in the study area.

Layer B is of particular importance to this investigation because it serves as the principal aquitard separating the upper and lower ground-water regimes.

In the subsurface layer B is a widespread nonglacial unit consisting mainly of clay, silt, and fine sand and organic material. Note that the base of layer A (Figure 4) is also the top of layer B. The base of layer B is shown on Figure 6. In the west, layer B is typically 50 to 150 ft thick.

Layer B is notably not present in part of the South Tacoma Channel and the central basin. Here, direct passage of water from layer A to underlying layer C would be more likely. In the central to eastern part of the study area, layer B appears to be present but very thin. The base of layer B has not been contoured in the eastern part of the study area due to the lack of adequate data.

Where layer B is missing, the distinction between layers A and C has been made by noting color changes in the drilling logs and by general stratigraphic position. Otherwise, the two can be lithologically similar.

Layer C

Underlying the Kitsap Formation (layer B), layer C consists of glacial drift representing the second oldest regionally identified glaciation. This glaciation is generally known as the Salmon Springs, but use of that term is not recommended here because of the possibility of incorrect definition. If, as indicated by the presence of layer A_1, deposits of a pre-Vashon glaciation exist above the Kitsap Formation, then designation of a pre-Kitsap glaciation as Salmon Springs may be erroneous. For the purposes of this paper, the name Salmon Springs is restricted to discussion of surface exposures to conform with work in the area by previous investigators.

The Salmon Springs Drift is well exposed east and south of the study area in the Puyallup and Nisqually river canyons. The Salmon Springs Drift is exposed just outside the study area boundary at the northeast end of the South Tacoma Channel. Deposits of the Salmon Springs Drift are predominantly stratified sand and gravel with thin, discontinuous layers of silt and clay. The Salmon Springs Drift does not have an identifiable continuous till sheet.

Layer C is well represented in test holes and water wells throughout the Clover/Chambers Creek basin (Figure 7). In the west part of the study area beneath

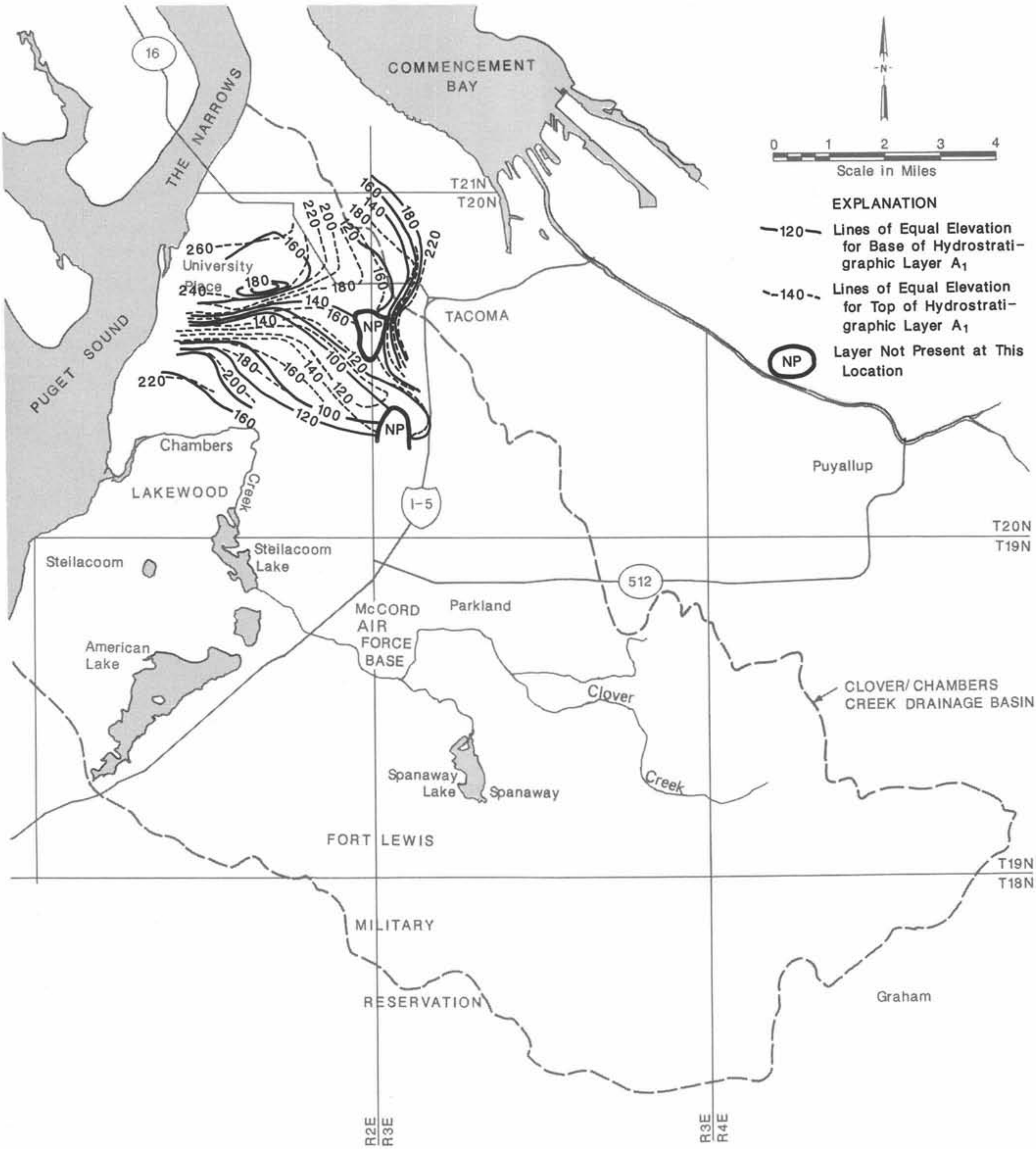


Figure 5. Contour map of the base of hydrostratigraphic layer A_1.

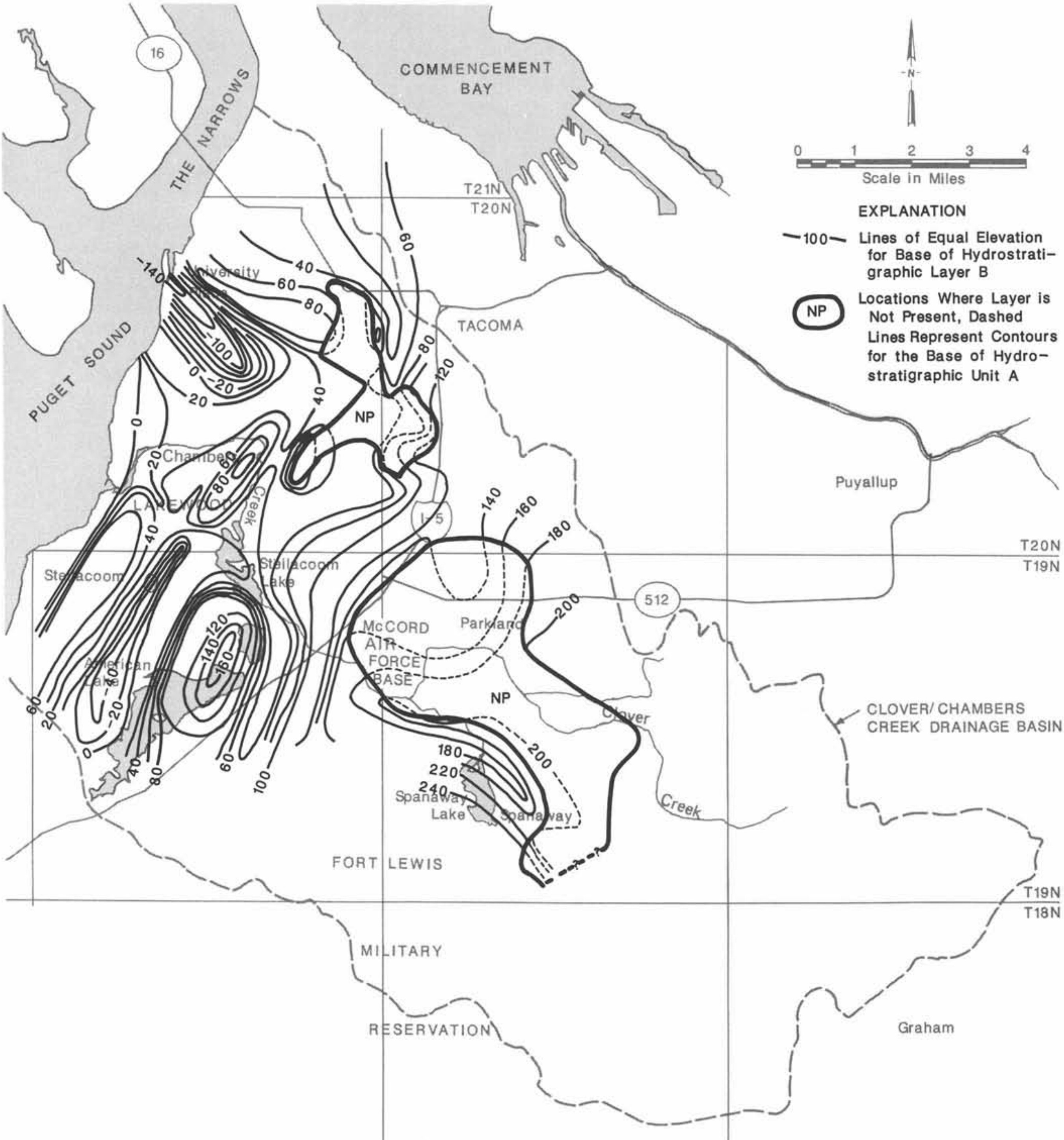


Figure 6. Contour map of the base of hydrostratigraphic layer B.

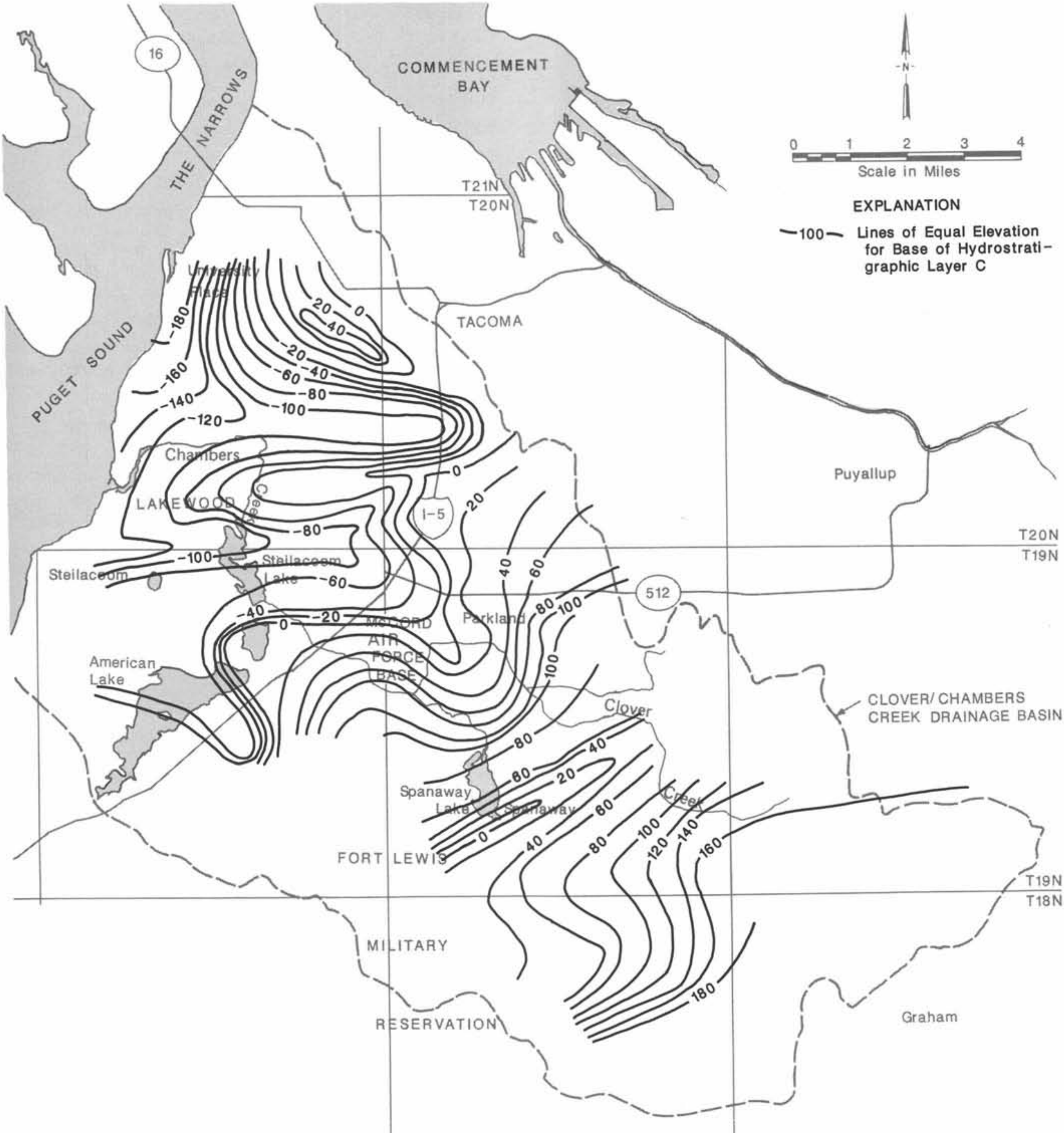


Figure 7. Contour map of the base of hydrostratigraphic layer C.

Steilacoom and Lakewood, layer C includes the basal member of the Kitsap Formation, a channelized aquifer of coarse gravel from which high well yields have been obtained. Layer C is typically 50 to 180 ft thick. Where it is overlain by fine-grained deposits of layer B, the aquifers of layer C can be expected to have a reasonable degree of protection from direct surface contamination. With the exception of regional upwell, most of the recharge to layer C probably occurs in the South Tacoma Channel and southeastern parts of the study area where layer B is absent, very thin, or discontinuous, permitting hydraulic continuity with layer A. The highly productive wells of the City of Tacoma in the South Tacoma Channel owe their high yields to the thick sequence of sand and gravel resulting from the interconnection of layers A and C.

Layer D

This nonglacial deposit, which has no local surface outcrop, is widespread throughout the western basin (Figure 8) and is typically about 50 to 200 ft thick. Stratigraphically, layer D is probably equivalent to the Puyallup Formation described by Walters and Kimmel (1968). However, use of that term is not recommended here due to the same ambiguities raised by the presence of layer A_1 and discussed in reference to layer C. The unit is easily and commonly recognized through drill log descriptions.

Unlike layer B, the materials of layer D contain very little gravel and consist of predominantly sand, silt, and clay. Its base is also far more uniform, indicating low-energy deposition on a mature surface. Underlying materials are commonly deeply weathered, indicating extensive subaerial exposure. Well logs note considerable vegetal material and volcanic ash. Layer D is considered to be an important, widespread aquiclude where present. Properly constructed wells developed beneath layer D, where both layers D and B are present, should be well protected from direct contamination.

To conform with published mapping, the term Puyallup Formation will only be used in conjunction with reference to surface exposures. The formation represents a lengthy interglacial period and is composed of a wide variety of sediments. The unit is not exposed in the Clover/Chambers Creek basin, but good exposures as much as 135 ft thick occur along the Puyallup River valley from Orting to Tacoma. Most of the Puyallup Formation consists of alluvial and lacustrine deposits. Volcanic ash and minor amounts of peat are typical. Extensive erosion and weathering of the Puyallup Formation occurred before the advent of the next glaciation.

Attributed to layer D is an important feature on the western edge of the study area. Several deep wells penetrate a very thick and continuous clay that is interpreted to be the sediment fill of a channel-shaped glacial lake. The eastern edge of the channel is parallel to and east of the existing Narrows. It is probable that the channel is an ancestral Narrows caused by glacial scour from an advancing Puget lobe glacier. Hydrologically, the clay-filled channel serves as a dam to ground water which flows through layers E and G from the east (Figure 3). Wells situated above the channel obtain water from aquifers within about 100 ft below sea level or penetrate aquifers far below sea level.

Layer E

This 50- to 200-ft-thick glacial layer is identified in many deeper wells throughout the basin (Figure 9). Layer E probably has the highest yields of the hydrostratigraphic layers identified in the Clover/Chambers Creek basin. Layer E is bounded on the west by the clay-filled ancestral Narrows channel discussed under layer D.

Layer E may be equivalent to drift of the Stuck Glaciation as defined by Crandell et al. (1958). The Stuck Drift is a fairly thin unit, rarely exceeding a thickness of 40 ft in exposures east of the study area along the Puyallup River valley. It consists of a slightly oxidized till 5 to 20 ft thick that is sandwiched between Stuck advance and recessional outwash sand and gravel. Fine-grained lake deposits indicating an ice-blocked lake have been identified in the upper part of the Stuck Drift near Sumner.

Layer F

Layer F consists of nonglacial sediments that may be equivalent to sediments of the Alderton interglaciation as defined by Crandell et al. (1958). The Alderton unit includes gravels deposited in stream channels and sand and silt deposited on a broad alluvial plain and in lakes. These materials are primarily erosional debris off the flanks of the Cascades. Layers of peat and volcanic ash are common in this unit. The only surface exposures of the Alderton Formation are east of the study area, and they indicate the Alderton is at least 100 ft thick in some areas. Beneath the study area, layer F has been identified in well logs, but data points for the base of layer F are sparse. Only about a dozen deep wells penetrate this layer. The available data indicate that layer F is present beneath most of the study area and also typically 100 ft thick (Figure 10). The sediments of layer F are generally fine grained, indicating deposition a considerable distance from the source. As a result, layer F forms an important regional aquitard.

Deeper Layers

Some very deep wells have penetrated hydrostratigraphic layers below layer F; however, the data are too limited to either map or to definitively characterize these deeper layers. East of the study area in the Puyallup valley, the Orting Drift has been mapped as stratigraphically below the Alderton Formation (tentatively layer F in this paper). It is very likely that the

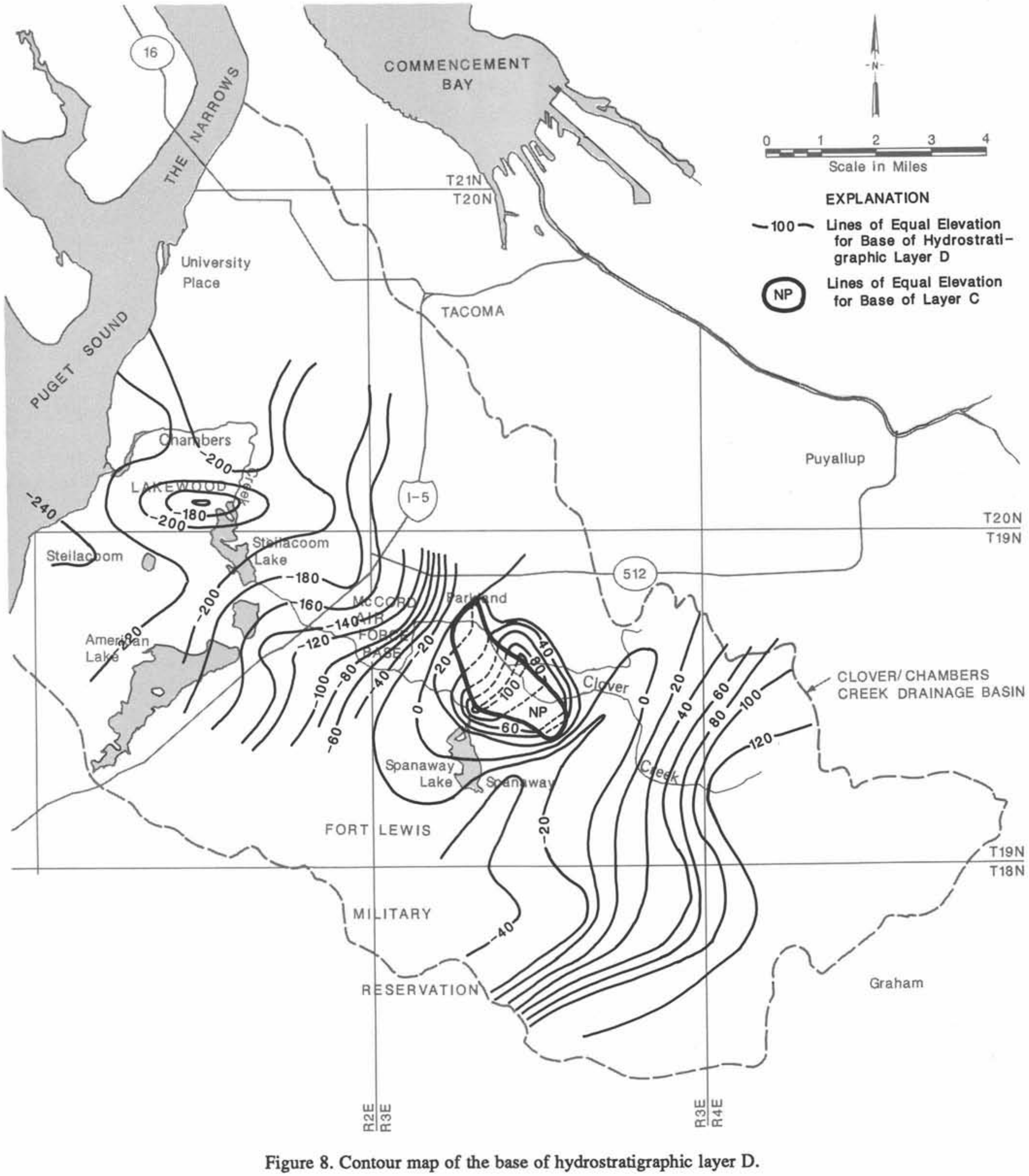


Figure 8. Contour map of the base of hydrostratigraphic layer D.

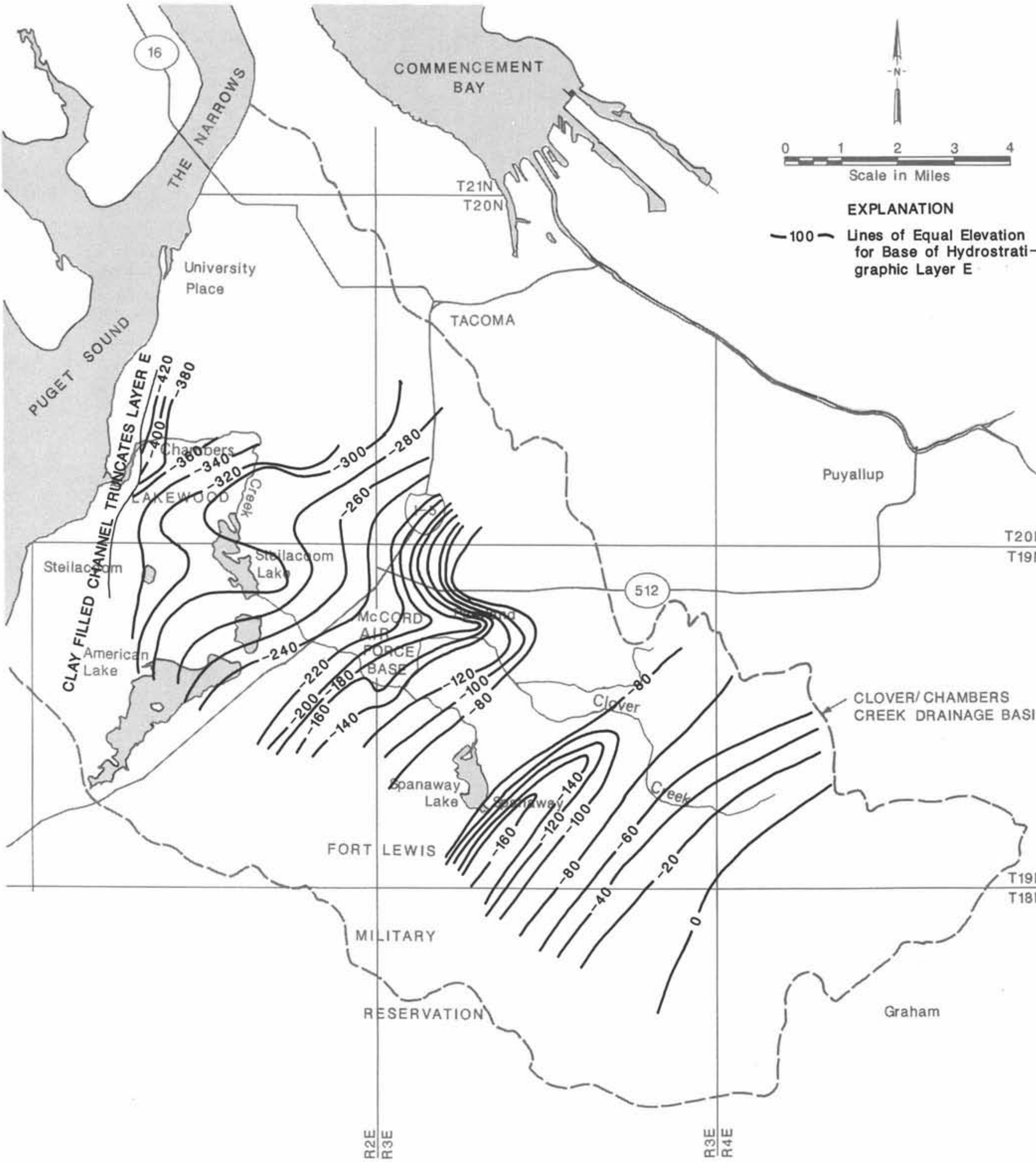


Figure 9. Contour map of the base of hydrostratigraphic layer E.

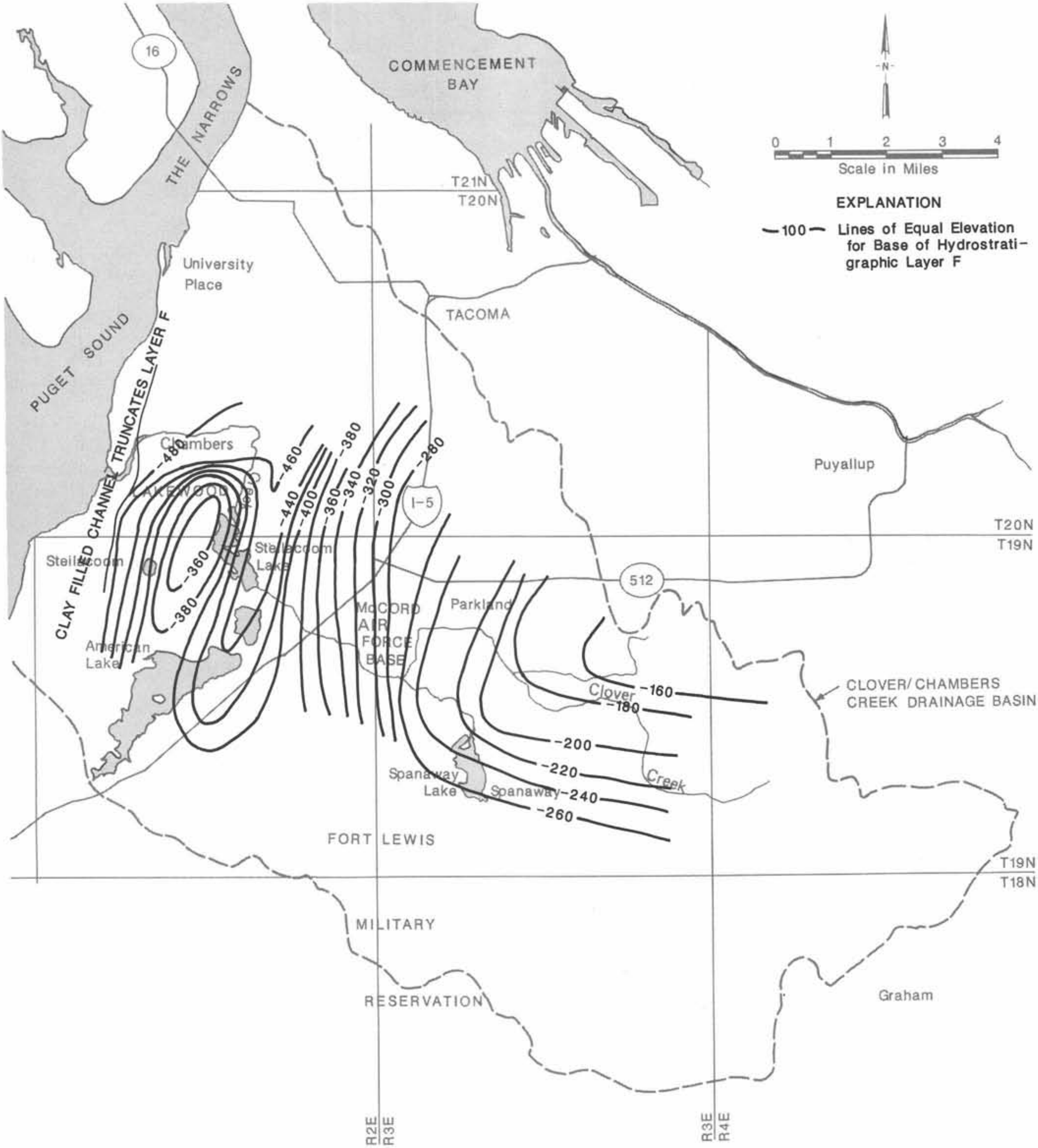


Figure 10. Contour map of the base of hydrostratigraphic layer F.

deeper hydrostratigraphic layers (that is, layer G in the cross-sections) identified beneath the study area include or are equivalent to the Orting Drift. The Orting Drift is the oldest Pleistocene glacial sequence identified in the area.

The base of the Orting Drift includes a thick gravel deposit consisting of central Cascade rock types. Most of the unit is stratified sand and gravel. At different elevations within the Orting Drift are continuous interbeds of brown till. The till is very compact and consists of unstratified gravel in a silty matrix. About 260 ft of Orting Drift has been exposed in the Carbon River valley east of the study area, and as much as 200 ft of the unit consists of gravel.

CONCLUSIONS

The hydrostratigraphic characterization of the Clover/Chambers Creek basin has greatly accelerated basin management activities. Probably the most significant factor to result from the effort was the recognition of major regional aquitards which contribute to the protection of deep regional ground-water resources. Even more significant was the recognition that large gaps or windows were present in two of these aquitards, hydrostratigraphic layers B and D. These aquitard windows increase the vulnerability of water resources to contamination by land-use activities. Knowledge of the vertical juxtaposition of layers A and C in the South Tacoma Channel wellfield and the direct hydraulic connection between the surface and the highly productive layer E in the central basin will allow regional planners to focus on protecting these sensitive areas from land-use activities with a high degree of pollution risk.

ACKNOWLEDGMENTS

The development of the Clover/Chambers Creek basin hydrostratigraphy was financed by a Washington Department of Ecology grant. This paper consists of excerpts of the authors' contributions to the Final Report, Clover/Chambers Creek Basin Geohydrologic Study, prepared by Brown and Caldwell (1985) for the Tacoma-Pierce County Health Department.

REFERENCES

Armstrong, J. E.; Crandell, D. R.; Easterbrook, D. J.; and Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in Southeastern British Columbia and Northwestern Washington: *Geological Society of America Bulletin*, Vol. 76, No. 3, pp. 321-330.

Brown and Caldwell, 1985, *Clover/Chambers Creek Geohydrologic Study*: Report for Tacoma-Pierce County Health Department, Tacoma, WA, 197 p.

Crandell, D.R.; Mullineaux, D.R.; and Waldron, H.H., 1958, Pleistocene sequence in southeastern part of the Puget Sound Lowland, Washington: *American Journal of Science*, Vol. 256, No. 6, pp. 384-397.

Maxey, G. B., 1964, Hydrostratigraphic units: *Journal of Hydrology*, Vol. 2, pp. 124-129.

Mullineaux, D. R.; Waldron, H. H.; and Rubin, M., 1965, *Stratigraphy and Chronology of Late Interglacial and Early Vashon Glacial Time in the Seattle Area, Washington*: U.S. Geological Survey Bulletin 1194-O, p. O1-O10.

Rogers, W. P., 1970, *A Geological and Geophysical Study of the Central Puget Sound Lowland* [Ph.D. thesis]: University of Washington, Seattle, WA, 123 p.

Walters, K. L. and Kimmel, G. E., 1968, *Groundwater Occurrence and Stratigraphy of Unconsolidated Deposits, Central Pierce County, Washington*: Washington Department of Water Resources Water Supply Bulletin 22, Olympia, WA, 428 p.

The Spokane Aquifer

JAMES R. JENSEN
Engineering Geologist

and

CAROL M. ECKART
Geologist

INTRODUCTION

The city of Spokane is located on the eastern edge of the state of Washington and near the northeastern border of the Columbia Plateau. The Spokane Valley is generally at elevation 2,100 ft; the adjacent highlands rise to 4,000 ft in elevation. The Spokane Aquifer, which is more correctly the Spokane Valley/Rathdrum Prairie Aquifer, is virtually the sole source of water supply for domestic use in the Spokane metropolitan area.

The Spokane Aquifer heads at the western end of Pend Oreille Lake and northern arm of Coeur d'Alene Lake in Idaho. It extends west and south beneath Rathdrum Prairie and westward down the Spokane River valley to the city of Spokane, running beneath the city and Hillyard Trough north of the city to connect with the Little Spokane River (Figure 1). The drainage area of the aquifer extends some 100 mi to the east and 145 mi southeast to the crest of the Bitterroot Mountains at the border between Idaho and Montana (Figure 2).

HUMAN OCCUPATION

Native Americans

The indigenous people of the area were hunters and gatherers, a riverine society heavily dependent on migrating salmon for food. They had neither the need nor the means to make use of the aquifer, as settlers, miners, and loggers have done. The importance of water to life was clearly understood by the Native Americans. Water held sacred status; each day was begun with a ceremony to bless the waters. Bathing and swimming in the rivers was an important part of the coming-of-age of a young person. Fouling the life-sustaining waters was simply not done. Allowing human waste to enter the water was forbidden—neither were animal remains disposed of in rivers or lakes, lest the species be insulted and not return to allow themselves to be hunted.

At the beginning of a salmon run—there were several during the year—a Salmon Chief was appointed to oversee the ceremonies, the setting of the fish traps, and the allocation of fishing sites. Fishing traps and weirs may have altered stream flow somewhat, but the overall effect on the hydrology of the aquifer would have been nil (Ross, 1987). The Native Americans of the Spokane area were not farmers; thus river banks and stream beds were not altered by irrigation.

Historic Occupation and Settlement

Spokan Falls (named after the Spokan Indians and spelled without the "e") was sited on May 11, 1873, when James N. Glover established a trading post in anticipation of the coming of the railroad. Glover did not have tremendous success in attracting settlers; however, in spite of setbacks, he built a two-story structure in 1876 that housed a bank, the post office, the city hall, a theater, and a public meeting hall. The city was officially incorporated in 1881. In 1890 its name became Spokane (Cochran, 1984).

REGIONAL GEOLOGY

Bedrock in the area is of granitic composition and has been mapped as Precambrian and Mesozoic (Griggs, 1973). Basalt flows overlying the granite are of Miocene age and were deposited on a surface of considerable relief. During the long period of erosion prior to the advent of the basalt, a drainage pattern with deep stream channels and adjacent highlands was established. During the Miocene the Columbia River basalts were extruded from rifts in the Columbia Basin upon an erosional surface of varied ages and degrees of relief. The Columbia River basalts cover an area of more than 100,000 sq mi (Baker and Nummedal, 1978). On the margins of the plateau, the basalt is interbedded with extensive deposits of siltstone and shale of the Latah Formation, deposited when drainages were blocked by the basalt eruptions.

The gravels that make up the Spokane Aquifer were deposited as a result of a series of catastrophic floods that discharged very large volumes of water from glacially dammed Lake Missoula (Bretz, 1969). During

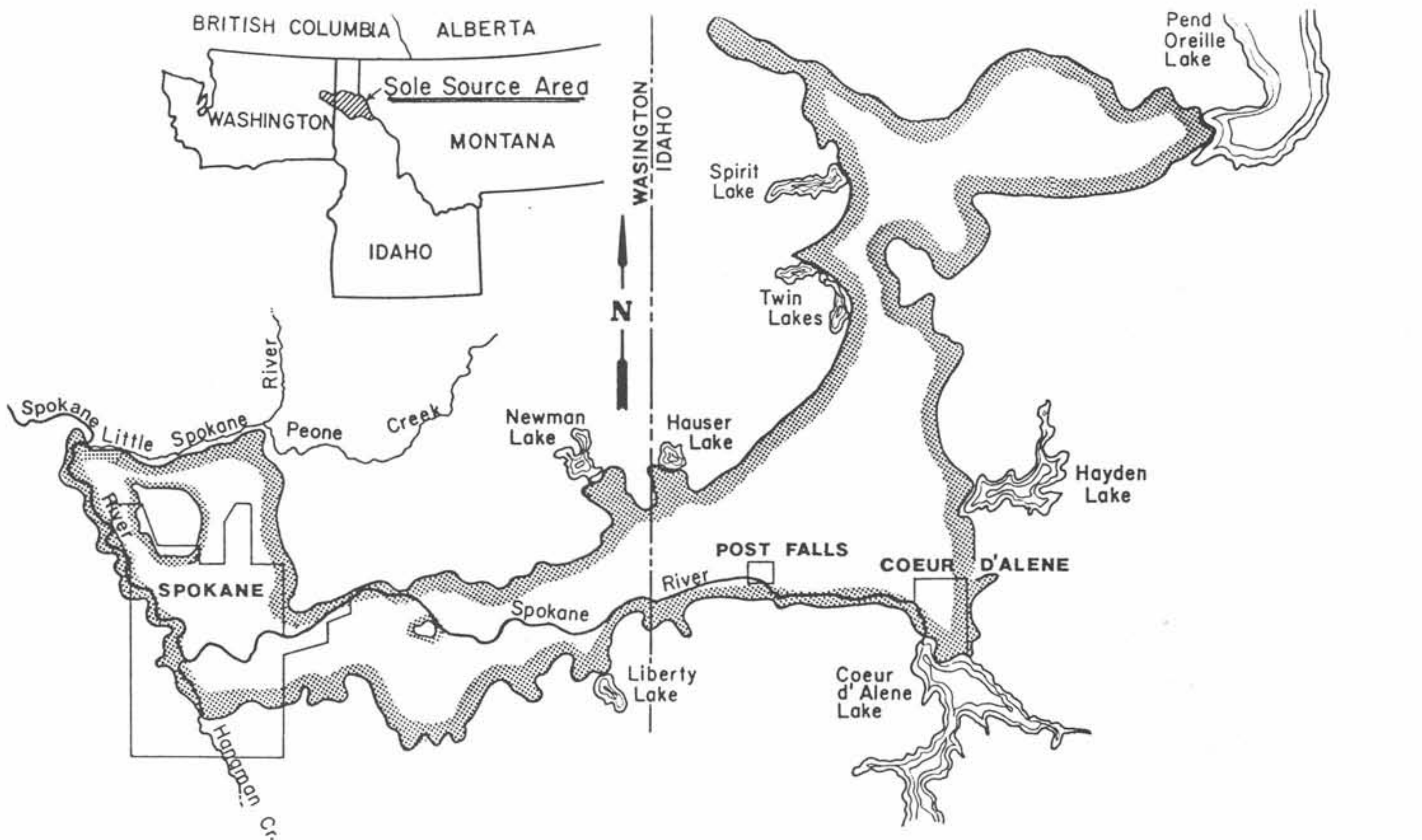


Figure 1. Spokane-Rathdrum Aquifer in Washington and Idaho. After Turner (1979).

Pleistocene time an advancing ice lobe occupied the basin of modern Pend Oreille Lake in northern Idaho, blocking the drainage of the Clark Fork River. Pardee (1942) believed that this glacial dam failed suddenly with the resultant draining of the lake discharging about 500 cu mi of water. This flood spilled down a valley now occupied by the south arm of Pend Oreille Lake, through what is now Rathdrum Prairie, down the Spokane River valley past what is now the city of Spokane, and onto the Columbia Plateau (Figure 1). On the basis of physiographic evidence, Bretz (1969) proposed as many as eight separate floods. By the early 1980s Waitt (1983), who first postulated only three floods, had found evidence of at least 40 floods. Even more recently, evidence supporting as many as 70 separate catastrophic floods has been described (Atwater, 1983; Glatzer, 1983).

This sequence of floods scoured and eroded materials from the Spokane Valley deposits and, during waning periods, filled scour channels and raised the level of the flood plain at each occurrence. The result of this flood activity is a heterogeneous and non-isotropic gravel-boulder deposit that is now the Spokane Aquifer.

EARLY GROUND-WATER USE

One of the prime considerations for the establishment of a city is an adequate and reliable source of water. Settlers found just the right combination in the Spokane Valley. Early in the history of the city, gravity flow was relied upon for domestic water. Soon the need for alternative sources was felt; well water was the obvious answer. Many of the downtown water wells were hand dug (Miller, 1987), and a few of these private wells are still in use for domestic purposes. The presence of large numbers of boulders made drilling water wells unattractive in earlier years. It was necessary to go deep to obtain adequate water, and it was a much simpler matter to excavate and shore a hand-dug shaft for a water supply. Bolke and Vaccaro (1979) studied selected wells in the city and reported that a well presently being used for irrigation was completed in 1888. Most wells in the 1979 list have been completed since 1950. The City of Spokane has since developed a public water system that is more economical and convenient than private sources.

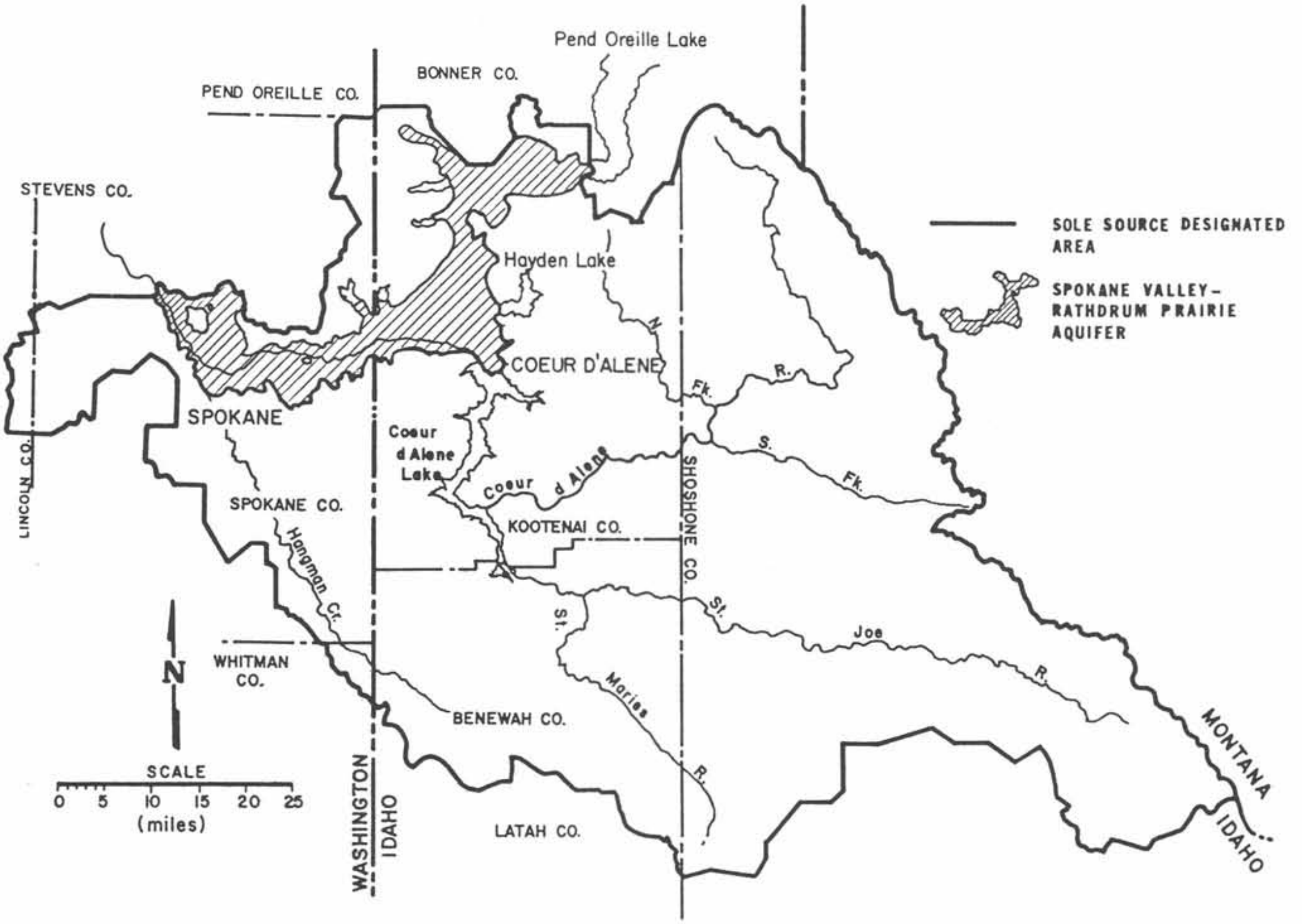


Figure 2. Spokane-Rathdrum Aquifer sole-source recharge area and stream-flow drainage area. After Turner (1979).

DESCRIPTION OF THE SPOKANE AQUIFER

Areal Extent and Thickness

The Spokane Aquifer, the western portion of the Spokane Valley/Rathdrum Prairie Aquifer, extends from just west of Post Falls, Idaho, westward to near Nine Mile Falls, Washington, a distance of approximately 27 mi (Figure 3). The Spokane River valley ranges from 4 to 8 mi wide and covers an area of 135 sq mi. The north and south boundaries coincide with the contact of the aquifer gravels with the crystalline rocks bordering the valley. Five Mile Prairie, northwest of the city of Spokane, is an inlier of pre-Tertiary rocks in the valley alluvium which splits the aquifer into the Lower Spokane River Valley on the west and the Hillyard Trough on the east (Figures 1 and 3). Upstream of Spokane there is another outcrop of Precambrian granitic rock just north of Opportunity, which splits the aquifer in a minor way.

The saturated thickness of the glaciofluvial deposits (Figure 4) is estimated to be a maximum of 500 ft (Vaccaro and Bolke, 1983). Newcomb (1953) determined a maximum depth of the Spokane River valley in two areas using seismic techniques. The upstream profile, located in Idaho 0.75 mi east of the state line, indicates that the bottom of the old buried channel is cut into granite to a depth of approximately 1,000 ft. The glaciofluvial deposits are 300 to 400 ft thick at elevation 1,600 to 1,750 ft. The remainder of the valley fill is highly consolidated material, probably Latah Formation siltstone and claystone.

The second profile was run across the valley north of Spokane and east of Five Mile Prairie in the Hillyard Trough. This valley enters from the north in such a position as to indicate that it was once the main valley of the Little Spokane River. The apparent base of the outwash gravel in the Hillyard Trough is at elevation 1,700 ft and is approximately 350 ft deep. Weigle and Mundorff (1952) report some deeper glacial materials in the logs of some wells at the aluminum plant near Mead, 2 mi north of the seismic line. The seismic information indicates that the base of the gravels is roughly 100 to

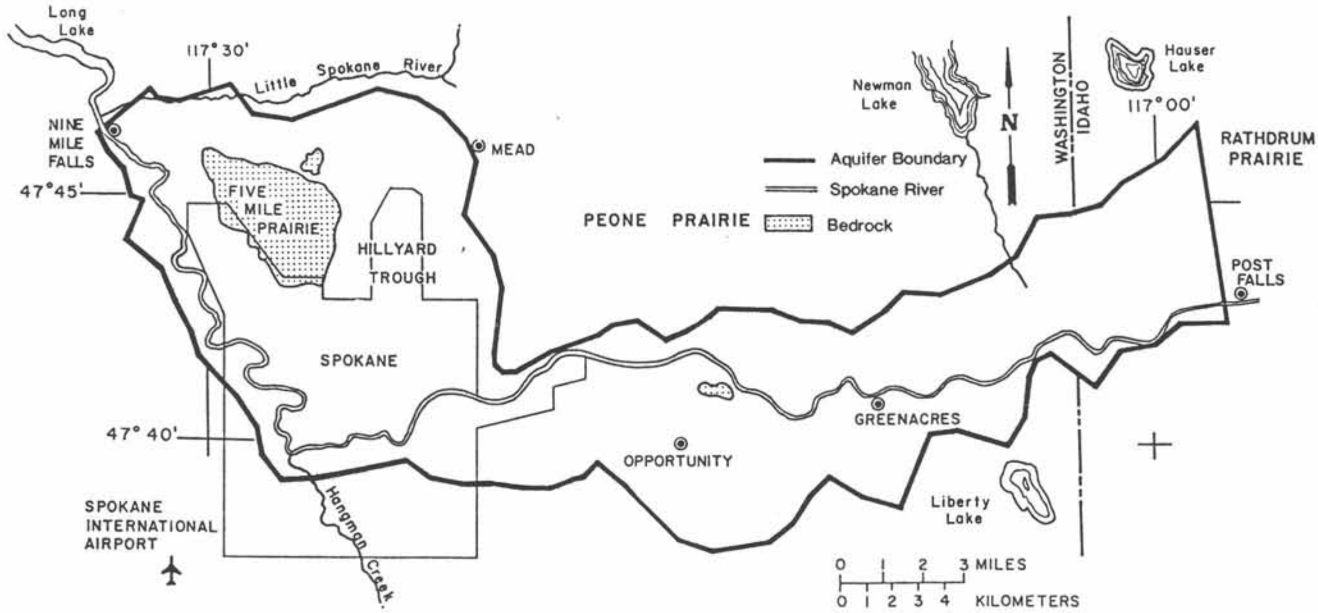


Figure 3. Location of study area. From Vaccaro and Bolke (1983).

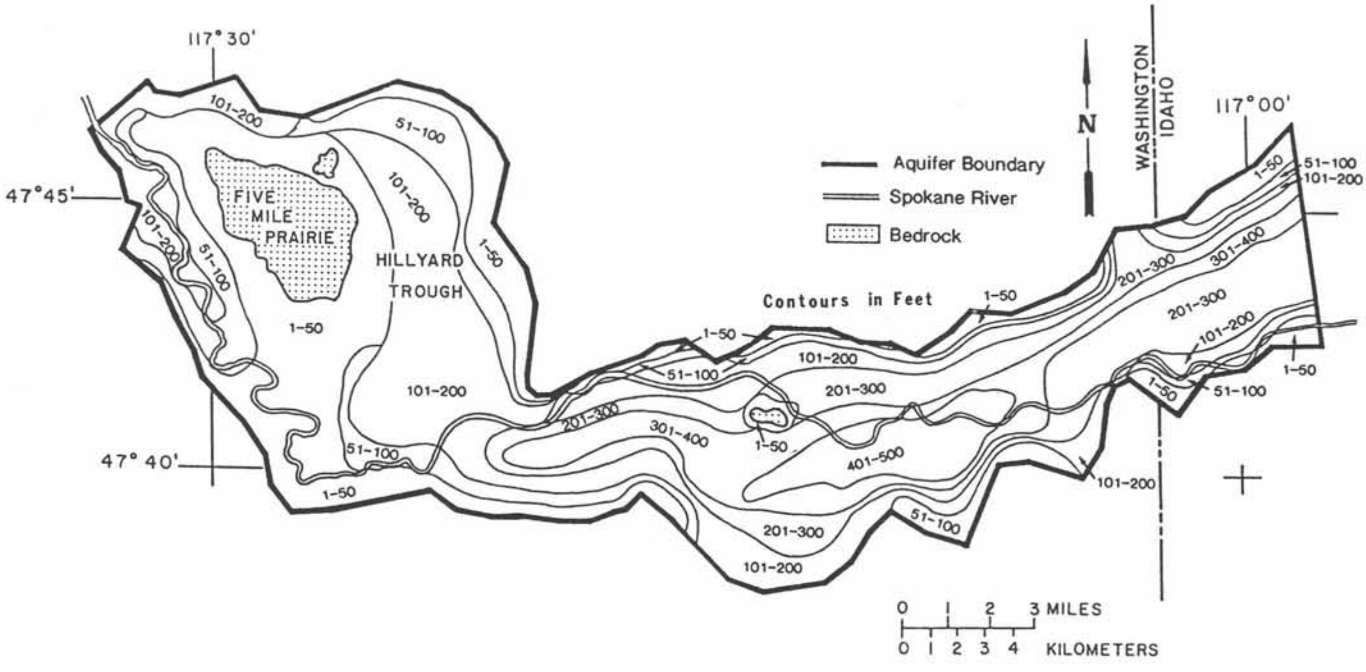


Figure 4. Saturated thicknesses of the Spokane Aquifer. From Vaccaro and Bolke (1983).

200 ft below the bedrock that creates the present falls of the Spokane River 4.5 mi south of the seismic line. The falls are at elevation 1,800 ft.

The Spokane Valley/Rathdrum Prairie Aquifer is unconfined throughout its total length. The water surface of the Spokane River through most of its length reflects the ground-water surface in the aquifer upstream of the city of Spokane. The Spokane River alternately gains and loses water to the aquifer. Only at its northern extent does the character of the aquifer change. Near the Little Spokane River the aquifer is artesian; apparently glaciolacustrine deposits from sources to the north have been deposited over the Spokane Aquifer and are an effective aquiclude. The Little Spokane River gains water from the Spokane Aquifer from many springs in this area. There has been more than one occurrence of water-

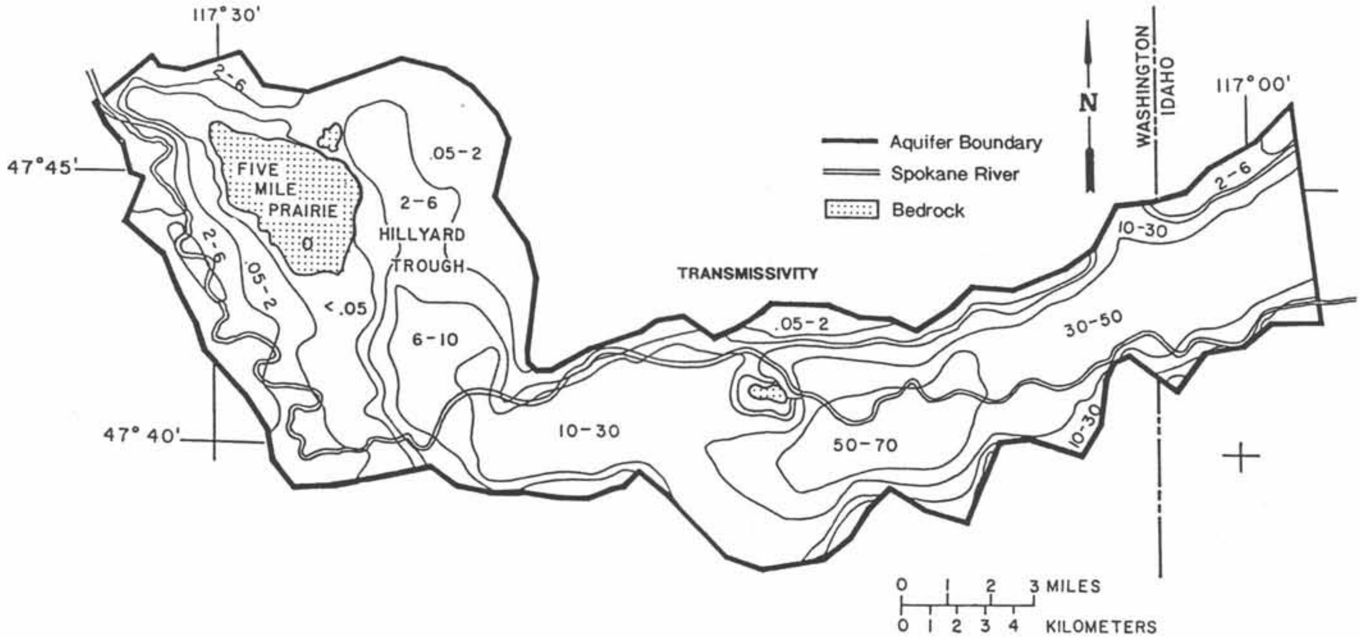


Figure 5. Transmissivity (in sq ft/sec) of the Spokane Aquifer. From Vaccaro and Bolke (1983).

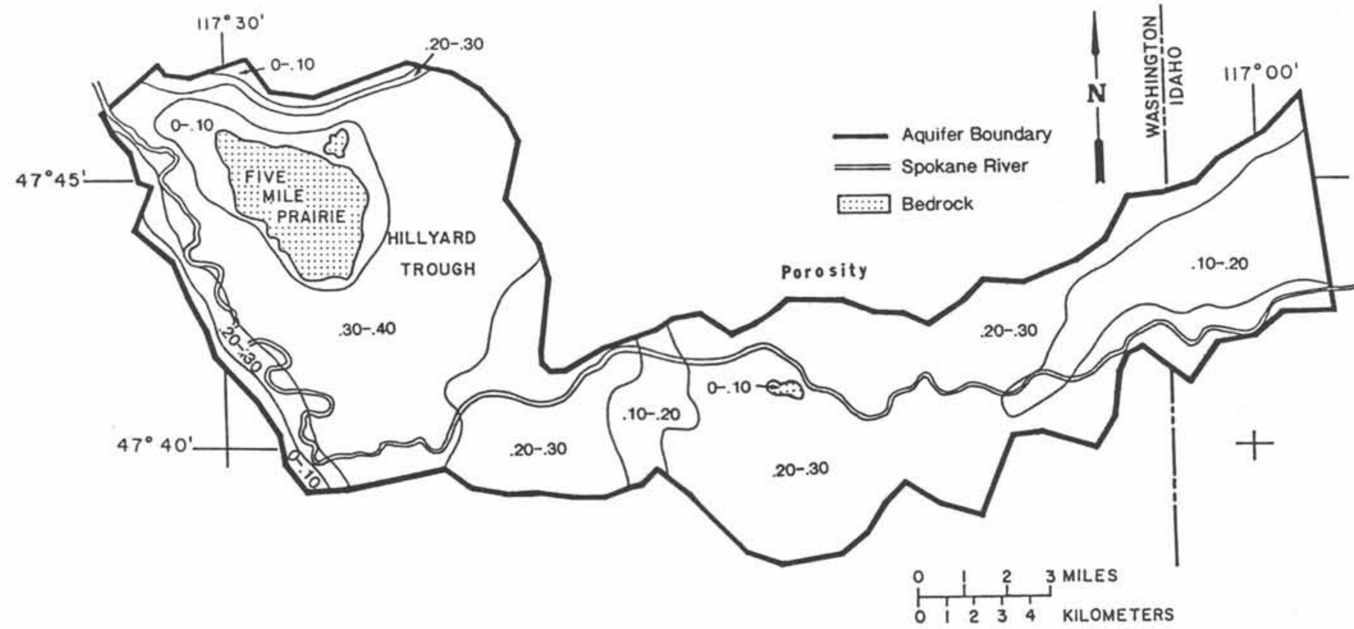


Figure 6. Porosity (dimensionless fraction) of the Spokane Aquifer. From Vaccaro and Bolke (1983).

well drilling that has penetrated the aquiclude and encountered water having sufficient head to blow out; on occasion this has created a glory hole which has proven impossible to contain.

Hydraulic Characteristics

Vaccaro and Bolke (1983) developed hydraulic parameters for the Spokane Aquifer in order to study water-quality characteristics by using digital modeling. The Spokane Aquifer is an excellent water producer; because of this, it has not been necessary to conduct any definitive study to determine the hydraulic character of the aquifer. Reasonable assumptions have been made in order to integrate numerical values into a mathematical study. Figures 4, 5, and 6 adopted from Vaccaro and Bolke (1983) are included to illustrate some of the hydraulic characteristics of the aquifer.

Values that characterize the hydraulics of the Spokane Aquifer follow:

Permeability – 0.01 to 0.07 ft/sec

Specific Yield – 0.05 to 0.20

Transmissivity – 0.05 to 70 sq ft/sec

Saturated Thickness – 50 to 500 ft (average >200 ft)

Porosity – 0.20 to 0.40

Volume of water flow through aquifer – 1,000 cfs

Velocity – 0.01 to 80 ft/day

The recharge area shown in Figure 2 includes the drainage basins of the St. Maries River, the St. Joe River, and the Coeur d'Alene River. These discharge into Coeur d'Alene Lake, which is the source of the Spokane River. Rathdrum Prairie, upstream of the outlet of Coeur d'Alene Lake, extends some 25 mi northeast to Pend Oreille Lake and averages about 6 mi wide. The Rathdrum Prairie area receives an average of 17.4 in. of precipitation annually. The entire drainage basin receives an average annual precipitation of 17 in. on the west to 33 in. on the east. The Clark Fork River drains western Montana west of the Continental Divide and feeds into Pend Oreille Lake, which, in turn, feeds into the Rathdrum Prairie Aquifer. There appears to be a supply of water adequate for any foreseeable expansion of Spokane. The problem is not water supply as much as it is water quality.

AQUIFER PROTECTION

As Spokane grew and construction materials were required, surface gravel was taken from the most convenient sources as needed. Eventually, these borrow sites developed into large pits whose depths were dictated by the ability of the operator to haul out and whose dimensions were a function of land ownership.

Following World War II, sanitary landfills were considered to be the answer to the disposal of wastes, and some of these pits became repositories of waste materials without regard for the impact of hazardous materials on the underlying aquifer. These actions were taken largely out of ignorance, without realizing the extent or the nature of the aquifer. After years of burying garbage and refuse in landfills, we have discovered that toxic, soluble compounds are leaching from these disposal dumps into our water systems. In recognition of the hazards associated with unregulated landfill practices, this method of waste disposal is being phased out. All sanitary landfills in Spokane County will be closed out by mid-1990 (Birks, 1986).

In an attempt to provide a positive, non-polluting method of waste disposal, Spokane County has embarked on a solid waste disposal and resource recovery system project. The system involves a mass burning technique that appears to have the capabilities of reducing all waste products to harmless ash and to generate power as a by-product.

In 1978 the federal Environmental Protection Agency designated the Spokane-Rathdrum Aquifer as a "Sole Source" of water supply for the Spokane/Coeur d'Alene area. As a result, the Washington Department of Ecology delegated a segment of its "208" areawide water-quality management program to the development of a Water Quality Management Plan for the aquifer. This plan has become the basic framework for statewide planning for ground-water protection (Turner, 1979).

The initial Spokane Aquifer Water Quality Management Plan report (Turner, 1979) and its 1983 update (Esvelt and Miller, 1983) clearly point out the areas of most concern in protecting the aquifer from further degradation. The three major areas of concern are domestic waste disposal, storm-water runoff, and chemical spills. Water quality is continually being monitored to assess the effectiveness of measures being implemented to protect the aquifer.

The protection of the aquifer is not solely a Spokane area concern, however. Communities upstream of Spokane must share in this endeavor. A combination of public awareness and cooperative human activities is the most viable approach to the protection of this regional natural resource.

ACKNOWLEDGMENTS

The authors thank Ehman J. Sheldon, City Administrator for Deer Park, Washington, and Damon M. K. Taam, Assistant Director of the Spokane Regional Solid Waste Disposal Project for providing us with valuable information concerning the Spokane Aquifer.

REFERENCES

Atwater, B. F., 1983, *Guidebook for 1983 Friends of the Pleistocene field trip to the Sanpoil River valley, northeastern Washington:* U.S. Geological Survey Open-File Report 83-456, 22 p.

Baker, V. R. and Nummedal, D., 1978, *The Channeled Scabland–A Guide to the Geomorphology of the Columbia Basin, Washington*: National Aeronautics and Space Administration, Washington, D.C., 186 p.

Birks, D., 1986, Spokane County landfill closures point to worsening garbage crisis: *The Labor World*: Spokane, WA, Vol. 88, No. 2, p. 1.

Bolke, E. L. and Vaccaro, J. V., 1979, *Selected Hydrologic Data for Spokane Valley, Spokane, Washington, 1977-78*: U.S. Geological Survey Open-File Report 79-333, 98 p.

Bretz, J H., 1969, The Lake Missoula floods and the Channeled Scabland: *Journal of Geology*, Vol. 77, No. 5, pp. 505-543.

Cochran, B. F., 1984, *Exploring Spokane's Past*: Ye Galleon Press, Fairfield, WA, 80 p.

Esvelt, L. A. and Miller, S. A., 1983, *Supplement No. 1 to Spokane Aquifer Cause and Effect Report, Summary Report of "208" Water Quality Results and Cause and Effect Relationships for Water Quality in the Spokane-Rathdrum Aquifer*: Spokane County Engineers Office, Spokane, WA, 38 p., 2 plates.

Glatzer, R., 1983, New information on the great Spokane flood: *EWU Explorer*, Eastern Washington University, Cheney, WA, Vol. 2, No. 1, pp. 8-13.

Griggs, A. B., 1973, *Geologic Map of Spokane Quadrangle, Washington, Idaho and Montana*: U. S. Geological Survey Miscellaneous Investigations Series Map I-768, 1 sheet, scale 1:250,000.

Miller, S. A., 1987, Personal communication, Spokane County Engineers Office, Spokane, WA.

Newcomb, R. C., 1953, *Seismic Cross Section Across the Spokane River Valley and Hillyard Trough, Idaho and Washington*: U. S. Geological Survey Open-File Report 53-199, 16 p., 18 plates.

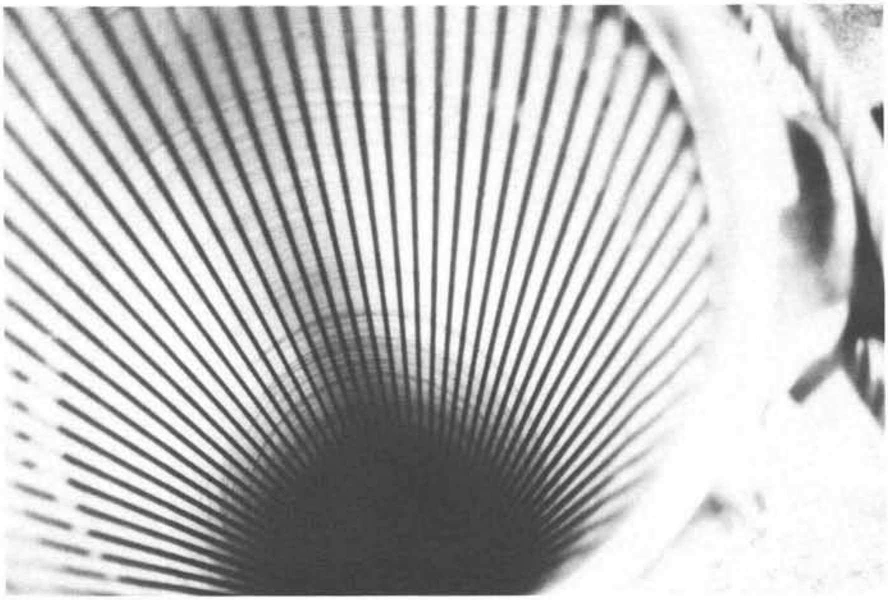
Pardee, J. T., 1942, Unusual currents in Lake Missoula, Montana: *Geological Society of America Bulletin*, Vol. 53, pp. 1569-1600.

Turner, R. S., 1979, *Spokane Aquifer Water Quality Management Plan*: Spokane County Engineers Office, Spokane County, Washington "208" Program, Spokane, WA, 102 p., 6 plates.

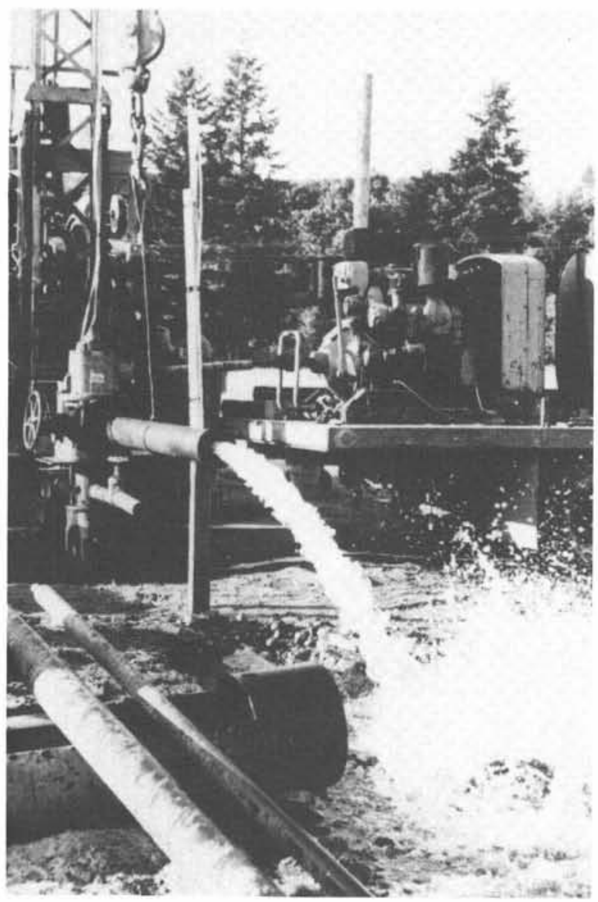
Vaccaro, J. J. and Bolke, E. L., 1983, *Evaluation of Water-Quality Characteristics of Part of the Spokane Aquifer, Washington and Idaho, Using a Solute-Transport Digital Model*: U.S. Geological Survey Open File Report 82-769, 75 p.

Waitt, R. B., 1983 [1984], *Tens of successive, colossal Missoula floods at north and east margins of Channeled Scabland*: U.S. Geological Survey Open-File Report 83-671, 29 p.

Weigle, J. M. and Mundorff, M. J., 1952, *Records of Wells, Water Levels, and Quality of Ground Water in the Spokane Valley, Spokane County, Washington*: U.S. Geological Survey Water Resources Division, State of Washington Ground Water Report 2, 102 p.



View down the inside of a length of 14-in.-diameter, 40-slot well screen similar to that used in some municipal wells in Washington. Photograph courtesy of CH2M Hill, Inc., Bellevue, WA.



Pumping test of an 8-in.-diameter test well at approximately 450 gpm at the site of a proposed fish hatchery on the Nisqually River near McKenna, WA. Photograph courtesy of Hart Crowser Inc., Seattle, WA.

The Trident Aquifer Study at Bangor, Kitsap County

JOHN B. NOBLE
Robinson & Noble, Inc.

INTRODUCTION AND PROJECT PURPOSE

Engineering studies began in 1974 to build the West Coast Trident Submarine Facility at the U.S. Navy's Bangor Ammunition Depot on the east side of Hood Canal, Kitsap County, Washington (Figure 1). The focal point of the Navy base is a delta-shaped pier with accompanying dry dock attached to an otherwise undisturbed shoreline. This entire structure is called the "Delta", and it can dock three submarines, including one in the dry dock position. The base, now fully constructed, also supports major auxiliary facilities and several thousand people. For this large a facility, a major potable water supply was required.

Test drilling was done under separate projects to determine the foundation conditions for the Delta and to explore for a water supply. In this area there is no regional public water supply; furthermore, all major water supplies are from wells. The foundation engineer had determined that beneath the Delta there was an artesian aquifer with a head of about 50 ft above sea level. The water-supply hydrogeologist had separately determined that a sub-sea-level aquifer existed at several inland points where the artesian head was at an elevation of 60 to 70 ft.

In early 1975 an offshore soil-sampling casing broke loose from its borehole in the artesian aquifer. Concurrently, a water-level recorder at a water-supply test well 4,600 ft inland showed a time-correlative drop of artesian pressure of about 4 ft. The obvious hydrologic relation between the two test borings joined the two projects and resulted in a 6-yr program whereby nearly 100 wells and deep piezometers were placed and water levels were monitored and managed during the construction phases of the Delta.

The onshore study defined a channel-shaped aquifer system that, as luck would have it, was virtually contained by the Navy's boundary fences (Figure 2). Offshore drilling showed the aquifer to extend beneath the Delta, almost as if the Delta itself were the controlling outlet. A truncated till of pre-Vashon age forms the offshore artesian cap (Figure 3). Excavation for the dry dock would require excavation of the capping glacial till, but not total removal. However, to guard against a rupture of the till cap, the foundation engineers required that offshore dewatering must be accomplished to reduce the artesian head from 50 ft above sea level to 67 ft below for a net change of 117 ft. In that a natural base flow of 2,000 gpm was estimated for the aquifer system, capture of that water plus storage depletion to lower the head was estimated to require drawing at least 4,000 gpm from dewatering wells. This quantity would have to be pumped for more than a year during the most active stage of construction. The regional aspects of the dewatering in a peninsular area dependent on ground water were indeed worrisome.

When sufficient hydrogeological data had been obtained through drilling and pumping (including a 15-day pumping test), a computer model was developed by a contracted research-oriented organization (Battelle Pacific Northwest Laboratories, 1977). Input to the model included good quality data and good interpretive boundaries. In the end, model predictions met real-world results very closely.

A plan was developed where dewatering was accomplished by a tiered system consisting of:

(1) Twelve "Purple" wells drilled into the cofferdam area of the dry dock. These offshore wells did the dewatering during the period of most active construction work. The artesian head finally reached 85 ft below sea level.

(2) Five "Red" wells drilled at the shoreline. These wells initiated the dewatering and allowed first-stage construction, including placement of the "Purple" wells. At their maximum use, they pumped 3,500 gpm and lowered the water level to 20 ft below sea level.

(3) Four "Blue" wells drilled 1,000 ft inland from the shoreline. These wells intercepted the top of the base flow toward the sea and effectively supplemented the "Red" wells. The "Blue" wells pumped about 1,000 gpm to waste at first, then began to supply the base's potable supply needs. The "Blue" wells remain today as the prime water supply.

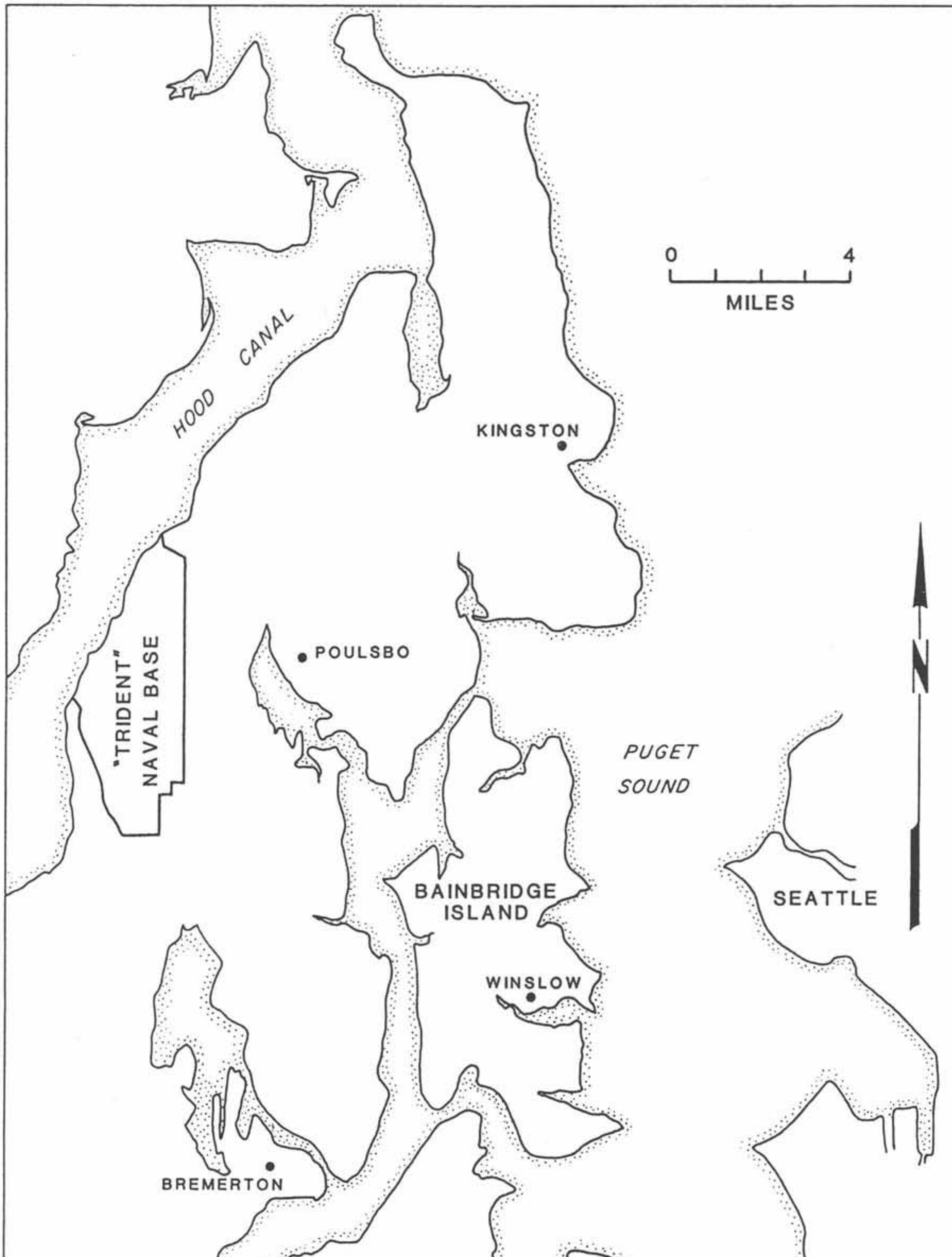


Figure 1. Location of Trident submarine base, Kitsap County.

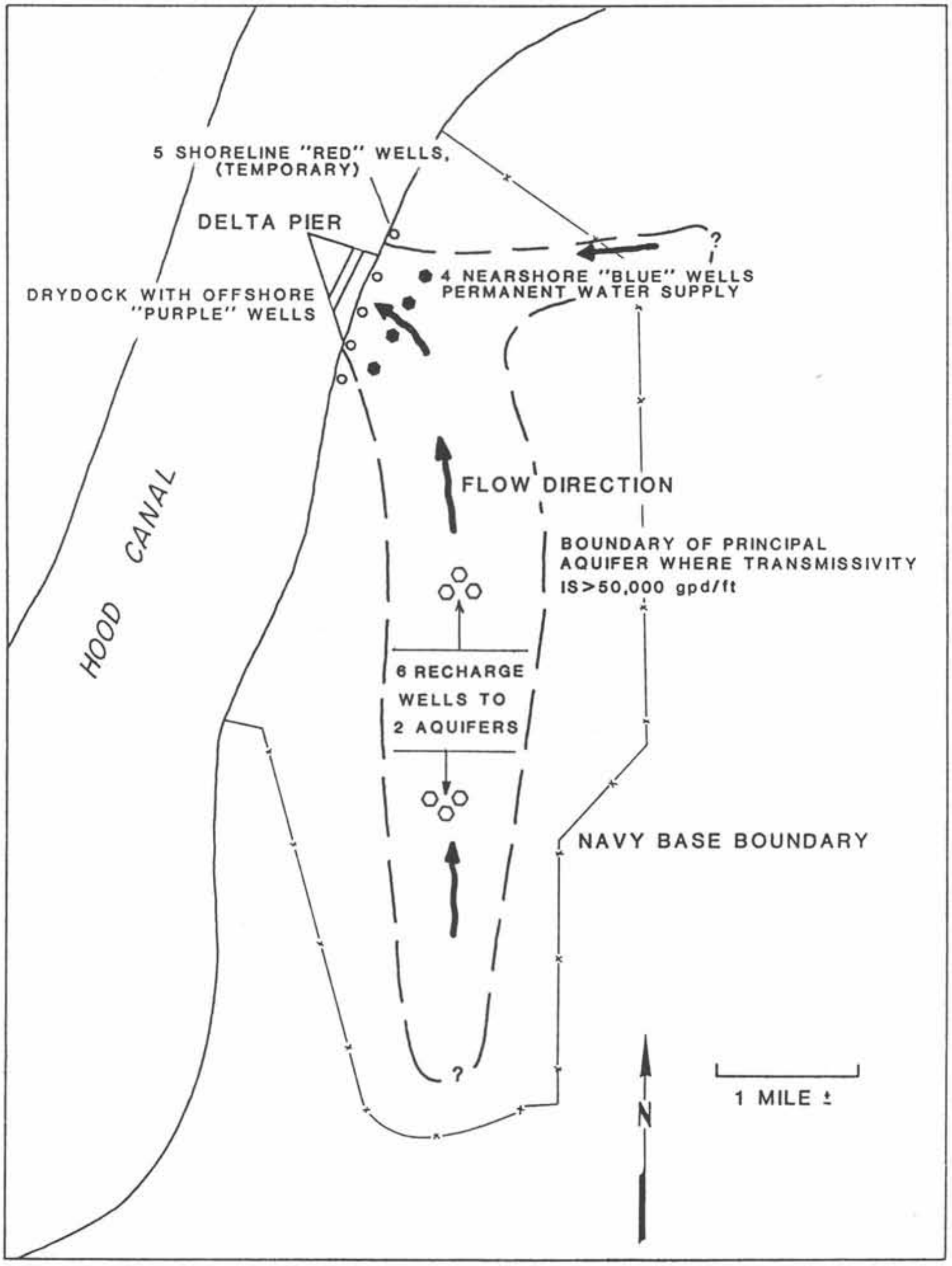


Figure 2. Schematic map of Navy base, aquifer boundary, and well locations.

(4) Six recharge wells in two fields, which are 7,000 and 14,000 ft upstream (south) of the Delta. At each field one well was completed in the deep aquifer and two in the sea-level aquifer (Figure 3). All surplus water from the "Blue" wells was routed to the recharge wells to maintain a safe artesian level at distance from the works. (These recharge wells may not have been necessary in the end and suffered major problems, discussion of which is beyond the scope of this paper.)

At the end of the 3-yr construction period for the dry dock, the project was on schedule and the dewatering plans worked perfectly. The "Red" wells have since been plugged and abandoned, the "Purple" wells remain as free artesian relief wells, and the "Blue" wells remain as base supply wells. The static water level at the "Blue" wells has been permanently reduced by about 30 ft. Effects on the area's ground-water levels at the south end of the system have dissipated and are no longer present.

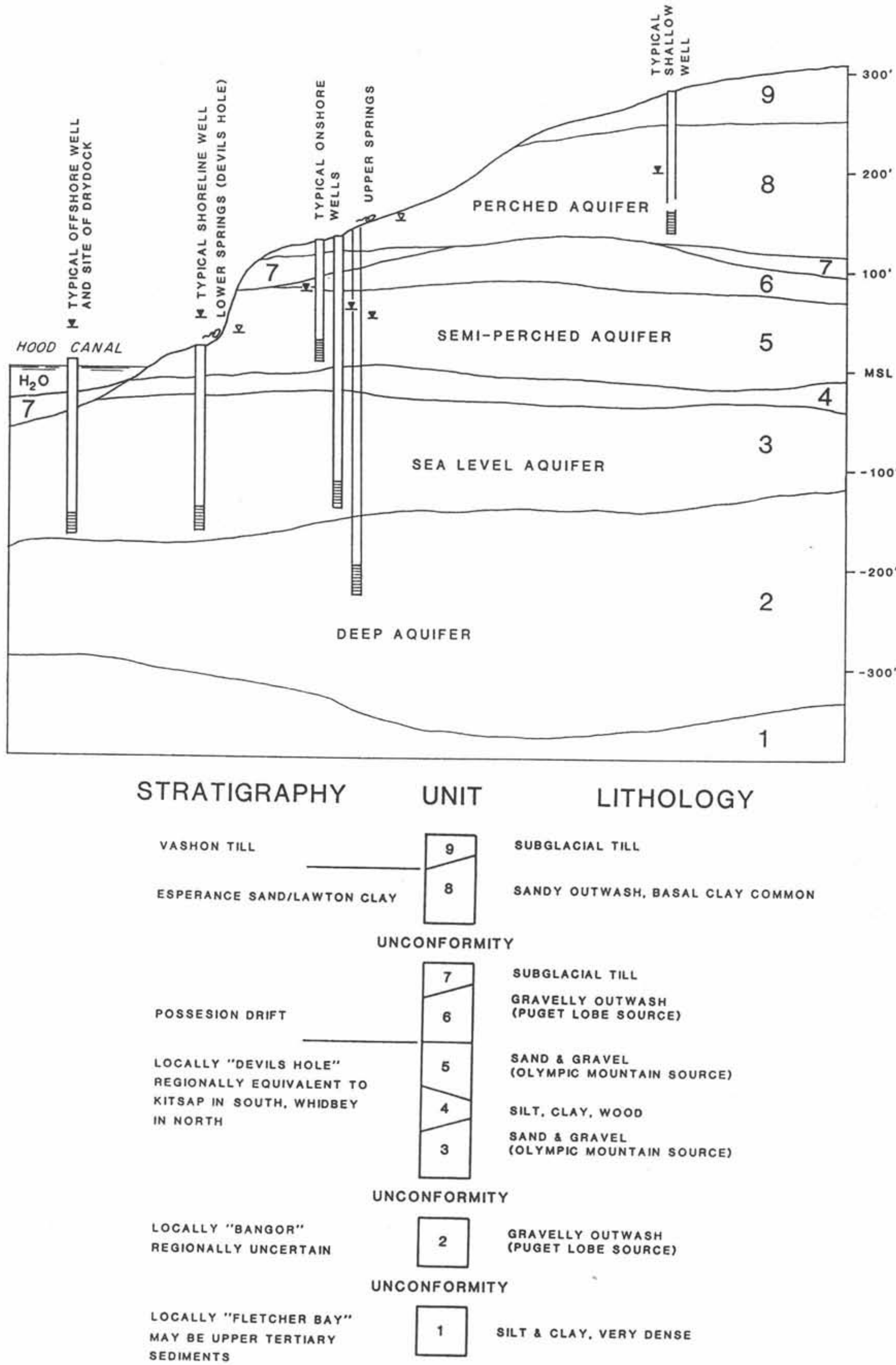


Figure 3. Schematic hydrographic section and wells between the Delta pier area and the south-central part of the Navy base.

Salt-water intrusion occurred at both "Purple" and "Red" wells, as was expected. Background chloride content was about 5 ppm, and increased to 1,150 ppm in the most affected "Red" well and 3,700 ppm at the most seriously affected "Purple" well. The "Blue" wells were not affected. (Sea water in Hood Canal contains about 18,000 ppm chloride.)

DRILLING PROGRAMS

The hydrogeologist responsible for the onshore aspects of the Trident base construction project contracted for and drilled 17 test wells whose depths ranged from 334 to 1,205 ft (Robinson & Noble, Inc., 1976, 1977, 1981). These wells were located throughout the base confines and effectively defined a multiple aquifer system. All wells were drilled by the top-drive rotary method, using Revert (organic polymer) drilling fluid, and cased with 6-in. steel casing. Prior to running casing, each well was electric logged (3-point resistivity) and gamma-ray logged. The logs were interpreted to define permeable zones and the wells were then cased with pre-slotted casing for pumping tests. Typically, the principal (sea level) aquifer was tested. After testing, the zone was equipped with a screened 2-in. piezometer pipe, and the slotted 6-in. casing was drawn back to the secondary (semi-perched) aquifer. In this way the typical test well remained as a permanent piezometer for two aquifers.

In addition to the test wells, the hydrogeologist (Robinson & Noble, Inc.) designed and managed the drilling of the four water-supply wells ("Blue" wells) and the six recharge wells. Concurrently, the 12 "Purple" wells and 5 "Red" wells were drilled under the management of the foundation engineer (Haley & Aldrich, Inc.). Well depths ranged from about 250 ft for the "Red" wells to 780 ft for the deepest recharge well. All of these wells were of 12-in. to 20-in. diameter, and all were drilled by the cable tool method. The deeper wells required multiple casing strings. All were completed with stainless steel screens, and most were gravel packed. At time of construction, all wells tended to have high efficiency, and each was tested at rates of 500 to 1,000 gpm or more.

HYDROGEOLOGY

Prior to the Trident project there were fewer than a dozen wells in Kitsap County proven at rates of greater than 600 gpm. A great many tests had been made and the vast majority indicated aquifers with transmissivities of less than 25,000 gpd/ft. Ironically, the Trident project demonstrated an aquifer system virtually contained within Navy property. The aquifers identified were simply designated "perched", "semi-perched", "sea level", and "deep", as shown on Figure 3. The principal aquifer is the sea-level aquifer which has a transmissivity of more than 100,000 gpd/ft. Figure 2 shows the sea-level aquifer boundaries, and Figure 3 depicts the hydrostratigraphic systems.

The geologic setting of the aquifers is a Pleistocene basin fill in the west-central Puget Sound lowland. Hood Canal is a glacially scoured, fjord-like trough. The trough's "footprint" is a major structural anomaly west of which rises the indurated bedrock of the Olympic Mountains.

In the test drilling at the Trident base, no consolidated rocks had been penetrated at a maximum depth of 978 ft below sea level. The oldest materials are silt- and clay-rich sediments designated by the author as the Fletcher Bay formation; they are similar to sediment beneath Bainbridge Island. The Fletcher Bay formation appears to be widespread and is assumed to be an early Pleistocene or late Tertiary basin fill of fine-grained sediments. No appreciable quantities of ground water have been encountered in the Fletcher Bay formation.

Above the Fletcher Bay formation is a glacial drift locally designated the Bangor formation by the author. Contained gravels appear to be of Puget lobe (continental glacier) source. Permeable zones within the Bangor formation comprise the deep aquifer.

Above the Bangor formation is a sequence of fluvial gravels separated by a distinct layer of silt and clay with considerable amounts of wood. Source rocks for the gravels appear to have been carried from the Olympic Mountains. Deposition was presumably during an interglacial episode. The author applied the local name Devils Hole formation to this stratigraphic sequence. Equivalent sediments nearby have been mapped as the Kitsap Formation (Garling et al., 1965). To the north the probable correlative unit is the Whidbey Formation (Easterbrook, 1968). The lower gravel member comprises the sea-level aquifer, which is the area's principal aquifer and the target of the dry-dock dewatering. Natural discharge from this aquifer is below the surface of Hood Canal. The silty middle member serves as a distinct aquitard, and the upper gravelly member comprises the greater part of the semi-perched aquifer. Springs issue from the contact between the upper and middle members. The Devils Hole formation is represented as units 3, 4, and 5 on Figure 3.

Above the Devils Hole formation is a sporadic glacial sequence designated as units 6 and 7 on Figure 3. These pre-Vashon deposits have a lithology suggestive of a Puget lobe source. As such, they may be correlative with the Possession Drift of Whidbey Island to the north (Easterbrook, 1968). Data points that define the top of this drift unit show that it has a drumloidal surface topography, effectively delineating a buried hill that lies upon a buried valley filled with the Devils Hole nonglacial sediments. The Possession (?) Drift serves as a base to the shallowest or perched aquifer system.

Above the Possession (?) Drift are sediments of the Vashon glacial stade, the youngest continental glaciation in this region. Unit 8 on Figure 3 commonly has a basal clay, probably correlative to the Lawton Clay found at Seattle (Mullineaux et al., 1965). Above the basal clay is a moderately permeable proglacial sand correlative with the Esperance Sand of western Snohomish County (Easterbrook, 1968). This sand hosts the perched aquifer from which the higher elevation springs issue. The perched aquifer was never a concern to the dewatering project, but it was later the subject of an extensive hazardous waste study.

The surface unit at the Navy base, Unit 9, is till of Vashon age that is typically found throughout the Puget Sound basin. The till is moderately permeable; rainfall infiltration can penetrate it and recharge the underlying aquifers. Geologists at the dry dock location mistakenly described the sea-bottom till as Vashon, whereas the onshore exploration showed that this till is probably of Possession age, as shown on Figure 3.

SUMMARY

The Trident Aquifer Study evolved around the multiple needs of construction dewatering, water-supply requirements, and water resource management. It was a satisfying study in that the various regulatory, geotechnical, and construction personnel coordinated the project through its successful conclusion. During the process this previously unknown aquifer system was identified to a degree not usual in the Puget Sound area, and the system was safely manipulated to allow a massive offshore construction project to be completed.

ACKNOWLEDGMENT

The author, several years after the fact, appreciates the management ability of the U.S. Navy's Officer in Charge of Construction (TRIDENT), who managed the entire project.

REFERENCES

Battelle Pacific Northwest Laboratories, 1977, *Report on the Analysis of Pump Test Data in the Trident Base Supply Wells (501-504)*: Prepared for Robinson & Noble, Inc., Tacoma, WA, [unpaginated].

Easterbrook, D. J., 1968, *Pleistocene Stratigraphy of Island County*: Washington Department of Water Resources Water Supply Bulletin 25, Olympia, WA, 34 p.

Garling, M. E.; Molenaar, D.; Bailey, E. G.; VanDenberg, A. S.; and Fiedler, G. H., 1965, *Water Resources and Geology of the Kitsap Peninsula and Certain Adjacent Islands*: Washington Division of Water Resources Water Supply Bulletin 18, Olympia, WA, 309 p., 5 plates.

Mullineaux, D. R.; Waldron, H. H.; and Rubin, M., 1965, *Stratigraphy and Chronology of Late Interglacial and Early Vashon Glacial Time in the Seattle Area, Washington*: U.S. Geological Survey Bulletin 1194-O, p. O1-O10.

Robinson & Noble, Inc., 1976, *Construction of Trident Wells 501-504 (Blue Wells) and Related Hydrogeology*: Prepared for OICC-Trident (U.S. Navy), 21 p., 4 plates.

Robinson & Noble, Inc., 1977, *Construction of Wells for Trident Recharge Fields 1, 2 and 3*: Prepared for OICC-Trident (U.S. Navy), 13 p., 7 plates, data appendix.

Robinson & Noble, Inc., 1981, *Ground Water Hydrology at the Naval Submarine Base, Bangor, Washington*: Prepared for OICC-Trident (U.S. Navy), 58 p., data appendix.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Effects of Decreased Irrigation on the Ground-water System in the Sequim-Dungeness Peninsula, Clallam County, Washington

BRIAN W. DROST
U.S. Geological Survey

INTRODUCTION

One of the oldest developed areas in western Washington is the Sequim peninsula in Clallam County. In recent years, however, the pattern of development has undergone a dramatic change. Much of the land that was originally used for irrigated agriculture has been subdivided for residential use. This change in land and water use has caused changes in the stresses on the ground-water and surface-water systems.

In 1978, the U.S. Geological Survey, in cooperation with the State of Washington Department of Ecology and the Board of Clallam County Commissioners, began a study of the ground-water system in the Sequim peninsula with the primary goal of predicting the potential long-term effects of the changing pattern of land use. This paper is abstracted from a publication (Drost, 1983) that reported the findings of the U.S. Geological Survey Sequim peninsula study.

In the only previous investigation of the ground-water resources of the peninsula, a reconnaissance-type study conducted during July-September 1960, Noble (1960, p. 9) concluded that, "An important secondary source of recharge (to the ground-water system) is directly from irrigation." This conclusion caused concern when land-use trends began to indicate a possible future decrease in irrigation. A decrease in recharge would tend to lower heads in the ground-water system, which could result in well failures, increased pumping costs, and seawater intrusion. The purpose of the 1978 study was to examine the effects of decreased irrigation on the ground-water system of the peninsula.

A computer model was used to simulate three-dimensional ground-water flow in the aquifers and to estimate the possible future effects on the ground-water system of possible changes in land use and irrigation practices.

Most of the data used in constructing the model were collected by the U.S. Geological Survey, the State of Washington Department of Ecology, and the Clallam County Department of Public Works during the period September 1978 to September 1980. These data include (1) monthly water-level measurements in about 65 wells, (2) daily staff-gage readings at 10 surface-water sites, (3) a continuous record of discharge at one surface-water site, (4) monthly discharge measurements at 20 surface-water sites, (5) surveyed land-surface altitudes at about 75 sites, and (6) drillers' records of about 1,400 wells. Most of these data are contained in two U.S. Geological Survey reports (Drost, 1983, 1986). The remaining data are available in files of the U.S. Geological Survey in Tacoma, Washington. Additional data were obtained from Dion and Sumioka (1981), Grimstad and Carson (1981), Noble and Balmer (1980), and Walters (1971).

The Sequim peninsula is an area of about 60 sq mi in northwestern Washington (Figure 1). The peninsula extends into the Strait of Juan de Fuca to the north and is bounded on the south by the foothills of the Olympic Mountains.

The area has been extensively irrigated since about 1898 with water from the Dungeness River, which originates in the mountains to the south and flows through the middle of the peninsula. Prior to irrigation the area was sparsely vegetated and was subject to dry summers (Keeting, 1976). As of 1960, the area was used primarily for agriculture and supported a population of about 5,000 people. In the mid-1960s, land use in the area began shifting from agriculture to residential, resulting in population increases to about 7,000 in 1970 and 12,000 in 1980.

HYDROGEOLOGIC SETTING

Geometry of the Aquifers and Confining Beds

The surficial sediments in the study area are mostly unconsolidated glacial, alluvial, and glaciomarine deposits (Othberg and Palmer, 1980a, b, c). Mudstones, siltstones, and some sandstones are exposed at Bell Hill, just south of the study area (Tabor and Cady, 1978) and probably underlie the unconsolidated deposits beneath

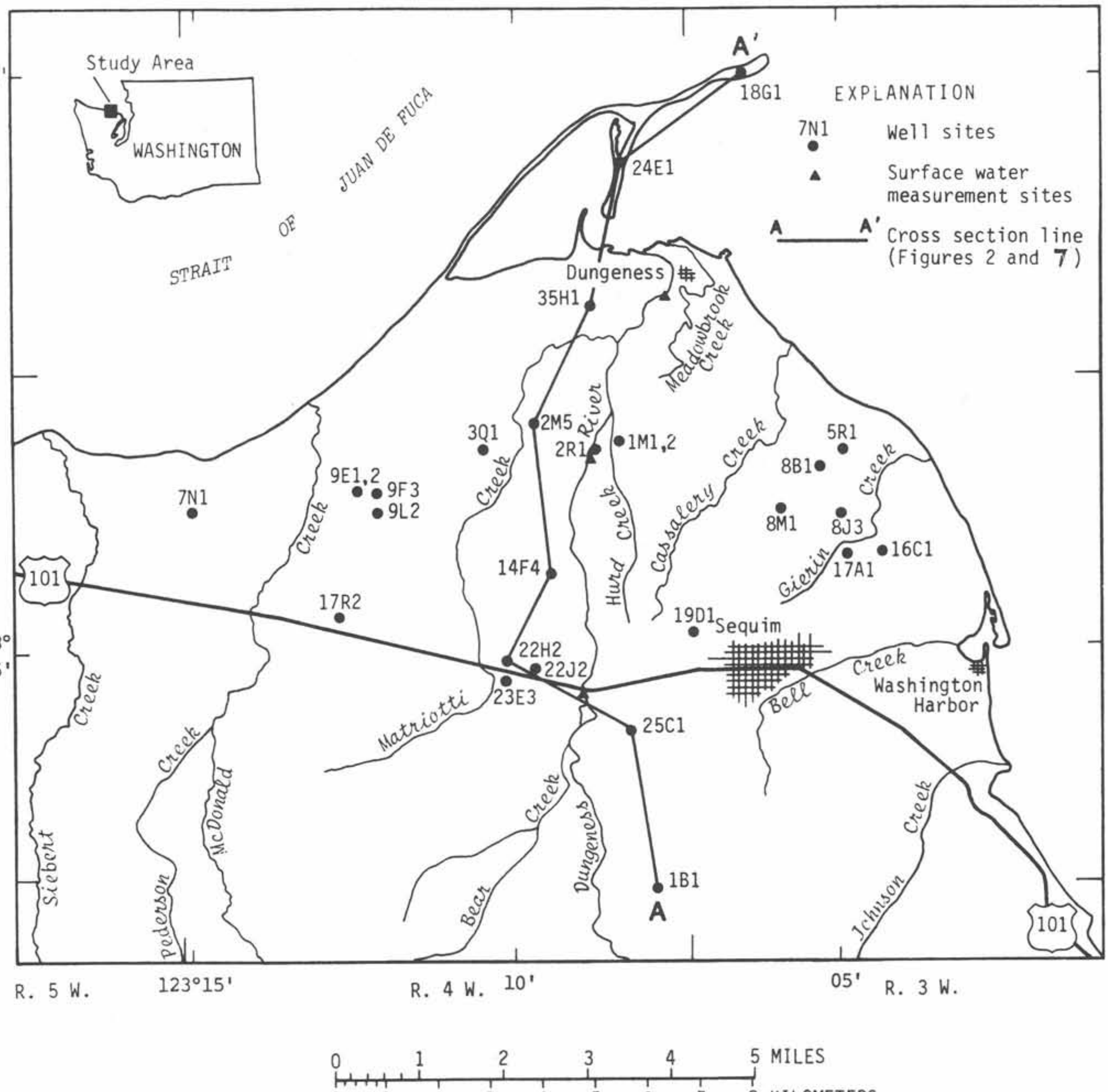


Figure 1. Location of the Sequim peninsula study area.

most of the study area. The consolidated rocks, when compared (using specific-capacity data) with the unconsolidated deposits, are impermeable and are treated as the base of the ground-water system in parts of the study area.

The unconsolidated deposits were divided into geohydrologic units on the basis of examination of more than 1,100 drillers' logs. Three aquifers and two confining beds were identified and are shown in Figure 2. The aquifers are composed of sand and gravel, with some till, silt, and clay. In the upland regions where it directly overlies bedrock, the water-table aquifer is composed largely of till and clay, with minor amounts of sand and gravel.

The water-table aquifer extends throughout the study area and includes at least seven geologic units identified by Othberg and Palmer (1980a, b, c): alluvium, older alluvium, Everson glaciomarine drift, Everson sand,

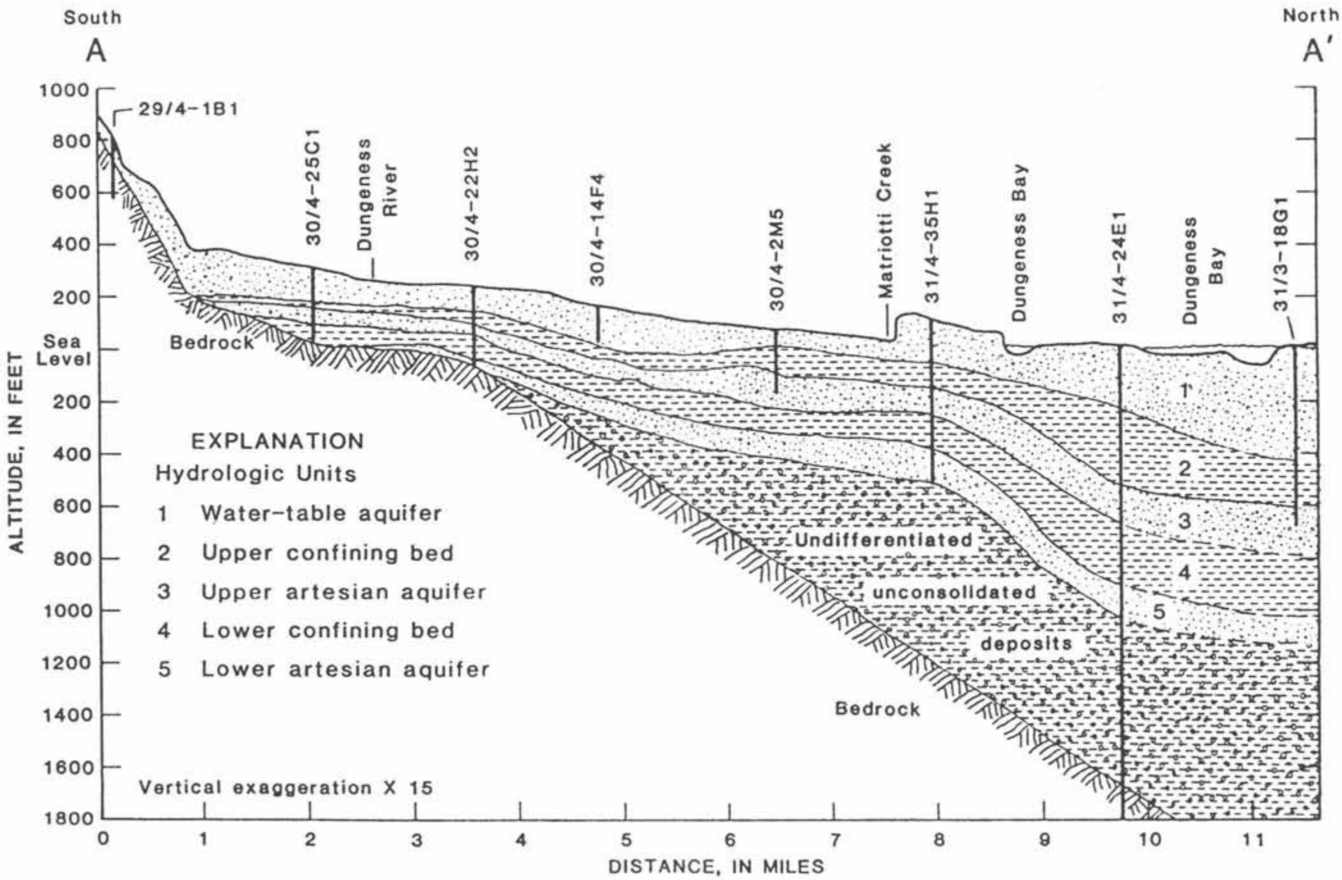


Figure 2. Schematic geologic section of the study area.

Vashon recessional ice-contact and outwash deposits, Vashon till, and Vashon advance outwash. All of these are of Quaternary age.

The artesian aquifers apparently are not exposed in the study area and were not described by Othberg and Palmer. The saturated thickness of the water-table aquifer ranges from a few feet to more than 100 ft and probably averages about 75 ft.

The upper artesian aquifer is present in only part of the study area. Where present, its thickness ranges from a few feet to more than 100 ft and averages about 75 ft. In the foothill region in the southern part of the study area the upper artesian aquifer is absent, and the water-table aquifer directly overlies bedrock or the upper confining bed.

The lower artesian aquifer covers a slightly smaller area than the upper artesian aquifer. The thickness of the lower artesian aquifer is not well known.

The confining beds are composed of clay, silt, and till, with minor inclusions of sand in thin, discontinuous beds. The upper confining bed may correspond, at least in part, to the pre-Vashon silts and clays of Othberg and Palmer (1980a, b, c), but the lower confining bed was not described in their report.

The upper confining bed ranges in thickness from about 1 ft to more than 200 ft, but is between 25 and 75 ft thick throughout much of the study area. Few data are available regarding the lower confining bed. It probably ranges in thickness from less than 50 ft to more than 200 ft. Average thickness is probably on the order of 100 to 125 ft.

Data on the deeper unconsolidated materials were not sufficient to allow identification of individual units. There is at least one more aquifer in the deeper unconsolidated materials, and there may be several more. The deeper unconsolidated materials are treated as the base of the ground-water system in parts of the study area.

Recharge to the Ground-Water System

Precipitation Recharge

Average annual precipitation at the Sequim weather station is 16.1 in. (1919-79) and in the study area probably ranges from about 14 in. along the northeastern shoreline to 30 in. along the southern boundary.

About 60 percent of the precipitation occurs from October to February in most years.

Potential evapotranspiration, calculated by a modified Blaney-Criddle technique (U.S. Department of Agriculture, 1970), is nearly twice the average precipitation. At the Sequim weather station the average potential evapotranspiration (1919-79) is 30.2 in. This value is probably representative of the entire study area.

Actual evapotranspiration can be estimated by applying an assumed soil-moisture capacity (3 in. of water) to the monthly precipitation and potential evapotranspiration values. At the Sequim weather station, average annual evapotranspiration is 13.8 in. Throughout the study area, it probably ranges from about 12.7 in. (14-in. precipitation zone) to about 18.8 in. (30-in. precipitation zone).

When precipitation exceeds potential evapotranspiration and the soil-moisture capacity is exceeded, the excess water is assumed to be ground-water recharge because direct runoff is believed to be insignificant in the study area. Calculated average annual ground-water recharge ranges from about 1.3 in. (14-in. precipitation zone) to about 11.2 in. (30-in. precipitation zone) and is about 2.3 in. at the Sequim weather station. The average recharge rate from precipitation was calculated to be about 15 cfs.

All weather data used in the above calculations are from the U.S. Weather Bureau (1920-1965; 1965), U.S. Department of Commerce (1965-1973), or National Oceanic and Atmospheric Administration (1974-1979).

Irrigation-System Recharge

Large quantities of water are continuously diverted from the Dungeness River. The water flows through a complex system of irrigation ditches belonging to nine irrigation companies and districts established between 1895 and 1921. The major ditches and their relation to the area's surface-water system are shown in Figure 3. There are also several times as many miles of secondary ditches and laterals not shown in Figure 3. The water is used primarily for irrigation, but also for stock supply

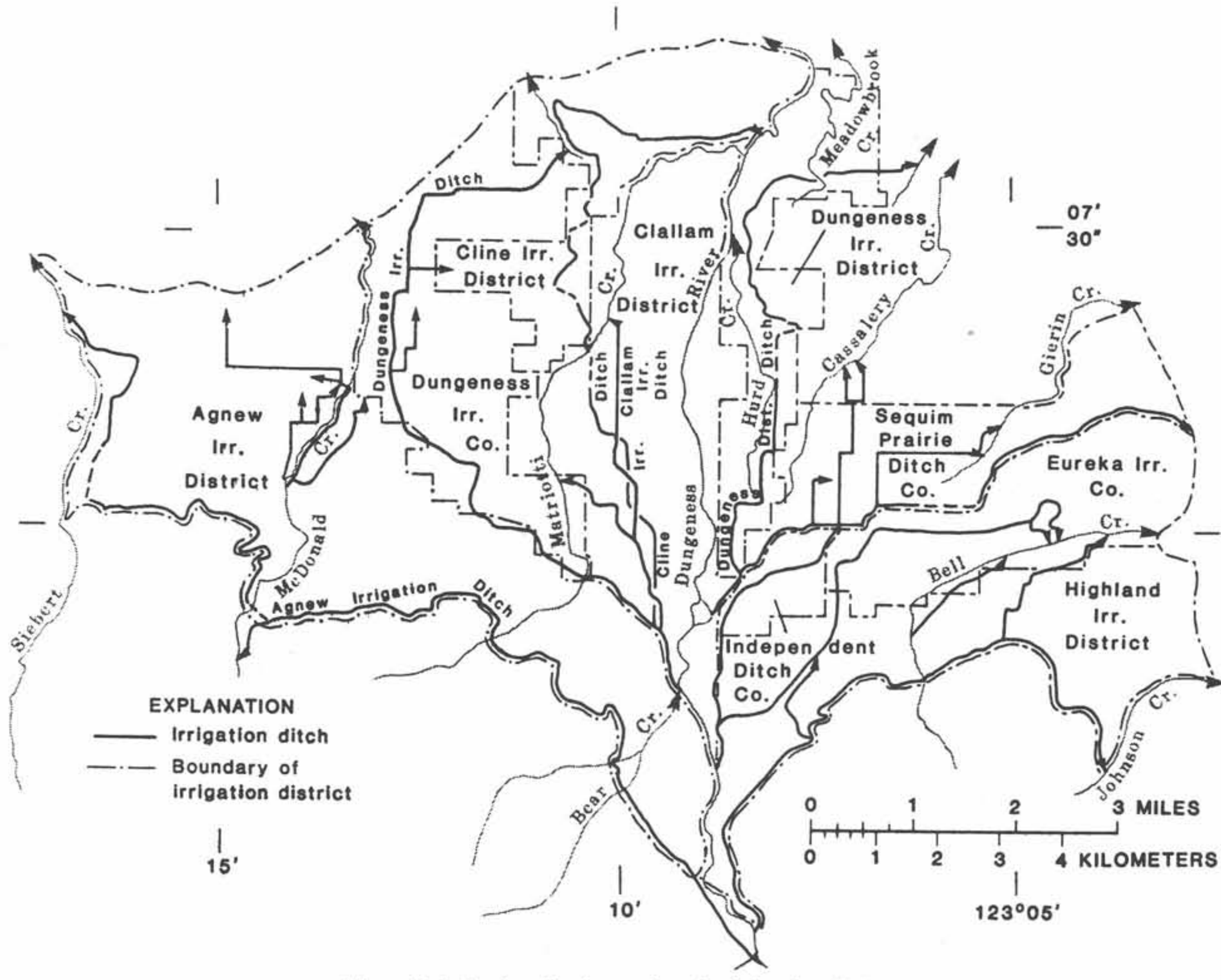


Figure 3. Irrigation districts and major irrigation ditches.

and fire protection in some areas, requiring year-round flow in most of the major ditches.

Water also is diverted from McDonald Creek by the Agnew Irrigation District at rates of about 20 cfs during the irrigation season and about 5 cfs during the non-irrigation season. Prior to this study, systematic discharge measurements had never been taken on the irrigation systems. The average irrigation diversion from the Dungeness River from September 1978 to August 1980 was about 67 cfs. Average diversion was about 100 cfs during the irrigation season, April-September, and about 33 cfs during the rest of the year.

The effect of ground-water recharge from irrigation can be observed in the relation between flows in the irrigation ditches and water levels in the water-table aquifer. An example is given in Figure 4, which shows the flow in the Independent Irrigation Ditch compared with the water level in well 30/3-19D1, which is 49 ft deep and within 100 ft of the ditch.

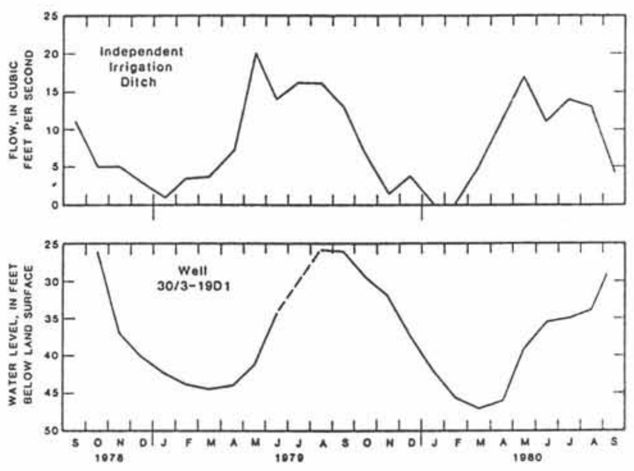


Figure 4. Flow in the Independent Irrigation Ditch and water levels in well 30/3-19D1, September 1978-September 1980.

An estimate of ground-water recharge from irrigation systems was made using diversion data for the Dungeness River and McDonald Creek, estimates of tail waters (water returned from ditches to surface-water bodies), and estimates of evapotranspiration. This resulted in an average rate of ground-water recharge of 70 cfs. Figure 5 shows the relation between estimated recharge and changes in water levels in the water-table aquifer during the period September 1978-September 1980. Water levels in the water-table aquifer show a definite response to increases in recharge from irrigation. Wells in the foothills, where irrigation systems have little or no effect, appear to respond primarily to increases in recharge from precipitation.

Ground-Water Movement

General ground-water flow directions can be inferred from Figure 6, which shows the configuration of the water table for March 1979. Ground-water movement is perpendicular to the water-table contours shown in the figure. Although the altitude of the water table changes seasonally, the general pattern of flow remains constant.

In addition to lateral flow, there is also vertical flow in the ground-water system. Vertical flow occurs between aquifers through the confining beds. Figure 7 shows the general vertical flow directions in the study area. The diagram assumes that the relatively small amount of flow into and out of the bedrock and the undifferentiated unconsolidated deposits does not significantly affect the flow system.

Hydraulic Characteristics of the Aquifers

Knowledge of the hydraulic characteristics of the aquifers and confining beds is necessary in order to evaluate stresses on the ground-water flow system. These characteristics include hydraulic conductivity, transmissivity, specific yield, storage coefficient, and hydraulic connection between streams and the water-table aquifer.

Values of lateral hydraulic conductivity were estimated for the water-table aquifer from specific-capacity data. The data were first adjusted, using the Jacob method (in Bentall, 1963), to account for partial penetration. Then transmissivity values were calculated using the Theis method (in Bentall, 1963). Transmissivity values were divided by saturated thickness to obtain values of lateral hydraulic conductivity.

These values of lateral hydraulic conductivity (calculated for about 500 wells) were plotted on a map of the area, and zones of lateral hydraulic conductivity were outlined. Within each zone, lateral hydraulic conductivity was made equal to the median of all the values in the zone. The median values (13 zones) ranged from 2.1 ft/day (till) to 410 ft/day (alluvium).

Transmissivity values were estimated for the upper artesian aquifer from specific-capacity data. The data were first adjusted, using the Jacob method (in Bentall, 1963), to account for partial penetration. Then transmissivity values were calculated using the Brown method (in Bentall, 1963).

The values of transmissivity (calculated for 46 sites in the upper artesian aquifer) were plotted on a map of the area, and zones of transmissivity were outlined. Within each zone, transmissivity was made equal to the median of all the values in the zone. The median values (four zones) ranged from 800 sq ft/day (toward the foothills) to 60,000 sq ft/day (northeast of Sequim).

Data were available for only three sites in the lower artesian aquifer. The three transmissivity values were of the same order of magnitude as the respective transmis-

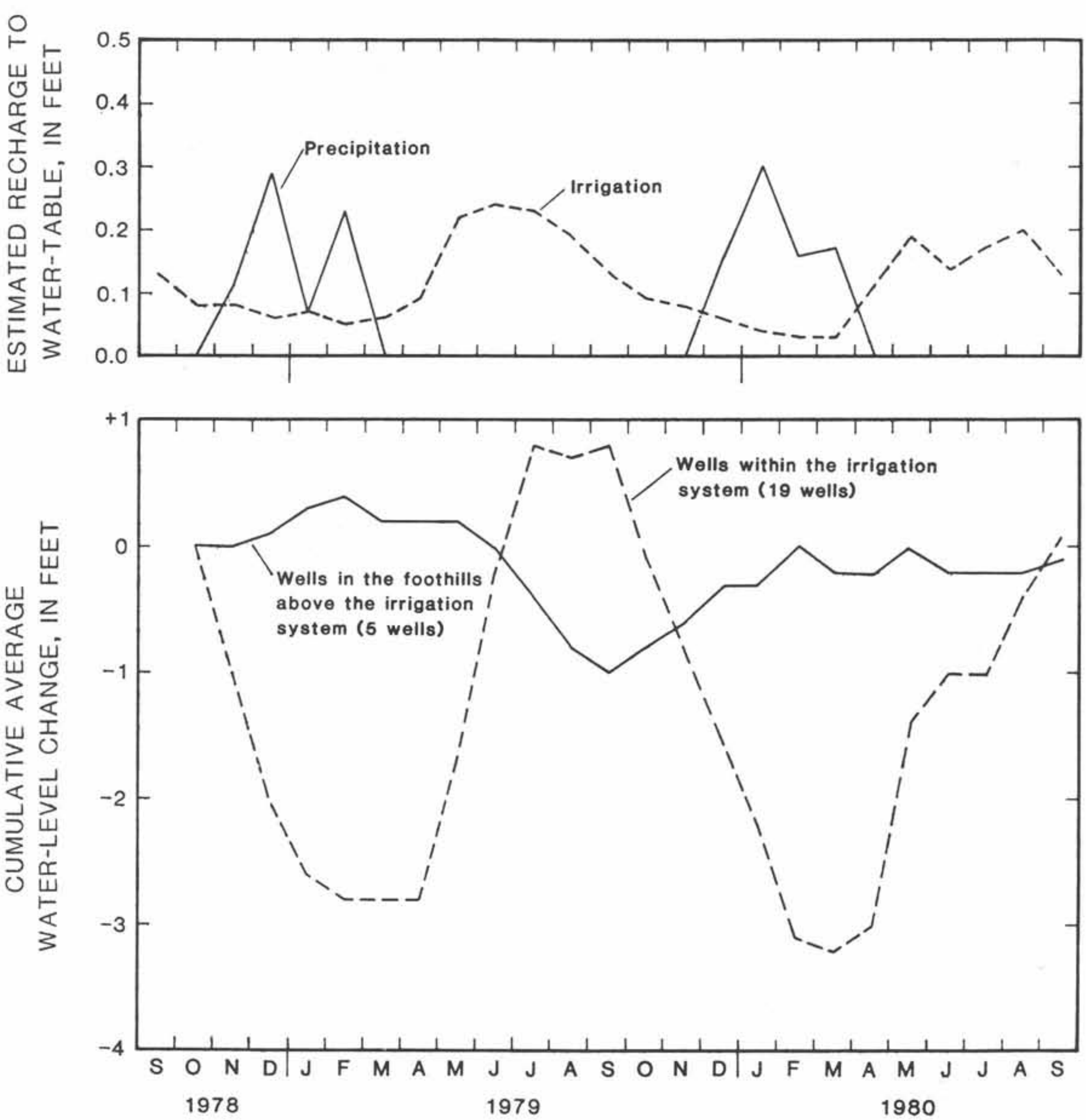


Figure 5. Estimated irrigation and precipitation recharges and changes in water levels in the water-table aquifer.

sivity zones outlined in the upper artesian aquifer. Therefore, the transmissivity distribution in the lower artesian aquifer was assumed to be approximately the same as in the upper artesian aquifer.

The specific yield of the water-table aquifer was determined by using measured water-level changes from mid-March to mid-July 1979 (Figure 8). The change in volume of saturated material represented in the figure is an increase of about 1,400 million cu ft.

Average inflow to the aquifer was estimated to be 96 cfs from mid-March to mid-July 1979. Estimated outflow for the same period was about 80 cfs. The difference in inflow and outflow resulted in an increase of 170 million cu ft of water stored in the water-table aquifer.

The change in the volume of water stored, divided by the change in the volume of saturated material, indicated the average specific yield to be 12 percent.

Storage coefficients for the artesian aquifers were estimated by using a calculation for the expansion of water and assuming that there is no compression of the

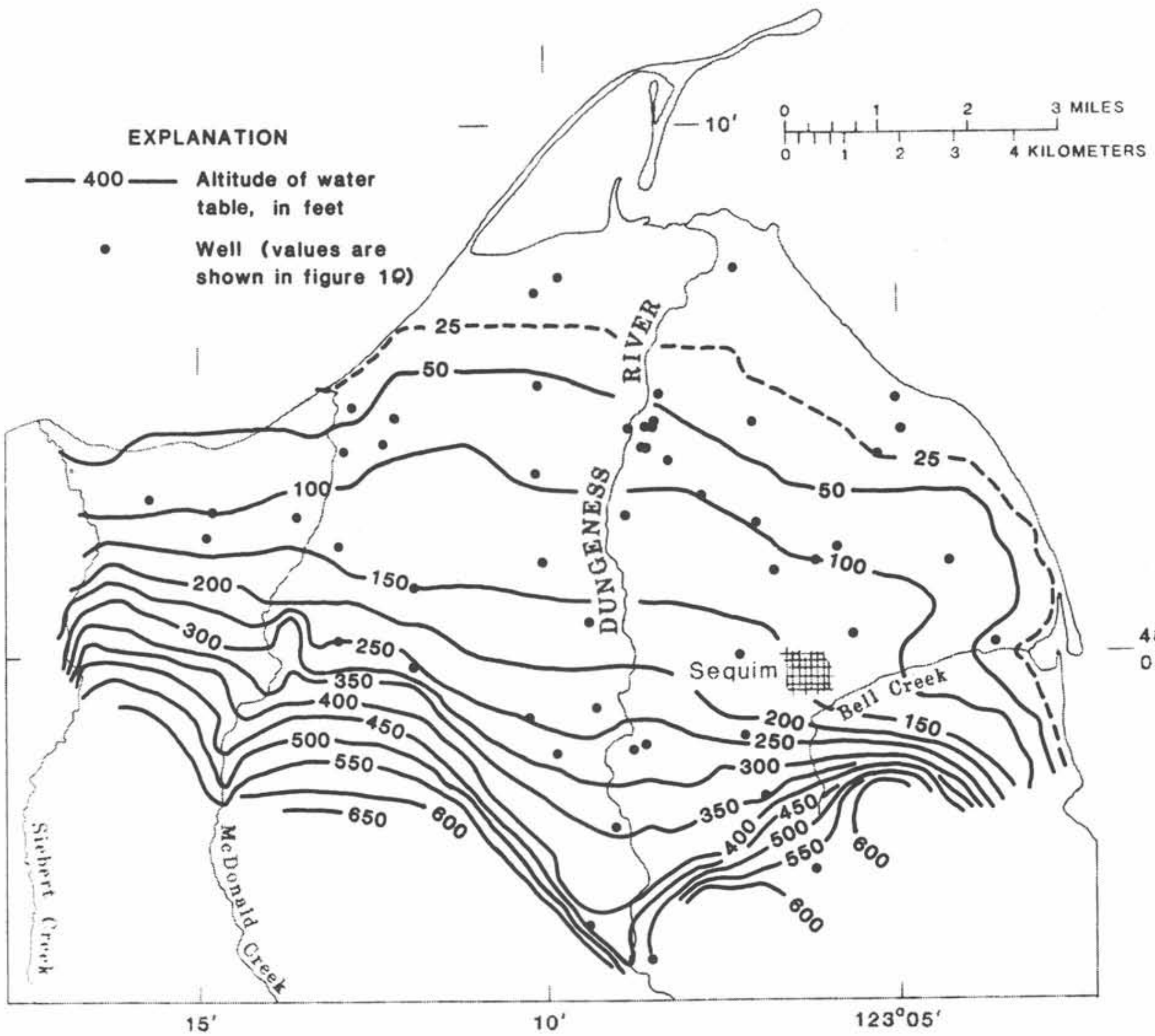


Figure 6. Altitude of the water table in March 1979.

aquifer and release of water from the confining beds. The formula is modified from Jacob (in Lohman, 1979):

$$S = \theta \times \gamma \times b \times \beta \qquad (1)$$

where S = storage coefficient,

θ = porosity,

γ = specific weight per unit area ($0.434 \text{ lb in.}^{-2}\text{ft}^{-1}$),

b = aquifer thickness (ft), and

β = reciprocal of the bulk modulus of elasticity of water ($3.3\times10^{-6} \text{ in.}^2\text{lb}^{-1}$).

Assuming a porosity of 0.2, three zones of storage coefficient were calculated; 7.2×10^{-6}, 2.1×10^{-5}, and 3.6×10^{-5}. The storage coefficient distribution in the lower artesian aquifer was assumed to be the same as in the upper artesian aquifer.

Stream-Aquifer Hydraulic Connection

The Dungeness River loses water to and gains water from the water-table aquifer. Monthly discharge measurements were made at four sites on the river from September 1978 through February 1980. The measured gains and losses were usually less than 10 percent of the total flow in the river. Because the discharge measurements themselves are probably accurate only to within ±5 percent, these directly measured gains and losses can be used only as a general indication of the stream-aquifer hydraulic connection.

Creeks in the study area also lose water to and gain water from the water-table aquifer. Most of these creeks have mean flows of only a few cubic feet per second and probably exchange only small amounts of water with the aquifer.

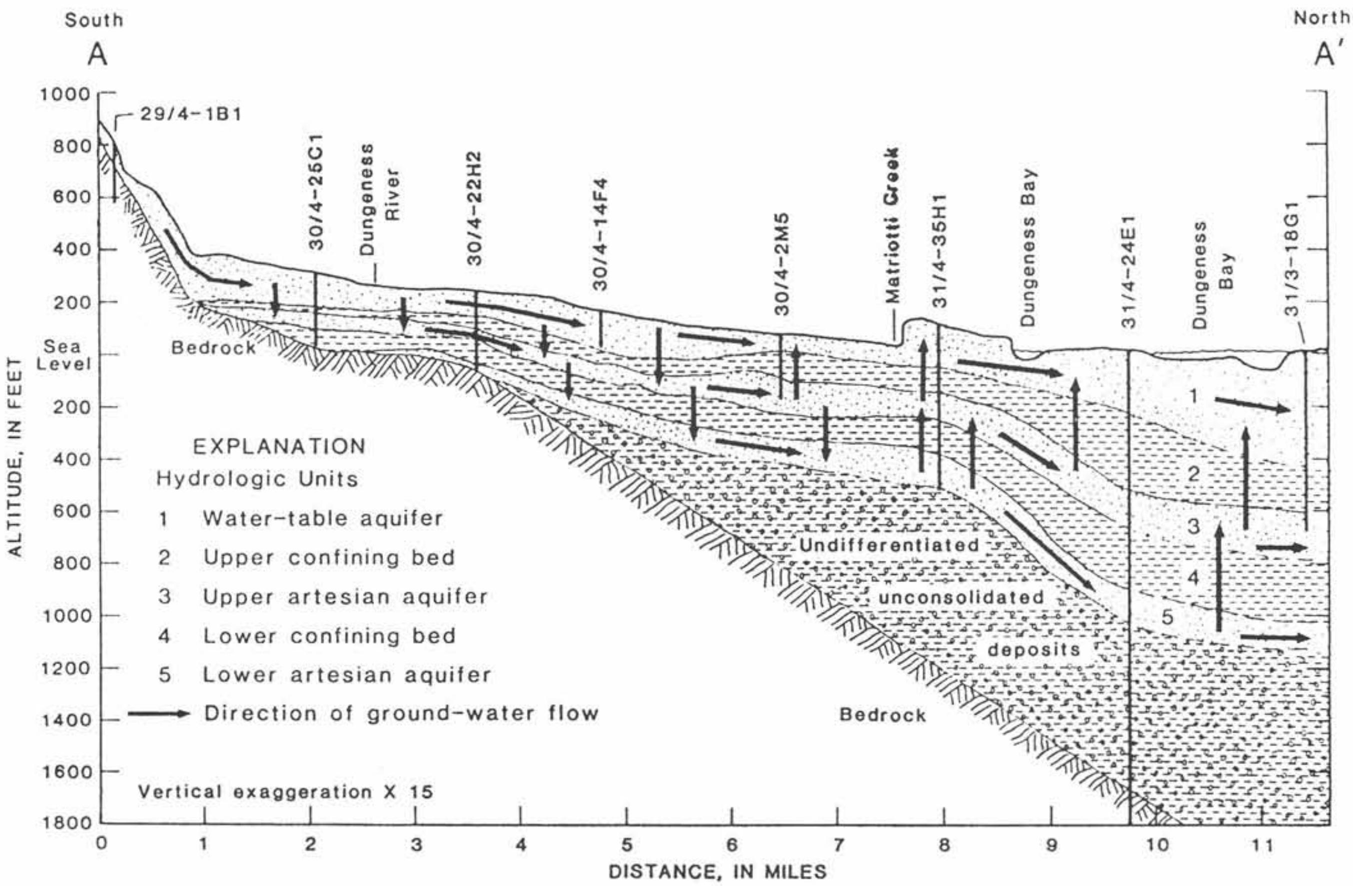


Figure 7. Schematic cross-section of the ground-water system.

DIGITAL GROUND-WATER-FLOW MODEL

A three-dimensional digital ground-water-flow model was used to simulate the movement of ground water in three layers—the water-table, the upper artesian aquifer, and the lower artesian aquifer. The model simulates ground-water flow by solving a set of simultaneous-difference equations using the strongly implicit procedure (Trescott, 1975). Storage and horizontal components of flow in the confining beds were assumed to be insignificant, allowing vertical leakage through the confining beds to be incorporated into the vertical component of the anisotropic hydraulic conductivity of adjacent aquifers. Vertical flow within the aquifers was considered to be insignificant. All vertical flow in the model is through confining beds. The hydraulic connection between streams and the water-table aquifer was simulated using additions to the Trescott model from S. P. Larson (1976).

The northern and eastern boundaries of the model approximate the shoreline, where, during steady-state simulations, each node was assigned a specific head value (constant head) that was based on measured water levels. During some transient simulations these nodes were changed to constant flux (continuous rate of flow) nodes, based on flows calculated by steady-state simulations. The freshwater-seawater interface is probably offshore. The most seaward well, 31/3-18G1 (Figure 1), extends 657 ft below sea level and taps fresh water. No attempt was made to model the freshwater-seawater interface.

The model's western boundary is along Siebert Creek, where each node is a river node in which the river level is held constant but the water level in the aquifer can change.

The model's southern boundary roughly approximates the 600-ft topographic contour. The water-table aquifer extends southward beyond the model boundary. The use of constant-head nodes along the southern boundary, based on measured water levels, allows the model to calculate the ground-water inflow from the portion of the water-table aquifer outside of the model. The 600-ft level was selected as the farthest position southward where data were sufficient to accurately simulate the water-table aquifer.

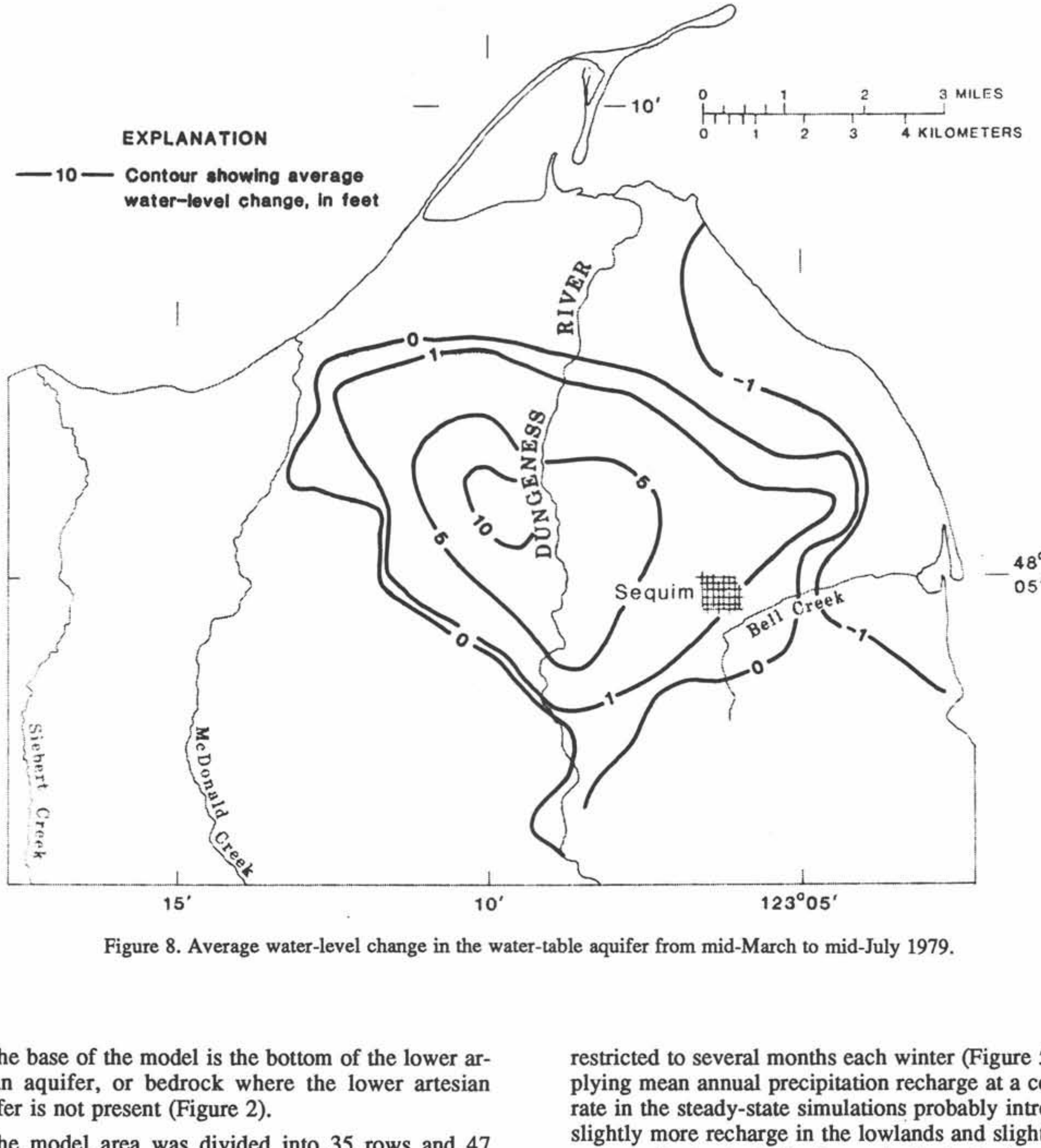


Figure 8. Average water-level change in the water-table aquifer from mid-March to mid-July 1979.

The base of the model is the bottom of the lower artesian aquifer, or bedrock where the lower artesian aquifer is not present (Figure 2).

The model area was divided into 35 rows and 47 columns of square grid blocks measuring one-quarter of a mile on a side.

Mean annual recharge from precipitation applied at a continuous average rate of 15.2 cfs (precipitation recharge) was used for both steady-state and transient simulations. The majority of recharge from precipitation occurs in the southern foothills of the modeled area. In the foothills, the low permeability of the materials above the water table (mostly till) slows infiltration of recharge from precipitation to the water-table aquifer. This results in recharge that is generally continuous, even though the periods of excess precipitation are restricted to several months each winter (Figure 5). Applying mean annual precipitation recharge at a constant rate in the steady-state simulations probably introduced slightly more recharge in the lowlands and slightly less recharge in the foothills than actually took place at the time simulated, March 1979.

The average rate of recharge during March 1979 from the irrigation system (32.3 cfs) was calculated by subtracting estimated tail waters (2.4 cfs) from measured diversions (34.7 cfs). Evapotranspiration and consumptive uses in March were assumed to be insignificant. The areal distribution of the recharge was determined by calculating leakages to the aquifer along each main ditch and assigning the calculated rate of leakage to each grid block through which the main ditch passes. Any excess recharge in each irrigation district is assumed to be leakage from the numerous secondary ditches and laterals and was applied evenly over the entire district. The method of calculating leakage from the main ditches to the aquifer was as follows:

$$Q_L = (k_D (h_D - h_A) A)/m \qquad (2)$$

where Q_L = rate of leakage from irrigation ditch to water-table aquifer, L^3/T,

k_D= vertical hydraulic conductivity of the bed of the ditch, L/T,

m = thickness of the bed of the ditch, L,

h_D = elevation of the water surface in the ditch, L,

h_A = elevation of the head in the aquifer, L, or if h_A is below the bottom of the bed of the ditch, then the elevation of the bottom of the bed of the ditch is used, and

A = area of the bed of the ditch (wetted perimeter), L^2.

The ratio k_D/m is called the leakage coefficient. This parameter probably varies from ditch to ditch and within each ditch. However, a single value for the leakage coefficient, 1 (ft/day)/ft, was assumed for all locations and produced values of leakage that fit the leakage rates calculated from the diversion measurements and estimates of tail waters.

Most leakage from the irrigation system, at least in March, occurs from the ditch system and not from water actually spread on the fields. During the height of the irrigation season, a greater proportion of the recharge probably occurs as leakage from excess water applied to fields, but it probably still represents a small portion of the total leakage.

The leakage between the water-table aquifer and the Dungeness River and eight creeks is calculated by the model using equation 2, substituting parameters for the river or creeks in place of the ditch parameters. The altitude of the river bed of the Dungeness was obtained from a flood study by the U.S. Department of Housing and Urban Development (1980). The river-bed elevations of the creeks were obtained from 1:24,000-scale U.S. Geological Survey topographic maps. The area of the bed and the depth of water for each river node were obtained from the data collected during March 1979 at the measurement site nearest each node along the river and creeks.

The leakage coefficient for the river nodes was initially assumed to be 1 (ft/day)/ft. During calibration of the steady-state model various leakage coefficients from 0.1 to 100 (ft/day)/ft were tried. The results of these trial runs were compared to measured values of water-table elevation and estimated leakage from the Dungeness River (Figure 9). The value of leakage coefficient that gave the best agreement with measured heads and estimated leakage was 2.0 (ft/day)/ft. This value was used for all steady-state and transient simulations.

All parts of the Dungeness River and Siebert and McDonald creeks which pass through the modeled area were represented by river nodes. The six other creeks were represented by river nodes only along their lowermost 1 to 1.5 mi. These creeks receive almost all of their flow (from ground water and the irrigation system) along the portions represented in the model.

The constant heads used in the model were estimated from water levels measured in March 1979. For the water-table aquifer, the large number of available measured heads (Figure 6) resulted in constant head values that were quite accurate. For the artesian aquifers, relatively few values of head were available along the coastline. Constant-head boundaries in the artesian aquifers were assigned on the basis of the few available measured heads and were adjusted during model calibration.

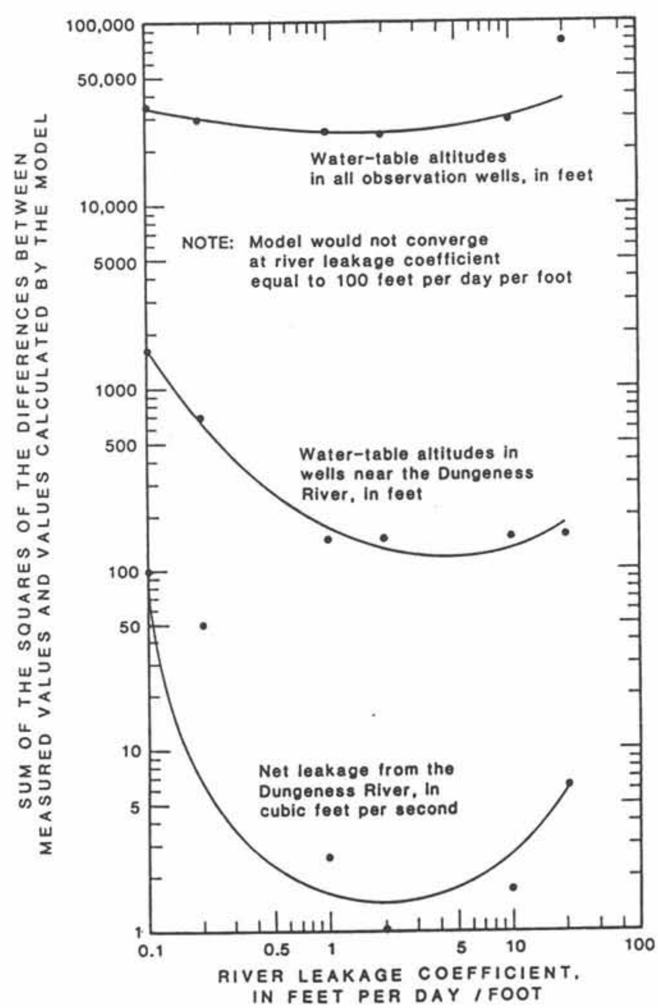


Figure 9. Comparison of measured water-table altitudes and Dungeness River leakage to values computed by the model using various river leakage coefficients.

The altitude of the bottom of the water-table aquifer was constructed using drillers' logs. These data were entered into the model. An average value was used for the area enclosed by each grid block.

Values of hydraulic conductivity, transmissivity, specific yield, and storage coefficient that were used in the model were calculated by methods discussed above. The distribution of transmissivity and storage coefficient were assumed to be the same for both artesian aquifers.

Vertical leakage through the confining beds was simulated by estimating a vertical leakage coefficient that was based on the vertical hydraulic conductivity and the length of the flow path (confining bed thickness). Vertical leakage is computed as the product of the head difference between adjacent layers and the vertical leakage coefficient. Thicknesses of confining beds were determined from drillers' logs. The value of vertical hydraulic conductivity of the confining beds used in the model was $5x10^{-3}$ ft/day. This value was determined during model calibration as the one yielding the best simulation of heads in all three aquifers. The value fits the range given by Johnson (1963) for laboratory samples of clay to silt size ($1x10^{-5}$ ft/day to 1 ft/day).

In March 1979, pumpage from the ground-water system was insignificant. Total pumpage, virtually all for domestic use, was estimated to be about 2 cfs. Most of this water was pumped from individual domestic wells and small public-supply systems (20 homes or less). Public supply for Sequim was obtained from a modified infiltration gallery along the Dungeness River outside of the modeled area. The only significant pumpage for March (0.05 cfs or greater within a single grid block) was for the Sunland Development (estimated at 0.13 cfs), and was obtained from one well tapping the upper artesian aquifer. This was the only well represented in the steady-state simulations. For the transient simulations, pumping (annual average rate) was greater, but was still insignificant when compared with the average rate of flow in the ground-water system. Total pumpage in the transient simulations was 1.6 cfs.

Steady-State Simulation

Average conditions existing during March 20-31, 1979, were used for steady-state calibration of the model. This period was selected for calibration because (1) water levels were generally stable; (2) flow in the Dungeness River was generally constant; (3) precipitation was insignificant (0.12 in.); (4) evapotranspiration was minimal; and (5) essentially all irrigation water was restricted to the major ditch systems (no field irrigation).

Calibration was accomplished by holding all model input constant except hydraulic conductivity of the water-table aquifer, transmissivity, vertical leakage coefficients, and river leakage coefficients. Hydraulic conductivity in the water-table aquifer and transmissivity in the artesian aquifers were adjusted only by changing the boundaries of the zones of conductivity and transmissivity. In all cases, the value assigned to a zone of hydraulic conductivity or transmissivity was the median value derived from all specific-capacity tests in that zone. The model proved to be insensitive to the value of vertical leakage coefficient, showing significant head changes only when the tested value differed by two orders of magnitude or more (from the final value used, $5x10^{-3}$ ft/day). The river-leakage-coefficient value was adjusted during calibration (Figure 9) to obtain the best reproduction of heads in the water-table aquifer and measured leakage in the Dungeness River.

The reliability of the calibration can be checked by comparing measured heads and river leakages with heads and leakages calculated by the model. Comparisons of measured and calculated heads are shown in Figure 10 (water-table aquifer) and Table 1 (upper artesian aquifer). No measured water levels were available for the lower artesian aquifer. Well 30/4-9L2, open to the undifferentiated deposits beneath the lower artesian aquifer, had a water-level altitude of 54.1 ft in March 1979, which was probably slightly less than the water-level altitude in the lower artesian aquifer at the same site. The model-calculated water-level altitude was 58.1 ft.

Average measured river leakage from the Dungeness River gage to Dungeness (near the mouth of the river) for March 20-31, 1979, was 20 cfs. Leakage calculated by the model was 19 cfs. The measured leakage includes approximately 1.25 mi of river not simulated in the model but believed to be insignificant with regard to the total leakage.

Meadowbrook Creek (the only outflowing creek not significantly affected by irrigation tail waters) had a measured discharge of 5.2 cfs on March 16, 1979. Basi-

Table 1. Comparison of measured and model-calculated water-level altitudes in the upper artesian aquifer, March 1979

	Water-level altitude (ft)		
Well no.	(1) Measured	(2) Calculated by model	Percent difference $\frac{(2)-(1)}{(1)} \times 100$
30/3-8J3	42.1	43.0	+2
-8M1	42.2	48.8	+16
-16C1	37.4	41.8	+12
-17A1	44.7	49.0	+10
30/4-3Q1	100.4	67.3	-33
-7N1	68.7	62.8	-9
-22J2	152.1	145.4	-4
-23E3	118.1	138.8	+18
-25C1	271.4	269.1	-1

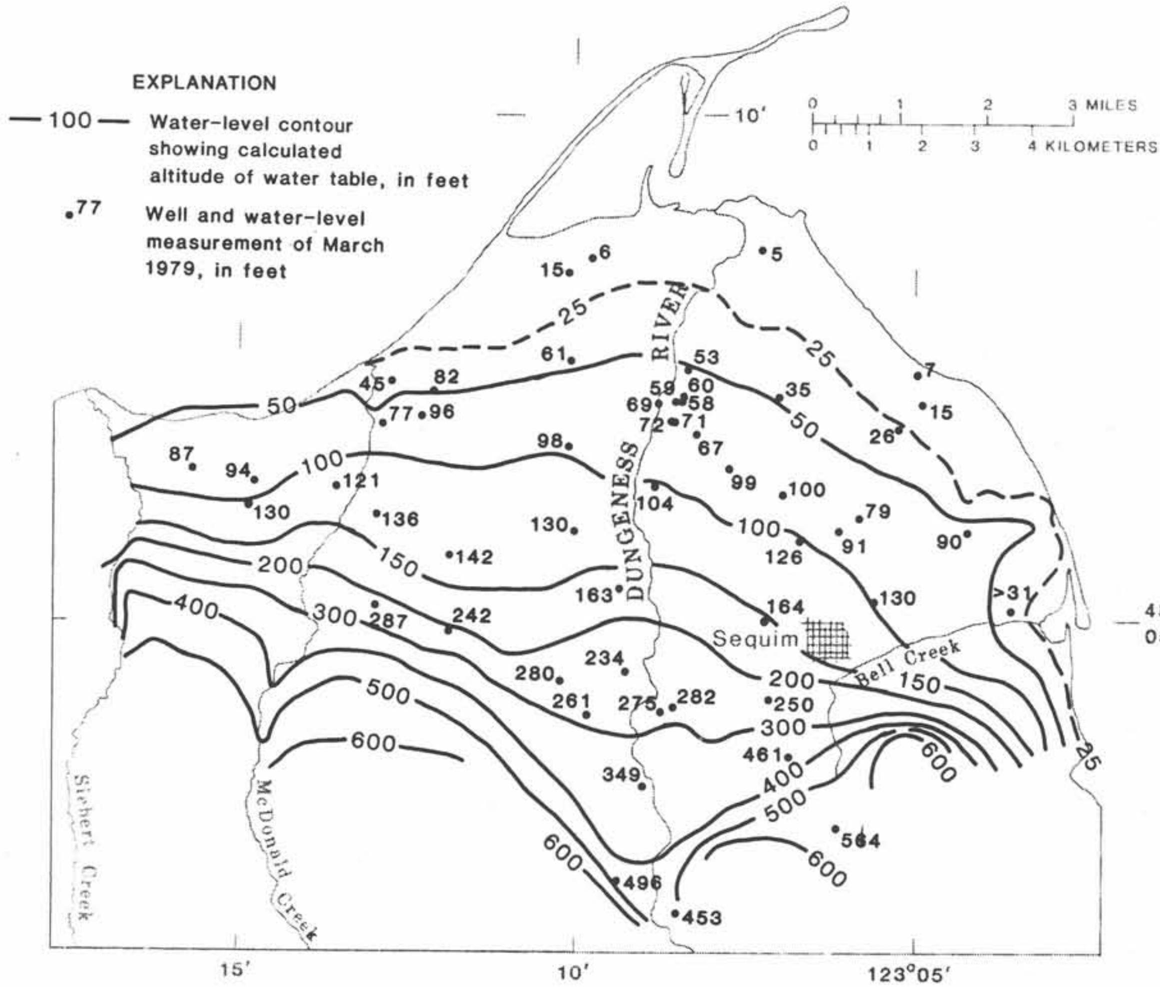


Figure 10. Comparison of measured and model-calculated water-level altitude in the water-table aquifer, March 1979.

cally all flow in Meadowbrook Creek was leakage from the water-table aquifer. Leakage from the aquifer to the creek was calculated to be 5.0 cfs by the model.

The water budget of the ground-water system for the modeled area, as calculated in the steady-state calibration, is shown in Figure 11. Total calculated flow through the ground-water system was 82 cfs, including 32.3 cfs, or about 40 percent of the total flow, from irrigation leakage. During the prime irrigation season (April-September) irrigation leakage probably represents an even greater percentage of the total flow (Figure 5).

Transient Simulation

The present trend in land use in the study area may lead to eventual abandonment of the irrigation system. This would cause ground-water conditions to return gradually to conditions similar to those existing before construction of the irrigation system. Because data are not available for the period prior to irrigation, a transient model was constructed to show the potential effects of no recharge from irrigation.

Seasonal fluctuations of the ground-water system were considered to be of secondary interest and importance. It was assumed that the gross changes caused by termination of the irrigation system would be at least several times greater than the seasonal fluctuation of water levels (presently about 4 ft, Figure 5).

The transient model used basically the same input as the steady-state model, except that no recharge from the irrigation systems was included in the transient model and the storage coefficient was added. Starting heads and flow rates in the transient model are the heads and flow rates calculated by the steady-state model.

The transient model was run using two different sets of boundary conditions. One set (constant-head condition) used exactly the same boundaries as in the steady-state model. In the other set (constant-flux condition) the constant-head boundary along the coastline was

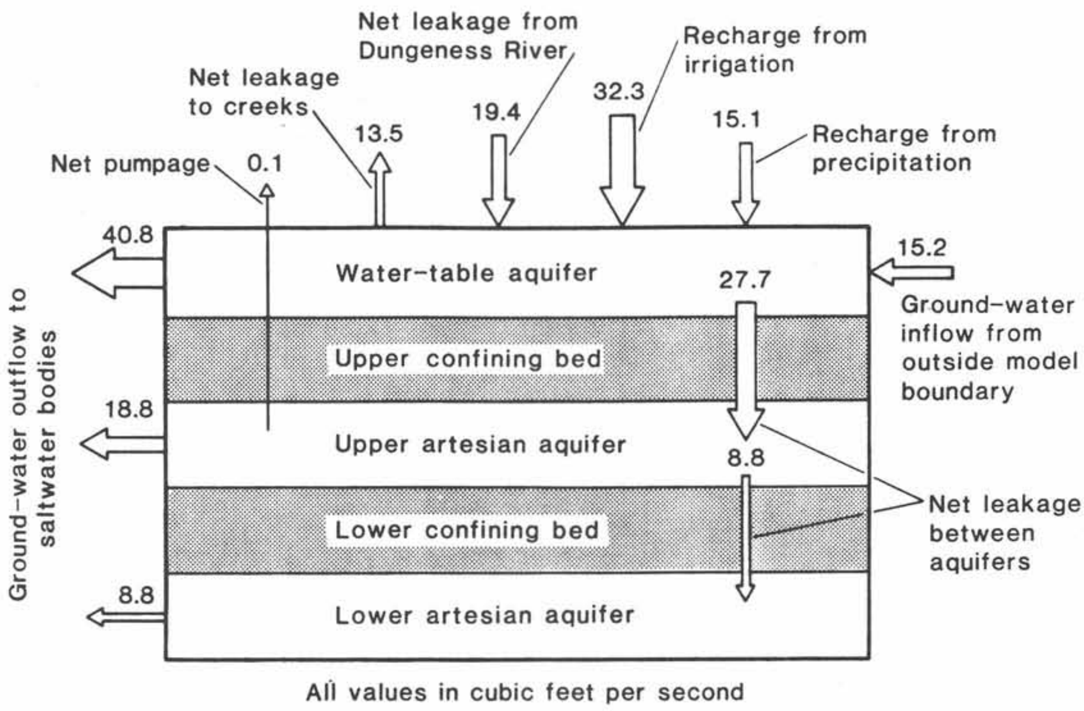


Figure 11. Ground-water budget for March 1979, calculated by steady-state model.

changed to a constant rate of outflow as calculated by the steady-state model. The constant-head condition led to simulations in which calculated drawdowns were generally somewhat less than what would probably occur, while the constant-flux condition produced calculated drawdowns that were generally somewhat greater than what would probably occur.

Model simulations indicate that an abrupt termination of the irrigation system would cause water levels to decline significantly, reaching a new equilibrium in 10 to 20 yr (Figure 12). Figure 12 represents the decline in water level (drawdown) at a point in the water-table aquifer where the calculated drawdowns would be greatest. All transient simulations were run for 20-yr periods to be certain that the effects caused by no recharge from irrigation would stabilize.

Drawdowns that would be caused by termination of the irrigation system were calculated for each aquifer for various combinations of boundary conditions and river leakage. In each case, the calculated drawdowns are more severe for the constant-flux condition than for the constant-head condition. Actual drawdowns would lie somewhere between the two extremes. The greatest impact would be in the water-table aquifer (Figures 13 and 14) where drawdowns would probably average about 20 ft, indicating that some parts of the aquifer could be completely unsaturated and several hundred wells could be dry or nearly so. The artesian aquifers would be less severely impacted with probable average drawdowns of about 10 ft. The artesian aquifers would be completely saturated, but the lowered heads would result in greater pumping costs.

Some potential for seawater intrusion could result from termination of the irrigation system. In some coastal areas, when using constant-flux conditions, calculated heads in the water-table aquifer were below sea

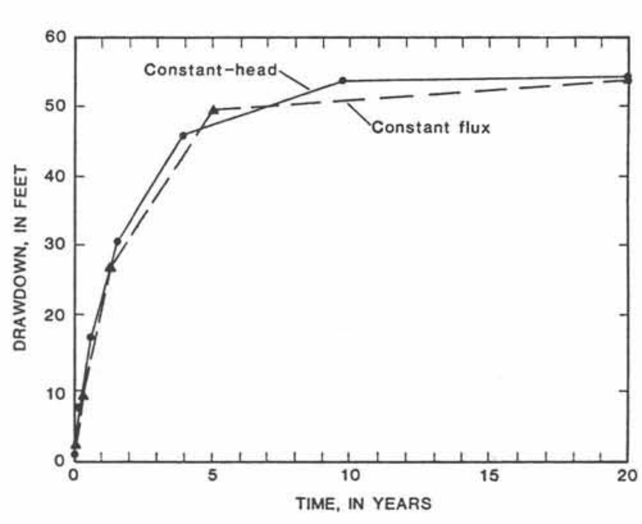


Figure 12. Drawdown at node 26,34 in the water-table aquifer, computed by the model assuming no irrigation and river leakage coefficient of 2.0 (ft/day)/ft.

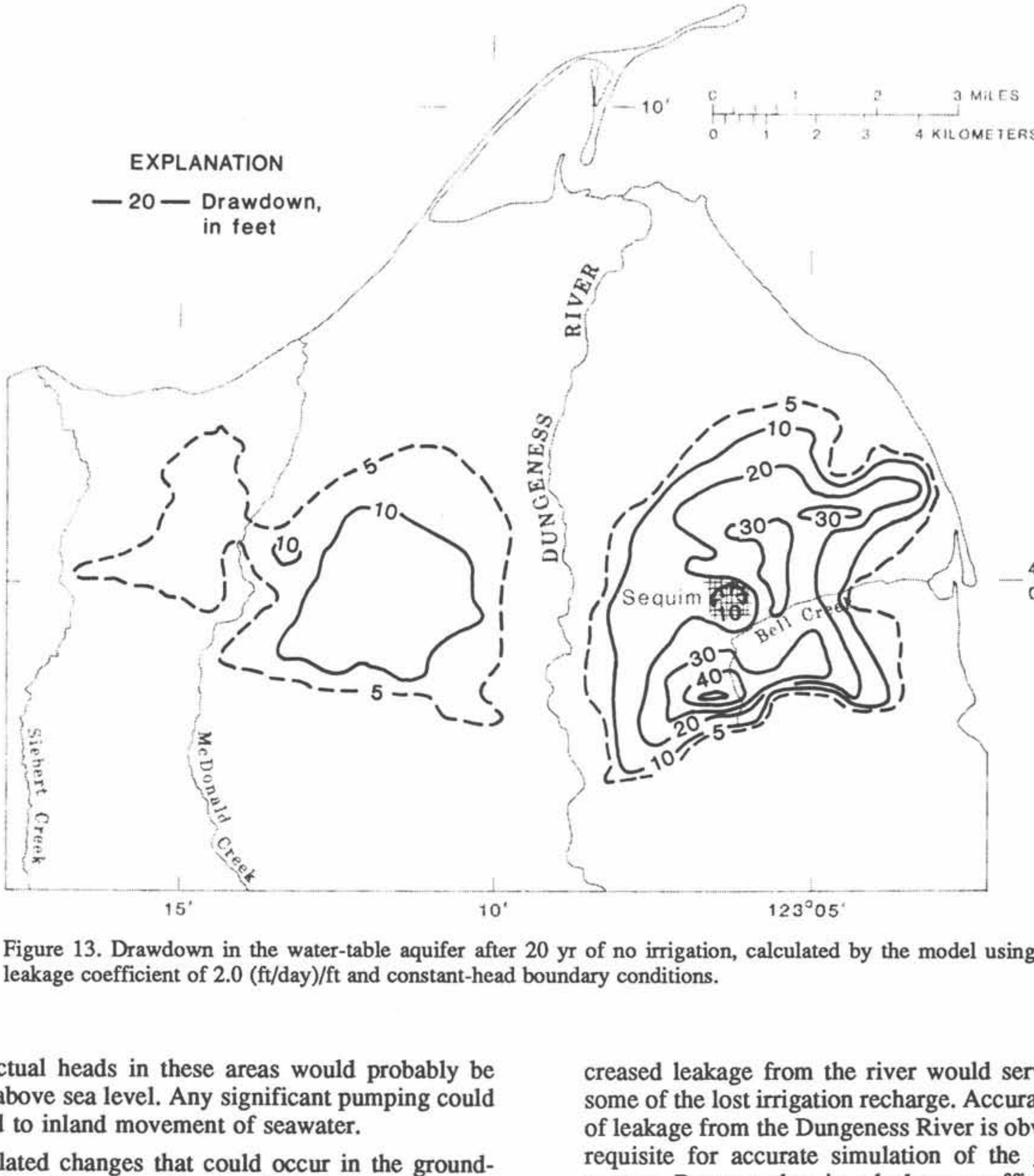


Figure 13. Drawdown in the water-table aquifer after 20 yr of no irrigation, calculated by the model using river leakage coefficient of 2.0 (ft/day)/ft and constant-head boundary conditions.

level. Actual heads in these areas would probably be slightly above sea level. Any significant pumping could then lead to inland movement of seawater.

Calculated changes that could occur in the ground-water budget due to termination of the irrigation system are shown in Table 2. Total flow through the ground-water system could be reduced by 15 to 30 percent. Net leakage from the Dungeness River could increase by 40 to 80 percent. The creeks, which have a net inflow from the ground-water system in the steady-state model, could have a net loss to the ground-water system. This could mean that most of the small creeks would be dry or nearly dry most of the time.

The calculated drawdowns in the water-table aquifer (Figures 13 and 14) and the calculated changes in the ground-water budget (Table 2) indicate that the Dungeness River would be an important factor if the irrigation system were terminated. The calculated drawdowns are very small near the Dungeness River, showing that increased leakage from the river would serve to replace some of the lost irrigation recharge. Accurate simulation of leakage from the Dungeness River is obviously a prerequisite for accurate simulation of the ground-water system. Because the river-leakage coefficient was not determined independent of the model, the model was run using leakage coefficients one order of magnitude greater than and less than the "ideal" coefficient of 2.0 (ft/day)/ft (Figure 9).

The effects of changing the river-leakage coefficient can be seen in Table 3 and Figures 15 and 16. Increasing the coefficient by a factor of ten does not significantly change the computed drawdowns. However, decreasing the coefficient by a factor of ten drastically increases drawdown. The high and "ideal" values of river leakage coefficient (which assume ratios of vertical hydraulic conductivity of the river bed to the horizontal conductivity of the underlying aquifer that are about 1/20 and 1/200) are reasonable values to ex-

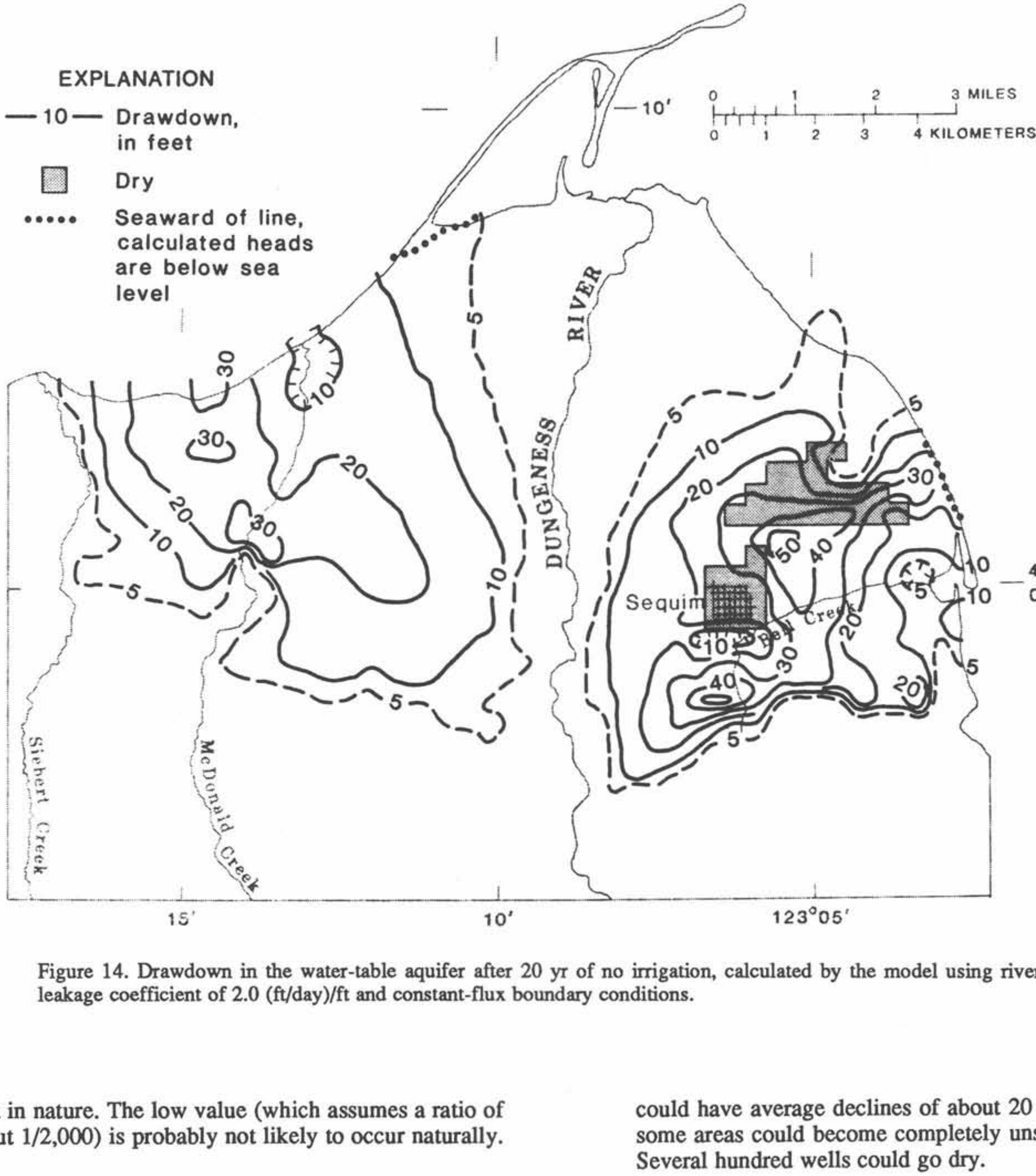


Figure 14. Drawdown in the water-table aquifer after 20 yr of no irrigation, calculated by the model using river leakage coefficient of 2.0 (ft/day)/ft and constant-flux boundary conditions.

pect in nature. The low value (which assumes a ratio of about 1/2,000) is probably not likely to occur naturally.

SUMMARY AND CONCLUSION

(1) The digital model simulated the ground-water flow system within the accuracy of the input data.

(2) The model confirms that leakage from the irrigation system is the largest source of recharge to the ground-water system. The leakage occurs primarily from the ditch system, not from water actually applied to fields.

(3) Termination of the irrigation system would lead to lower heads throughout the ground-water system. The ground-water levels in the water-table aquifer could have average declines of about 20 feet, and some areas could become completely unsaturated. Several hundred wells could go dry.

(4) Understanding the relation between the Dungeness River and the ground-water system is critical to predicting the possible effects of termination of the irrigation system. The simulations indicate that the lost ground-water recharge from irrigation would be partially replaced by increased leakage from the river. The magnitude of the recharge from the river would depend primarily on the river leakage coefficient. Because this coefficient is not directly measurable, a range of values was used in the model to indicate a range of possible water levels resulting from termination of irrigation.

Table 2. Comparison of calculated ground-water budgets from steady-state model and transient model after 20 yr of no irrigation, with river leakage coefficient of 2.0 (cu ft/day)/ft

	Calculated flow rate (cfs)		
		Transient model	
Ground-water flow	Steady-state model	Constant-head condition	Constant-flux condition
Inflow (all to water-table aquifer)			
Ground water (from uplands)	15.2	16.2	15.7
Precipitation recharge[1]	15.1	15.0	14.7
Irrigation recharge	32.3	--	--
Dungeness River net leakage	19.4	7.1	34.2
Net leakage from creeks	--	1.1	5.1
Total	82.0	59.4	69.7
Net flow between aquifers			
Water table to upper artesian	27.7	21.9	27.9
Upper artesian to lower artesian	8.8	7.7	8.8
Outflow			
Net leakage to creeks	13.5	--	--
Net pumpage			
Water-table aquifer	--	1.2	1.2
Upper artesian aquifer	0.1	0.3	0.3
Lower artesian aquifer[2]	--	.0	.0
Ground water (all at shorelines)			
Water-table aquifer	40.8	36.4	40.8
Upper artesian aquifer	18.8	13.9	18.8
Lower artesian aquifer	8.8	7.7	8.8
Total	82.0	59.5	69.9
Change in storage (inflow-outflow)	--	-0.1	-0.2

[1] Precipitation recharge in all three cases is input as 15.1 cfs. In transient model, when a node goes dry, the precipitation recharge at that site is changed to zero.

[2] Pumping rate input to the transient model is actually 0.05 cfs; the 0.0 results from rounding off.

Table 3. Comparison of drawdowns and selected ground-water flow rates computed by the model using various river leakage coefficients

River leakage coefficient[2]	Shoreline boundary condition	Drawdown (ft) after 20 years of no irrigation, computed by model[1] — Water table aquifer[3], Node 3, 25	Water table aquifer[3], Node 13, 27	Water table aquifer[3], Node 19, 32	Water table aquifer[3], Node 26, 34	Upper artesian aquifer[4], Node 3, 25	Upper artesian aquifer[4], Node 13, 27	Upper artesian aquifer[4], Node 29, 28	Lower artesian aquifer[4], Node 3, 25	Lower artesian aquifer[4], Node 13, 17	Lower artesian aquifer[4], Node 24, 26	Calculated flow rate, (cfs) — Net leakage from Dungeness River	Net leakage from creeks	Net ground-water flow
0.2	Constant flux	24.00	16.04	31.00 (dry)	56.99	37.81	36.21	9.59	39.27	38.79	30.30	23.6	0.9	55.1
2.0	Constant flux	2.52	.74	17.56	54.47	17.90	17.28	1.01	19.42	19.32	12.71	34.2	5.1	69.7
2.0	Constant head	.03	.52	17.22	54.88	.13	2.84	.99	.06	1.26	3.60	27.1	1.1	59.4
20.0	Constant head	.00	1.00	16.53	54.76	.10	2.45	.00	.05	1.05	2.83	32.1	-2.1	61.7

[1] For leakage of 0.2, drawdown and flow rates are computed after 10 yr of no irrigation. The model would not compute beyond 10 yr because of an excess number of dry nodes.
[2] Equals vertical hydraulic conductivity of the river bed divided by the thickness of the river bed, in (ft/day) ft.
[3] Nodes are located near shoreline, near Dungeness River, near center of aquifer (relatively unaffected by Dungeness River), and in upland area, respectively.
[4] Nodes are located near shoreline, near center of aquifer, and at farthest upland extent of aquifer, respectively.

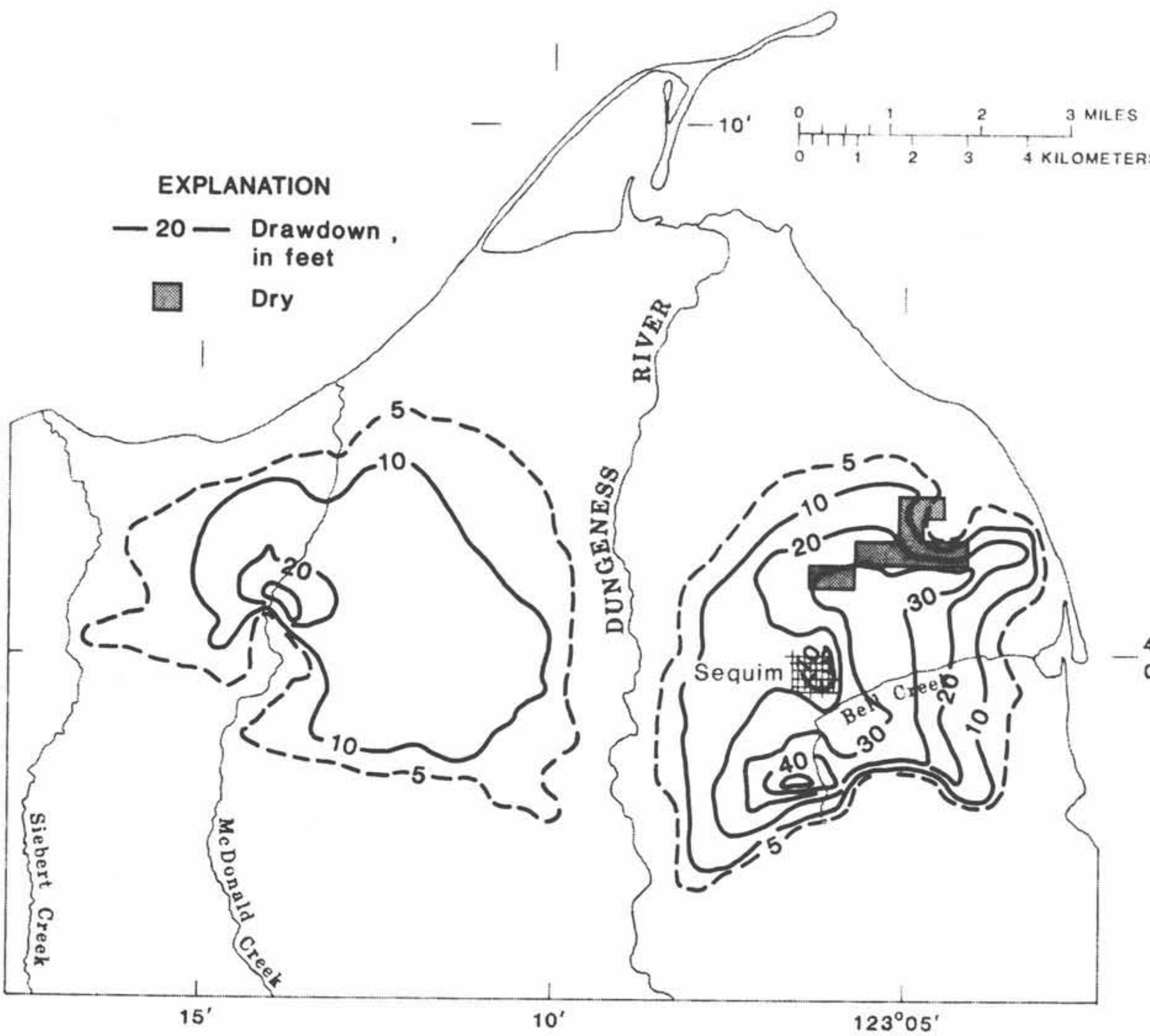


Figure 15. Drawdown in the water-table aquifer after 20 yr of no irrigation, calculated by the model using river leakage coefficient of 20 (ft/day)/ft and constant-head boundary conditions.

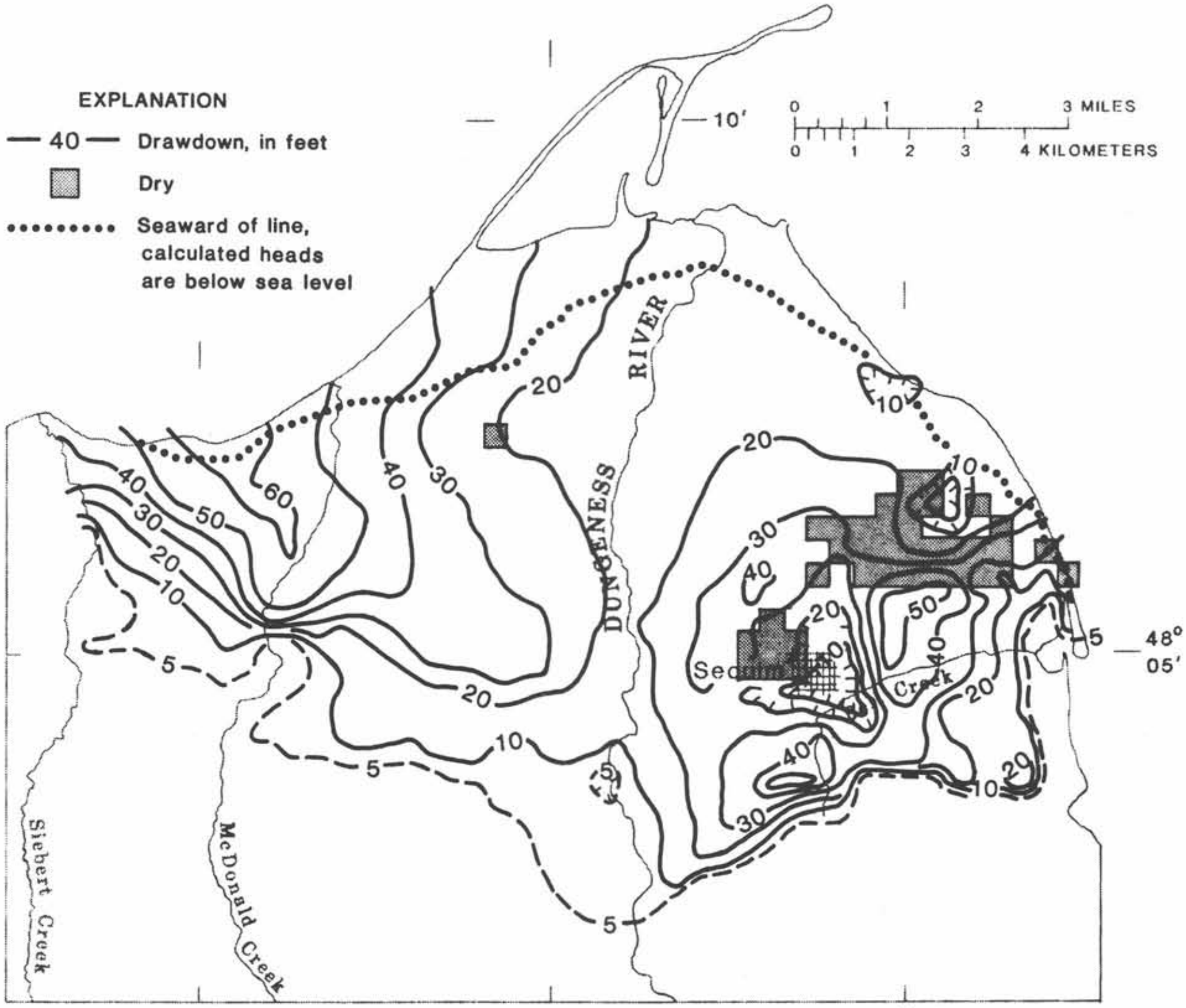


Figure 16. Drawdown in the water-table aquifer after 10 yr of no irrigation, calculated by the model using river leakage coefficient of 0.2 (ft/day)/ft and constant-flux boundary conditions. The model would not run beyond 10 yr due to the large number of dry nodes.

REFERENCES

Bentall, R., 1963, *Methods of Determining Permeability, Transmissivity, and Drawdown*: U.S. Geological Survey Water-Supply Paper 1536-I, pp. 272-282 and 332-340.

Dion, N. P. and Sumioka, S. S., 1984, *Seawater Intrusion into Coastal Aquifers in Washington, 1978*: Washington Department of Ecology Water-Supply Bulletin 56, Olympia, WA, 13 p., 14 plates.

Drost, B. W., 1983, *Impact of Changes in Land Use on the Ground-Water System in the Sequim-Dungeness Peninsula, Clallam County, Washington*: U.S. Geological Survey Water-Resources Investigations Report 83-4094, 61 p.

Drost, B. W., 1986, *Water Resources of Clallam County, Washington: Phase 1 Report*: U.S. Geological Survey Water-Resources Investigations Report 83-4227, 263 p., 5 plates.

Grimstad, P. and Carson, R. J., 1981, *Geology and Ground-Water Resources of Eastern Jefferson County, Washington*: Washington Department of Ecology Water-Supply Bulletin 54, Olympia, WA, 125 p.

Johnson, A. I., 1963, *Application of Laboratory Permeability Data*: U.S. Geological Survey open-file report (unnumbered), 34 p.

Keeting, V., 1976, *Dungeness–The Lure of a River*: Sequim Bicentennial History Book Committee, 190 p.

Larson, S. P., 1976, written communication, U.S. Geological Survey, Reston, VA.

Lohman, S. W., 1979, *Ground-Water Hydraulics*: U.S. Geological Survey Professional Paper 708, 70 p., 9 plates.

National Oceanic and Atmospheric Administration, 1974-1979, *Climatological Data, Washington*: National Oceanic and Atmospheric Administration, Vols. 78-83.

Noble, J. B., 1960, *A Preliminary Report on the Geology and Ground-Water of the Sequim-Dungeness Area, Clallam County, Washington*: Washington Department of Conservation Division of Water Resources Water-Supply Bulletin 11, Olympia, WA, 43 p.

Noble, J. B. and Balmer, D. K., 1980, Hydrologic analysis of proposed plat for Carlsborg Mill Village, Clallam County, Washington. In *Draft Environmental Impact Statement, Carlsborg Mill Village, Clallam County, Washington*: J. J. Sleavin and Associates, Inc., Tacoma, WA, 69 p.

Othberg, K. L. and Palmer, P., 1980a, *Preliminary Surficial Geologic Map of the Carlsborg Quadrangle, Clallam County, Washington*: Washington Division of Geology and Earth Resources Open-File Report 79-20, Olympia, WA, 1 sheet, scale 1: 24,000.

Othberg, K. L. and Palmer, P., 1980b, *Preliminary Surficial Geologic Map of the Dungeness Quadrangle, Clallam County, Washington*: Washington Division of Geology and Earth Resources Open-File Report 79-17, Olympia, WA, 3 p., 1 plate, scale 1:24,000.

Othberg, K. L. and Palmer, P., 1980c, *Preliminary Surficial Geologic Map of the Sequim Quadrangle, Clallam County, Washington*: Washington Division of Geology and Earth Resources Open-File Report 79-18, Olympia, WA, 4 p., 1 plate, scale 1:24,000.

Tabor, R. W. and Cady, W. M., 1978, *Geologic Map of the Olympic Peninsula, Washington*: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000.

Trescott, P. C., 1975, *Documentation of Finite-Difference Model for Simulation of Three-Dimensional Ground-Water Flow*: U.S. Geological Survey Open-File Report 75-438, 103 p.

U.S. Department of Agriculture, 1970, *Irrigation Water Requirements*: U.S. Soil Conservation Service Engineering Division Technical Release No. 21, 79 p.

U.S. Department of Commerce, 1965-1973, *Climatological Data, Washington*: U.S. Department of Commerce, Vols. 69-77.

U.S. Department of Housing and Urban Development, Federal Insurance Administration, 1980, *Flood Insurance Study, Clallam County, Washington*: U.S. Department of Housing and Urban Development, 45 p.

U.S. Weather Bureau, 1920-1965, *Climatological Data, Washington*: U.S. Weather Bureau, Vols. 24-69.

U.S. Weather Bureau, 1965, *Mean Annual Precipitation, 1930-57, State of Washington*: U.S. Soil Conservation Service Map M-4430, 1 sheet.

Walters, K. L., 1971, *Reconnaissance of Seawater Intrusion along Coastal Washington, 1966-68*: Washington Department of Ecology Water-Supply Bulletin 32, Olympia, WA, 208 p.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Chambers Creek Tunnel Dewatering and Impact on Ground-Water Users near Tacoma

LORI J. HERMAN
Hart-Crowser & Associates,Inc.

INTRODUCTION

The Chambers Creek tunnel was constructed south of Tacoma in Pierce County, Washington. The tunnel, which is approximately 2-1/2 mi long and 9 ft in diameter, was constructed as an interceptor for conveying sewage from several service-area trunk lines to a treatment plant just east of Puget Sound near Tacoma. Approximately two-thirds of the alignment was constructed below the water table, to a maximum depth below the water table of about 30 ft. The location of the tunnel project is shown on Figure 1.

This paper describes the results of a ground-water investigation to evaluate and design an effective dewatering system for tunnel construction while balancing the ability to maintain the water-supply source for the area residents. The ground-water issues were evaluated as part of the subsurface explorations and geotechnical engineering study (Hart-Crowser & Associates, Inc., 1982).

In order to achieve the most consistent tunneling ground conditions and to minimize the difficulty in dewatering during construction, the Chambers Creek tunnel was constructed largely through a shallow aquifer. The aquifer consists of glacial outwash sands and gravels and is the principal source of water for domestic use in the area. Data on the construction and operation of the water-supply wells were obtained, and predictions of aquifer response during dewatering were used to determine the risk of impact and evaluate alternatives for temporary water supply.

HYDROGEOLOGIC CONDITIONS

The tunnel project lies within the Chambers Creek basin, which contains a stream (Chambers Creek) that dissects a sequence of predominantly glacial deposits. The deposits are part of the thick regional sequence of glacial and interglacial sediments deposited in the Puget Sound lowland during the Vashon Stade of the Fraser glaciation (Walters and Kimmel, 1968).

The geologic sequence typically includes Vashon recessional outwash overlying advance outwash. The intervening till common to the Vashon sequence in the region is absent in the project area. The advance outwash comprises the water-table aquifer and is the principal zone tapped by area wells for water supply. Interglacial silt and sand and pre-Vashon till are present below the advance outwash in various portions of the project area, demarcating the bottom of the aquifer.

Ground-water flow within the advance outwash aquifer is generally from the northeast part of the project area toward the Chambers Creek valley. The creek flows to the west and discharges into Puget Sound. Chambers Creek is a regional discharge area for the water-table aquifer, as evidenced by numerous springs along the valley walls and regional ground-water flow gradients.

A generalized geologic profile along the tunnel alignment is shown on Figure 1. The four principal hydrostratigraphic units in the zone of construction from the ground surface to the creek bed are:

- Sandy gravel deposited as recessional outwash; unsaturated in the project area.
- Sand with gravel (Vashon advance outwash) comprising the water-table aquifer and the zone through which the tunnel was constructed.
- Interbedded silt and sand interpreted as interglacial lacustrine silt with lenses and layers of clean saturated sand.
- Till consisting of very dense, silty sand and gravel and considered relatively impermeable.

Differences in distribution of the hydrostratigraphic units along the alignment affected the tunnel dewatering conditions. Wright Ravine, located approximately midway along the tunnel alignment, marked a dividing point for these hydrostratigraphic differences. East of the ravine (zone C, Figure 1), interbedded silt layers in the upper part of the sand with gravel aquifer caused localized perched water and semi-confined aquifer conditions. Till marked the bottom of the aquifer east of the ravine and occurred within the tunnel zone. Areas of mixed-face tunneling ground and difficulty in completely dewatering were expected in this area. West of the ravine (zone B, Figure 1), the contact between the sand with gravel aquifer and the underlying interbedded silt

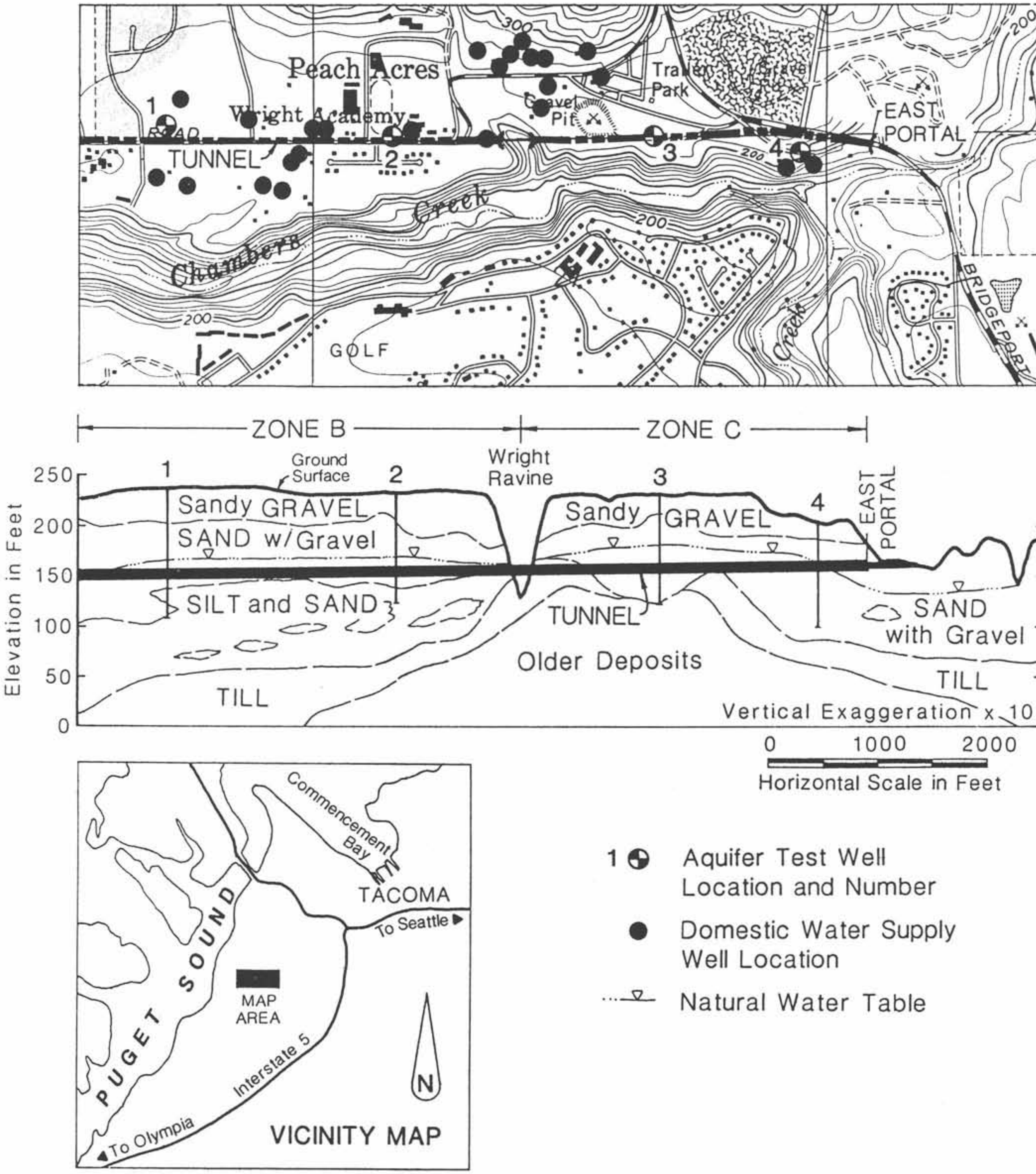


Figure 1. Location map and geologic profile for Chambers Creek tunnel project. Base from U.S. Geological Survey 7.5′ quadrangle of Steilacoom, Washington (1959, photo revised 1981).

and sand unit occurred close to the tunnel invert. In zone B it was anticipated that the limited saturated aquifer thickness below the tunnel grade might require a closer well spacing to achieve the required dewatering. In zone A (west of the dewatered area) the tunnel was constructed above the water table.

AQUIFER PROPERTIES

Pumping tests were conducted to evaluate aquifer properties. The aquifer test design included a pumping well and several monitoring wells arranged to obtain multi-directional observations. The monitoring wells were installed within the aquifer and within overlying and underlying silty layers to assess vertical hydraulic gradients and detect leakage. Constant rate, 24-hr pumping tests were conducted at four test locations (Figure 1). Representative log-log time versus drawdown curves are presented for each of the pumping tests on Figure 2. The aquifer characteristics determined from analyses of the test results are presented in Table 1.

The results of the aquifer testing indicated a delayed-yield effect in the time-drawdown response. The aquifer behaved as a confined to semi-confined system during the short-term period of testing, but the drawdown data suggested that a longer term unconfined condition would dominate because of the delayed-yield phenomena. The delayed yield is observed in the data

Table 1. Water-table aquifer characteristics

Test number	Aquifer test analysis method	Transmissivity (gpd/ft)	Storage coefficient (dimensionless)
Zone B Test 1	Boulton delayed yield	20,000	0.02
Zone B Test 2	Theis	20,000	0.00005
Zone C Test 3	Theis	39,500	0.01
Zone C Test 4	Boulton delayed yield	25,000	0.015

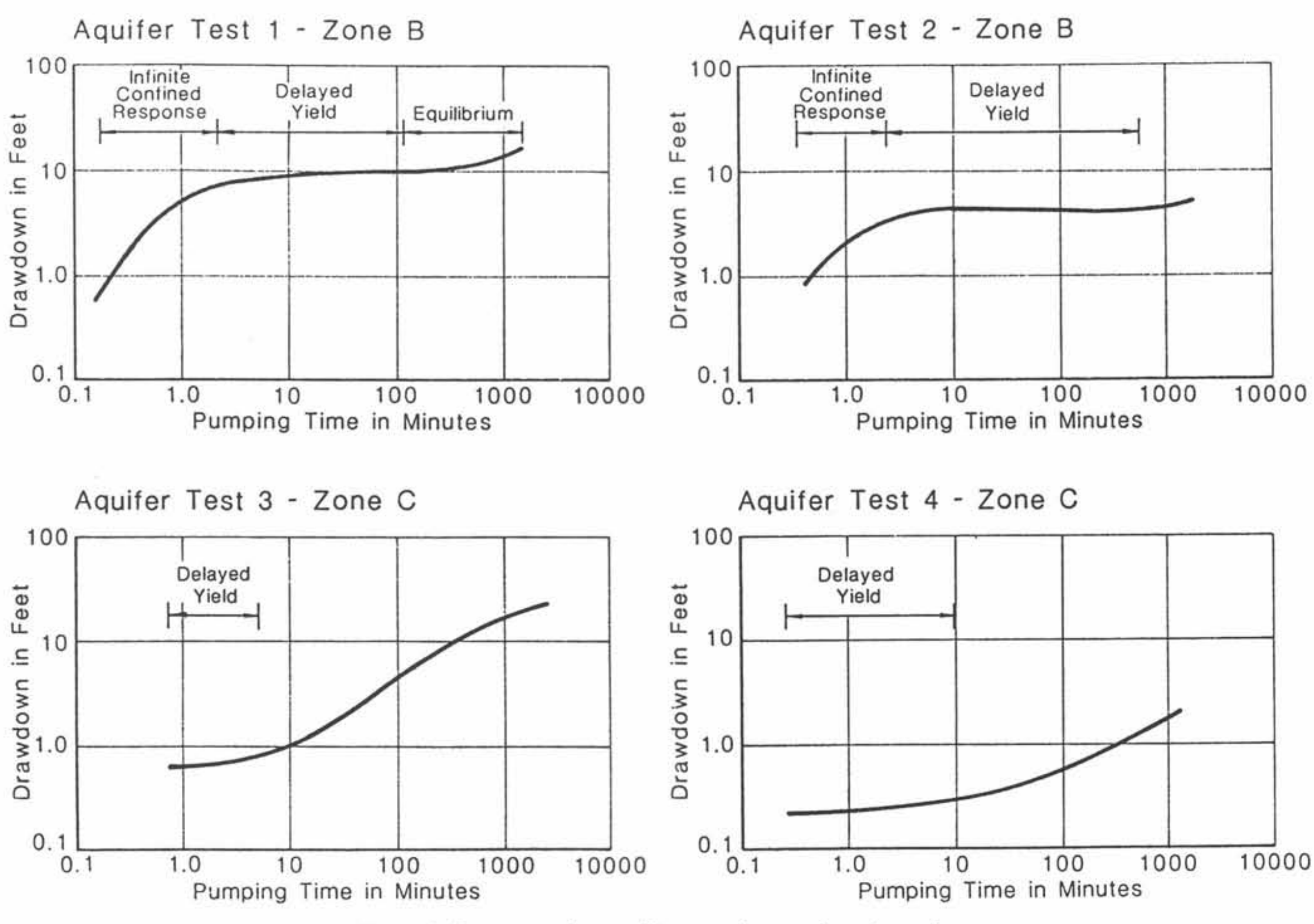


Figure 2. Representative aquifer pumping test drawdown data.

as a recharge effect due to leakage from the upper part of the aquifer and is reflective of changing storage properties of the aquifer. The larger storage coefficient of the unconfined condition (which occurs at later times) results in an increase in yield per foot of drawdown and consequently is significant to the dewatering analyses.

In tests 1 and 2 (zone B) the early time-drawdown data (when the aquifer exhibited the Theis non-equilibrium infinite, confined aquifer response) were used to evaluate the transmissivity of the aquifer. After a short time, a recharge effect was seen in the data due to leakage from the upper part of the aquifer. This recharge effect was seen immediately in tests 3 and 4 (Zone C-Figure 2) due to a thinner saturated section and fewer silty layers in the upper part of the aquifer. The delayed-yield effect caused a stability in the rate of drawdown as yield from the aquifer was balanced by replenishment with gravity drainage. At later times the effects of gravity drainage were small, as the rate of drawdown again reflects the Theis non-equilibrium aquifer response.

The time-drawdown data indicated a fairly consistent aquifer transmissivity throughout the dewatering zone, as shown in Table 1. The average aquifer thickness west of the ravine (zone B) was 25 ft, resulting in a hydraulic conductivity of approximately 1,000 to 1,500 gpd/sq ft. The average aquifer thickness east of the ravine (zone C) was 35 ft, resulting in a hydraulic conductivity of 500 gpd/sq ft.

DEWATERING SYSTEM DESIGN

The results of the aquifer pumping tests were used to design an appropriate dewatering system to control ground water during tunneling and to predict the effects of the dewatering on the water-supply wells in the area. A steady-state flow model (Powers, 1981) was used to evaluate the dewatering pumping rates, location and number of wells, and well spacing. A transient flow model (Leake, 1977) was used to evaluate the time needed to dewater and drawdown with distance over time. The system was modeled as flow to a continuous line-slot from a constant head recharge source to the north and with a discharge boundary to the south.

The pumping rates required during steady-state dewatering conditions were estimated to be on the order of 1,000 to 2,000 gpm. A single line of wells located north of the tunnel and parallel to the tunnel alignment was recommended in order to intercept ground-water flow toward the creek. The line-slot flow model was simulated by a series of wells to determine well spacing and pumping volume per well. It was estimated that approximately 50 to 60 wells spaced 100 to 200 ft apart would accomplish the desired dewatering. The wells were designed to pump 100 to 125 gpm during the initial pumping period in order to achieve aquifer storage depletion. As the aquifer was dewatered, the pumping rates would decrease to eventual steady-state flow rates on the order of 20 to 40 gpm. The time required to dewater the system and achieve a drawdown below the tunnel invert was estimated, based on the transient analysis, to be between 20 and 40 days.

The tunnel dewatering was actually accomplished with a series of 100- to 120-ft-deep wells installed on approximately 100-ft spacings in zone C and 50-ft spacings in zone B. The wells were placed approximately 5 to 10 ft north of and parallel to the center line of the tunnel. The wells were operating at least 2 weeks prior to the advance of the tunnel. Total system discharge rates were estimated to be between 1,000 and 2,000 gpm. The wells east of the ravine were pumped for approximately 1 yr. The wells west of the ravine were pumped for approximately 136 days.

The dewatering effectively controlled the ground water throughout most of the construction period. Some minor delays occurred during tunneling in the zone B area due to standing water in the tunnel invert. The water problems were caused by interfingering zones of silt and sand near the interface of unit 2 (sand with gravel aquifer) and unit 3 (underlying interbedded silt and sand). It was anticipated that dewatering would be more difficult in this zone because of the limited aquifer thickness below the invert from which to pump. Additional wells were installed in this zone to tighten the well spacing to about 50 ft and thus reduce the mounding between wells.

IMPACT ASSESSMENT

Predicted drawdown with distance was used in conjunction with the well inventory data to evaluate the risk to operating domestic wells during dewatering. The well inventory included obtaining information on the well depth, the completion details, pump setting, and drawdown during pumping. Individual pumping tests were conducted on each of the domestic wells to evaluate the operational conditions during extended use. It was found that in most wells the water levels stabilized at a particular drawdown level. The low discharge rates at which most of the pumps operated likely accounted for the stabilized pumping water levels, as most of the drawdown was associated with well loss and relatively negligible amounts of aquifer drawdown.

Risk of adverse effects of the dewatering was assigned to the wells based on the depth of the pump, the pumping water level, and the amount of drawdown available before the pumps would break suction. Wells in which water level drawdowns to within 2 ft of the pump intake occurred during a pumping condition and those completed within the water-table aquifer south of the tunnel alignment were considered at high risk and were placed on a temporary water line. Water levels were monitored in the remaining wells throughout construction.

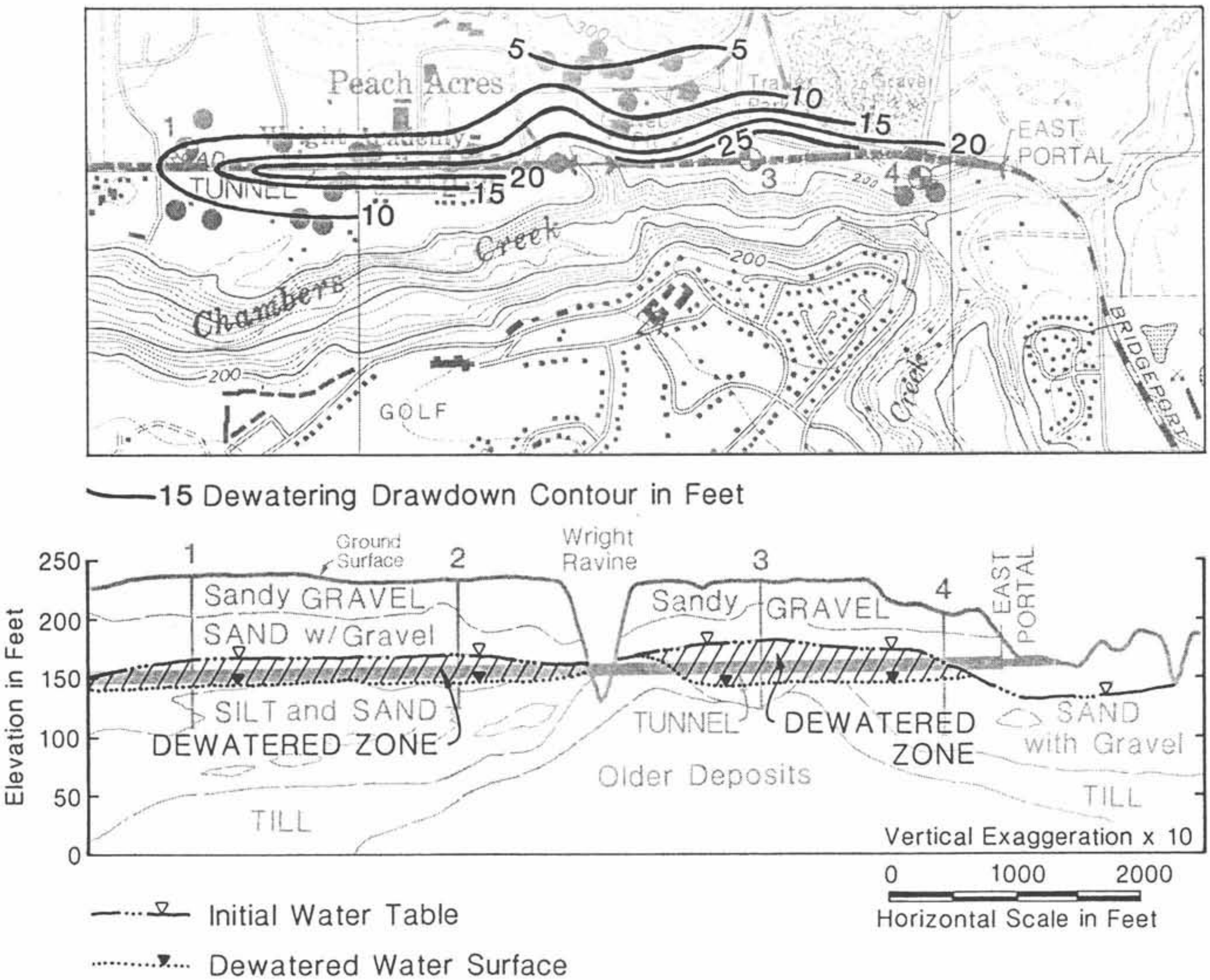


Figure 3. Ground-water drawdown depth during dewatering. Contour interval 5 ft. Base from U.S. Geological Survey 7.5′ quadrangle of Steilacoom, Washington (1959, photo revised 1981).

MONITORING PROGRAM RESULTS

Aquifer Drawdown

The monitoring program consisted of measuring and evaluating water-level data obtained in the observation wells and in the domestic wells. The water-level data were used to assess drawdown conditions in the tunneling zone and to monitor response of the domestic wells. A contour map of the ground-water drawdown experienced during dewatering of the aquifer is presented on Figure 3.

A plot of the observed drawdown with distance is compared with the predicted drawdowns for various times on Figure 4 for the initial 30 days of pumping in zone C. The data indicate that the predicted late time drawdowns more closely correlate with the observed response than do the early time-drawdown data. The analyses assumed a constant storage coefficient and constant discharge along the tunnel alignment. As indicated by the delayed-yield response during the pumping test, the responses of the aquifer storage properties were likely changing during the initial pumping period. In addition, the dewatering wells were brought on line as they were installed. Both of these conditions could contribute to the deviation of the predicted from observed response in the early time-drawdown data. At later times, the observed time-drawdown response more closely met the assumptions used in the analysis. The data also indicated that at greater distances from the dewatering wells, the time-drawdown response more closely agreed with the predictions and was conservative enough to place confidence in the well impact assessments.

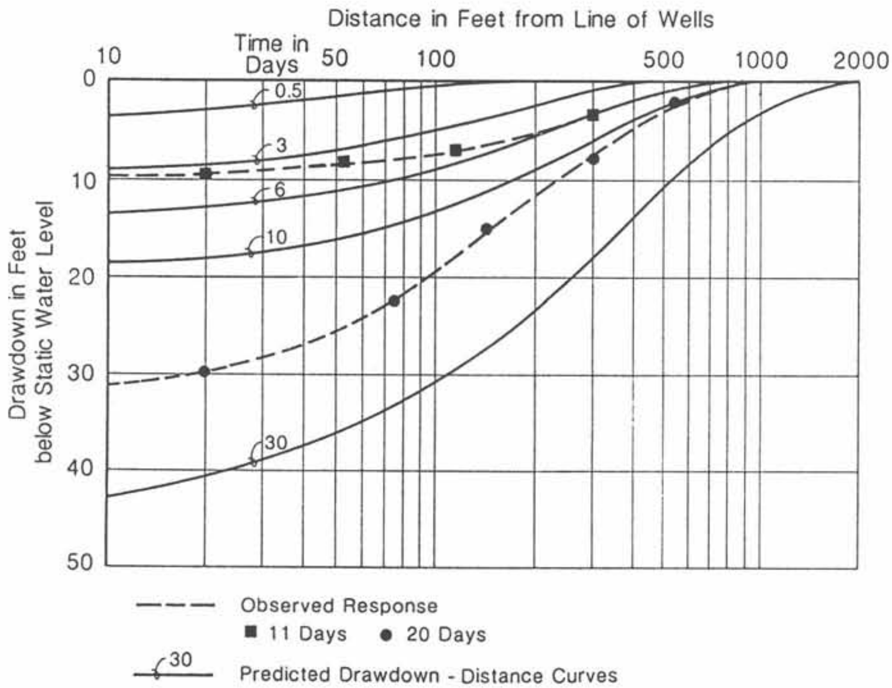


Figure 4. Comparison of predicted and observed aquifer drawdown with time.

Predictions of the aquifer response and water-level monitoring in zone B facilitated the continued operation of five water-supply wells during the dewatering, although as much as 11 ft of water-level decline occurred. Construction delays in zone C caused a longer period of dewatering than planned, resulting in larger drawdowns than expected and necessitating temporary water supplies. It was not until approximately 6 months into the dewatering that the zone C domestic wells were adversely impacted, requiring a temporary water system. If tunnel advance rates in zone C had been comparable to those for zone B, these wells would not have needed an alternative supply.

Aquifer Recovery

Domestic well monitoring following shut down of the dewatering system indicated that aquifer levels in zone B took roughly 150 days to recover and that the aquifer in zone C took about 3 yr to fully recover. These periods closely match the length of time during which dewatering was accomplished.

Most of the wells the owners chose to reinstate were monitored to full recovery levels, and few experienced problems with reinstating their original supply. One well required redevelopment. The water level in another well located on the west edge of the ravine had not fully recovered 1 yr after dewatering ceased. It is believed that backfill materials associated with the construction of a pipe bridge close to this well may have altered the local flow conditions and resulted in lower ground-water levels.

CONCLUSIONS

The exploration and testing program provided valuable insight into the conditions that would affect tunneling, as well as the data to assess impacts to the local community. Recognition of a delayed-yield aquifer response was critical to evaluating the transmissivity of the aquifer, the storage properties that would control the dewatering system design, and the time required to achieve a dewatered condition. A thorough well inventory and monitoring program allowed an early warning of potential problems with existing water-supply wells; this resulted in cost savings by eliminating unnecessary temporary water supplies.

REFERENCES

Hart Crowser and Associates, Inc., 1982, *Final Geotechnical Report, Chambers Creek Interceptor Tunnel, ULID 73-1, Pierce County, Washington:* Prepared for Kennedy/Jenks Engineers and Pierce County, WA, Vol. 1 and II, 150 p.

Leake, S. A., 1977, Simulation of flow from an aquifer to a partially penetrating trench: *Journal of Research of the U.S. Geological Survey*, Vol. 5, No. 5, pp. 535-540.

Lohman, S. W., 1979, *Ground-Water Hydraulics*: U.S. Geological Survey Professional Paper 708, 70 p.

Powers, J. P., 1981, *Construction Dewatering, A Guide to Theory and Practice*: Wiley Series of Practical Construction Guides, (Morris, M. D., Series Editor): John Wiley & Sons, Inc., New York, NY, 484 p.

Walters, K. L. and Kimmel, G. E., 1968, *Ground-Water Occurrence and Stratigraphy of Unconsolidated Deposits, Central Pierce County, Washington*: Washington Department of Water Resources Water Supply Bulletin 22, Olympia, WA, 428 p.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Management of Declining Ground-Water Levels in Part of Eastern Washington

THEODORE M. OLSON
Washington Department of Ecology

BACKGROUND

East-central Washington is a semiarid region in the center of the Columbia Plateau. The average annual precipitation is only about 9 to 15 in. and occurs primarily during the winter. Agriculture in this area prior to the early 1950s was primarily dry land wheat farming on a crop-fallow rotation basis. Ground-water use was limited to domestic supplies for communities and individual farmsteads.

The limited precipitation, coupled with the hot, low-humidity summers, created a need for supplemental irrigation. During the late 1950s, farmers began drilling deep irrigation wells, and notwithstanding pumping lifts as great as 500 ft, the economic benefits were obvious. Dramatic increases in crop yield with irrigation were apparent. During the 1960s, ground-water pumpage for irrigation tripled every 2 yr. The annual withdrawal was 14,000 acre-ft in 1963; 44,000 acre-ft in 1966; and 149,000 acre-ft by 1968. By 1966, declines in water levels were noted over large areas. A reduction in pumpage to 117,000 acre-ft occurred by 1970.

The Washington Department of Ecology (formerly the Department of Water Resources) recognized the potential future problems associated with water-level declines, such as well interference and general aquifer depletion. In August 1967, the Department informally closed from further appropriation for irrigation approximately 1,100 sq mi of east-central Washington. This closure provided time for the Department to conduct studies into the causes of the declines and means of correcting further declines in the ground-water levels. The study area includes the communities of Odessa, Ritzville, Lind, and Warden (Figure 1).

GEOLOGY AND HYDROLOGY

Ground water in east-central Washington occurs principally in a thick sequence of basalt flows referred to as the Columbia River Basalt Group. The major aquifers occur within flow contact zones consisting of unconsolidated sediments or rubbly basalt; these zones comprise approximately 25 percent of the total sequence. The dense central parts of the flows confine the ground water, and the water levels in the basalt sequence generally decrease with increasing aquifer depths. Regionally, ground-water movement is from northeast to southwest.

Three basalt units of the Columbia River Basalt Group are identifiable east of the Columbia River (Swanson et al., 1979) (Figure 2). In the western part of the Columbia Plateau, the Saddle Mountains and Wanapum basalts are exposed at or are near land surface. These units gradually thin to the north and east. The Grande Ronde Basalt underlies the Wanapum. Near Odessa, the basalts attain a total thickness of 4,465 ft, as shown by data from an exploratory oil well, locally referred to as Basalt Explorer.

Sedimentary deposits are generally interbedded with the Saddle Mountains Basalt flows, particularly near the plateau margins. With increasing distance east of the Columbia River, there is a corresponding thinning of sediments interbedded with basalt flows. Only one significant interbed is present in the east-central region, and it lies between the Wanapum and Grande Ronde basalts. This interbed is known as the Vantage Member (of the Ellensburg Formation) and attains a thickness of 25 to 30 ft, but is generally 10 to 15 ft thick.

Major irrigation wells range from 600 ft to more than 2,500 ft in depth. Aquifer test data show that the coefficients of storage in the Saddle Mountains, Wanapum, and Grande Ronde basalts range from 0.0015 to 0.006. The coefficients of transmissivity range from less than 10,000 to more than 200,000 gpd/ft; the average is approximately 50,000 gpd/ft (6,600 ft sq/day). Production data indicate that the upper flows of the Grande Ronde are more productive than those of the overlying Wanapum Basalt.

As part of the on-going data collection by the Washington Department of Ecology, annual water-level measurements are made in more than 450 wells. The measurements are made with air lines or with electric tapes each spring before the irrigation season begins. These measurements indicate the position of the water

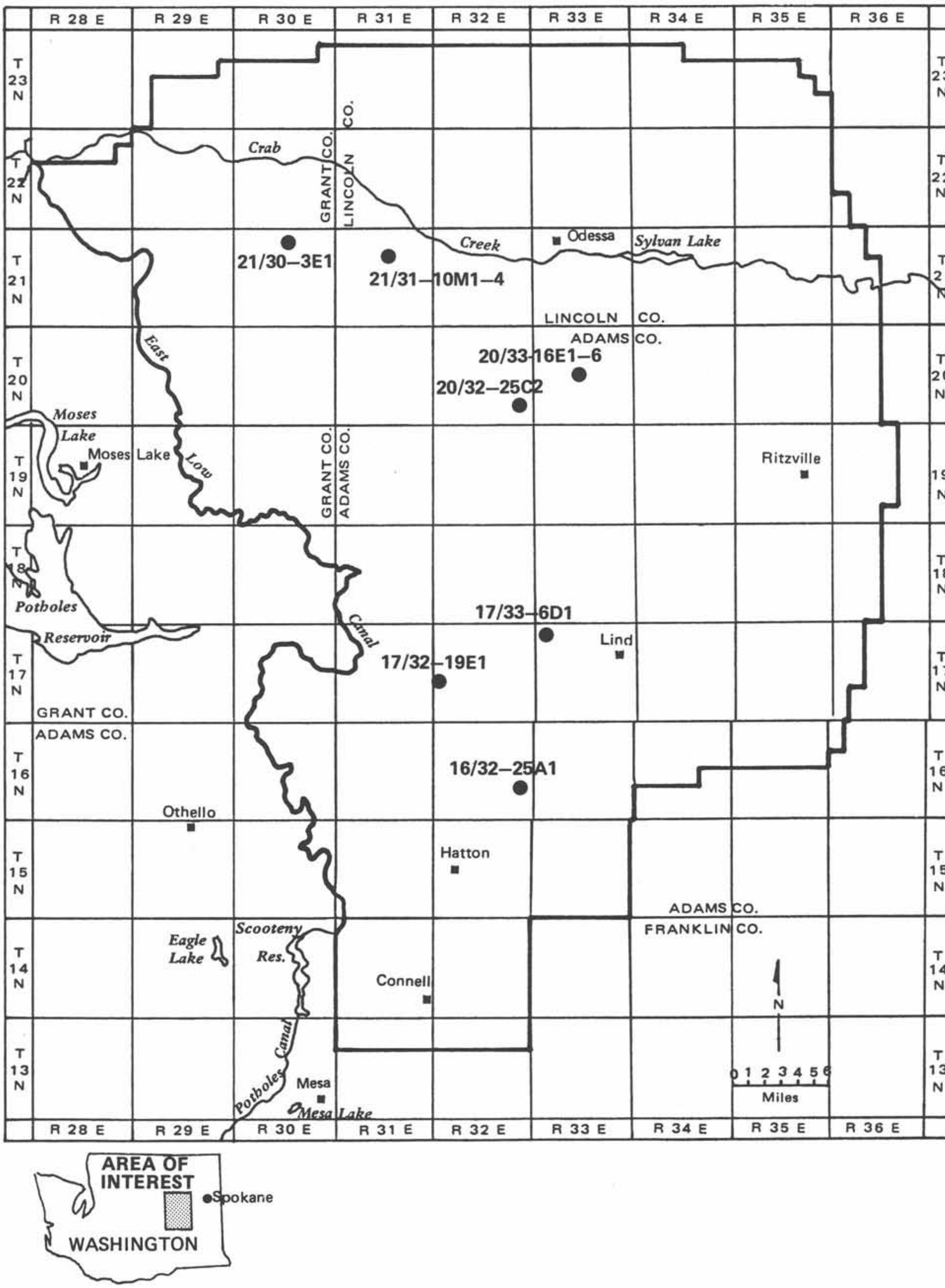


Figure 1. Odessa Ground-Water Subarea, eastern Washington.

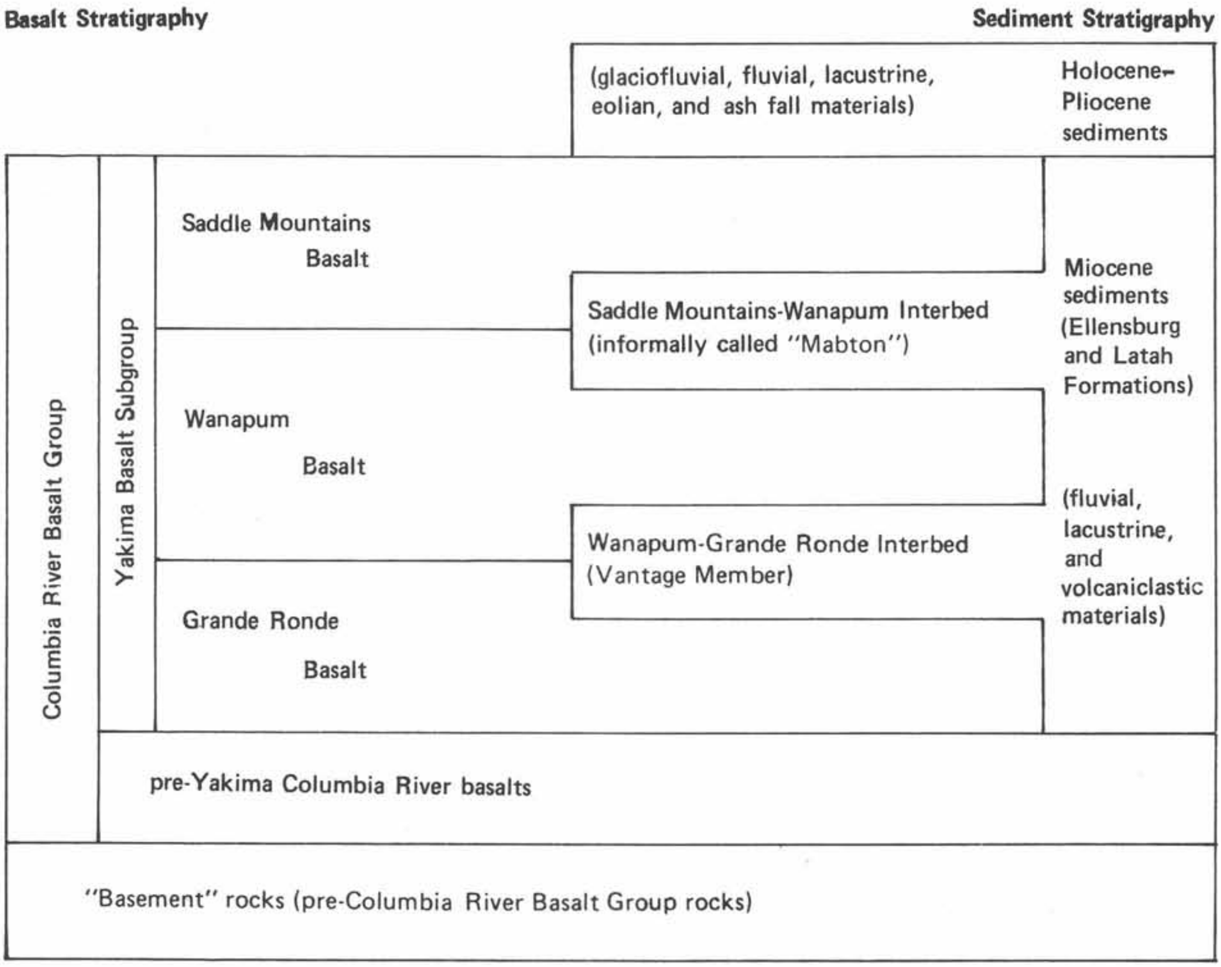


Figure 2. Stratigraphic terminology used in this report.

level after it has recovered from the previous irrigation season. The field measurement data are transferred to individual hydrographs for each well. The long-term water-level trend of each well is readily apparent from the hydrographs. The trend in some wells has become a straight line function showing an annual decline rate of as much as 20 ft/yr (Figures 3 and 4).

NATURE OF THE PROBLEM

Regulatory History

The moratorium of 1967 (for 1967-1972) became effective on all pending applications for new water rights within the Odessa Subarea. As provided by law (RCW 90.44.130, 1947), the Department of Ecology may establish management areas or subareas in order that overdraft of public ground water may be prevented so far as is feasible. On the basis of this jurisdiction, the Department established the Odessa Ground Water Subarea in January 1973. In conjunction with the 5-yr moratorium, the Department entered into cooperative agreements with the U.S. Geological Survey (Water Resources Division) and Washington State University Water Research Center. The moratorium allowed the Department time to evaluate the effects of large-scale ground-water withdrawals. The study by the U.S. Geological Survey resulted in a digital computer model using finite difference techniques to simulate an intensively pumped, multilayered, basalt aquifer system. For model analysis, the deeper pumped aquifers were treated as a single layer with drawdown-development leakage from an overlying confining layer. Verification of the model was achieved primarily by closely matching observed pumpage-related head declines ranging from 10 ft to more than 40 ft between March 1967 and March 1971. The results of this study and additional work are presented in joint Department and Survey publications by Garrett (1968), Luzier and Burt (1974), and Luzier and Skrivan (1975). Predictive capabilities of the model were used to evaluate pending applications for new permits.

At the end of the moratorium in 1972, and with available results of the various studies conducted, the Department set about the task of evaluating the study results

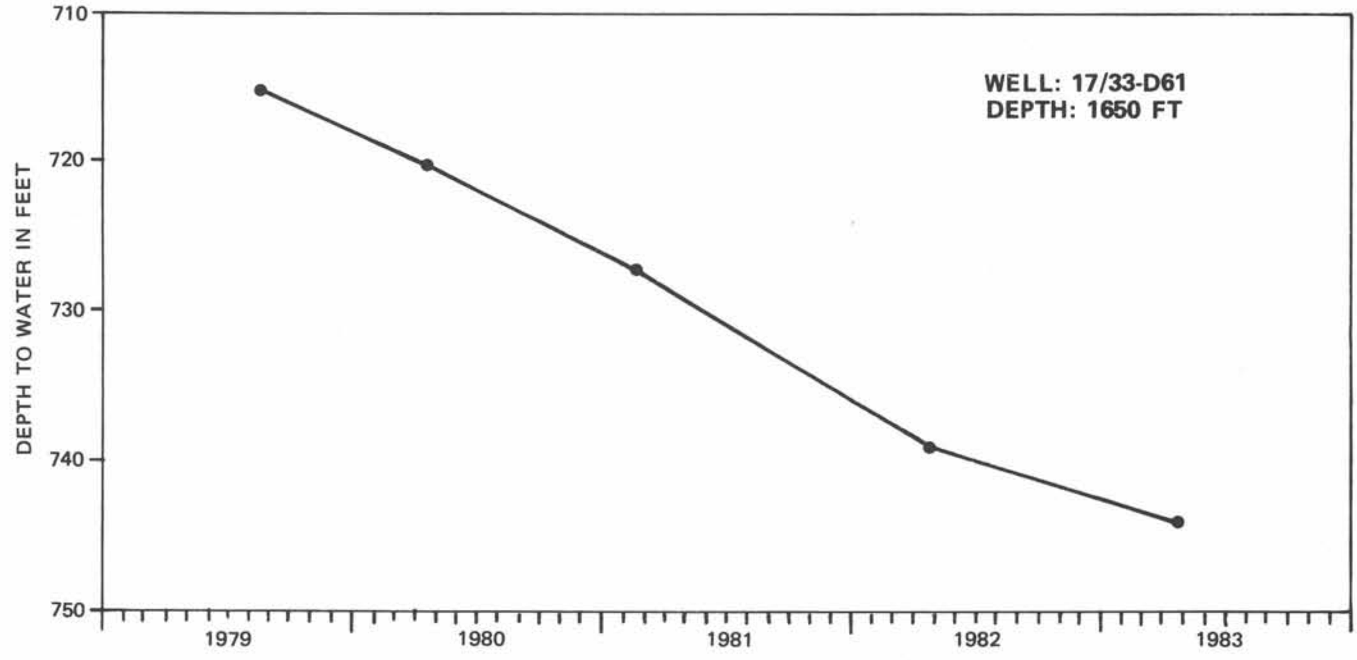


Figure 3. Hydrograph for irrigation well 17/33-6D1.

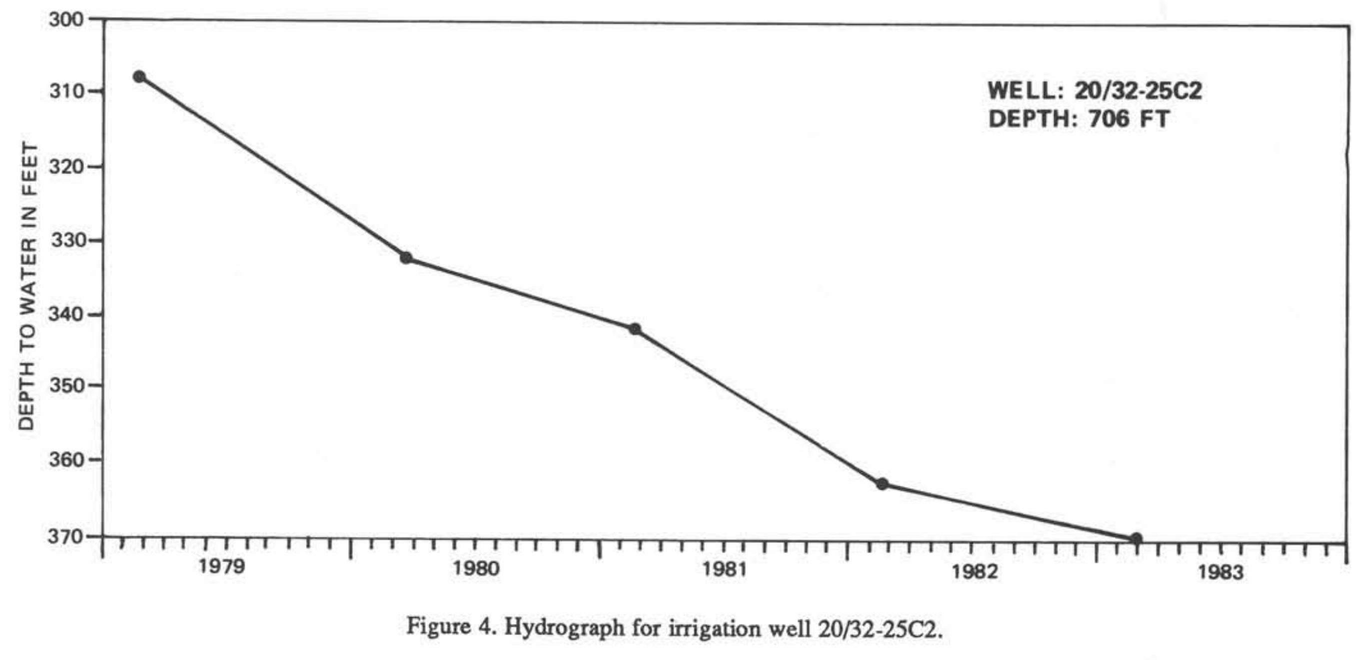


Figure 4. Hydrograph for irrigation well 20/32-25C2.

and applying these data to formulate management regulations for ground-water appropriation. These regulations are intended to insure the maintenance of a sustained yield while allowing for a reasonable and feasible pumping lift. During 1973 the Department drafted management regulations with the assistance of a concerned citizens organization. Public meetings were held to review the draft proposals and to solicit input. Public hearings were conducted on the final draft, with subsequent revisions as appropriate. The final regulations were ultimately adopted in January 1974 and codified under Chapters 173-128A WAC and 173-130A WAC.

The original management regulations include: the establishment of a geographic boundary within which the regulations apply (1,800 sq mi); controlled rate of annual decline not to exceed 30 ft in 3 yr; defined irrigation season of March 1 through September 30;

measurement of spring static water level; installation of flow meters; identification of aquifer systems by depth; and the holding of public meetings annually for the first 5 yr to review the regulations and amend them as necessary.

In February 1974, through the predictive capabilities of the U. S. Geological Survey numerical computer model, the Department selectively issued new permits for ground water. These permits met the criteria set forth in the management regulations.

As a result of the first public review of the regulations in 1975, amendments were made. These included extending the authorized irrigation season from 7 to 10 months (February 1 to November 30) and requiring reworked wells to be cased and sealed to eliminate all cascading water. The most recent revision to the regulations occurred in August 1982 and resulted in major amendments which: eliminated the requirement for flow meters and the identification of aquifer systems by depth; set the time period in which construction must begin after well permits are issued; enlarged the subarea by 162,000 acres (total area now 1,313,920 acres [2,053 sq·mi]); and provided for acreage expansion. The concept of acreage expansion is unique under western water law and allows certificate holders to expand their authorized irrigated acreage while not increasing actual historic withdrawal rates in gallons per minute or acre-feet/year within the maximum limits of the water right. To qualify for the program, the irrigator must document quantities of water withdrawn and acres irrigated for three previous consecutive irrigation seasons. If the expansion is approved, the irrigator may increase his irrigation to any amount of acreage, but is limited to historic water quantity. Additionally, a flow meter must be installed, the total water used must be reported by December 31 of each year, and the authorization is administered as a temporary change through an annual letter valid for one calendar year. No permanent change or amendment to any water right will be issued as part of this program.

Ground- Water Pumpage and Water-Level Response

The number of irrigation wells drilled in east-central Washington increased dramatically from the mid 1960s to the mid 1970s; there was a corresponding increase in pumpage. Within the Odessa Subarea in 1967, the pumpage was approximately 50,000 acre-ft from 137 wells. Within the general east-central Washington area for this same year, there were an additional 168 wells with pumpage of approximately 60,000 acre-ft. By 1977, the number of wells in the subarea increased to more than 250 with an annual pumpage of approximately 165,000 acre-ft. For this same year in east-central Washington, the total number of wells had reached 369 with pumpage of approximately 220,000 acre-ft. Thus, during this 10-yr period, the number of wells more than doubled and the pumpage quadrupled.

The ground-water withdrawal in 1967 was generally less than 1,000 acre-ft annually per township, with a few areas drawing as much as 10,000 acre-ft per year per township (Figure 5). By 1977, the annual withdrawal had increased to more than 25,000 acre-ft in some townships (Figure 6). The greatest increase occurred in the southern part of the Odessa Subarea southeast of Warden.

Accompanying the increased withdrawals were regional declines in ground-water levels. Between 1968 and 1978, levels declined more than 80 ft in the upper Wanapum Basalt (Figure 7). For this same period, the declines exceeded 100 ft in some geographic areas in wells which penetrated both the Wanapum and Grande Ronde basalts (Figure 8). For the period 1978-1981, water-level declines in the Wanapum Basalt southeast of Warden approached 15 ft/yr (Figure 9). Declines in wells penetrating both the Wanapum and Grande Ronde basalts exceeded 20 ft/yr in the area southeast of Warden for that period (Figure 10). The water-level changes (1968-1981) in the critical southern area are shown in cross sections A-A′ and B-B′ shown on Figures 11 and 12.

The declining water levels caused considerable concern among the irrigators. In an effort to keep ahead of the declines, many well owners deepened their wells. In most cases the deepening of a well was associated with a subsequent corresponding drop in water level (Figure 13). This drop in head, with increased well depth, reflects the lower potentiometric surface with depth.

Water-level declines in the wells penetrating only the Wanapum Basalt have been steady but not as severe as those in wells which penetrate both the Wanapum and Grande Ronde basalts (Figures 14 and 15). This greater rate of decline in wells producing from both basalt units is interpreted as a reflection of decreasing vertical permeability with increased depth, which thus restricts vertical ground-water movement. Generally, significant head changes occur across the Vantage Member and the uppermost Grand Ronde Basalt, where the head has been lowered as much as 100 ft. Where structural or stratigraphic changes affect the movement of ground water, the effect can be more significant. In contrast, in areas where the Wanapum Basalt is exposed or is present near land surface and where existing wells produce entirely from the Wanapum Basalt, water levels appear to reflect a water-table or semi-confined condition. This is believed to be related to the proximity of a source of recharge at land surface and greater vertical permeability within the upper part of the Wanapum Basalt.

In a continuing effort to monitor the changes in ground-water levels, piezometers have been installed in

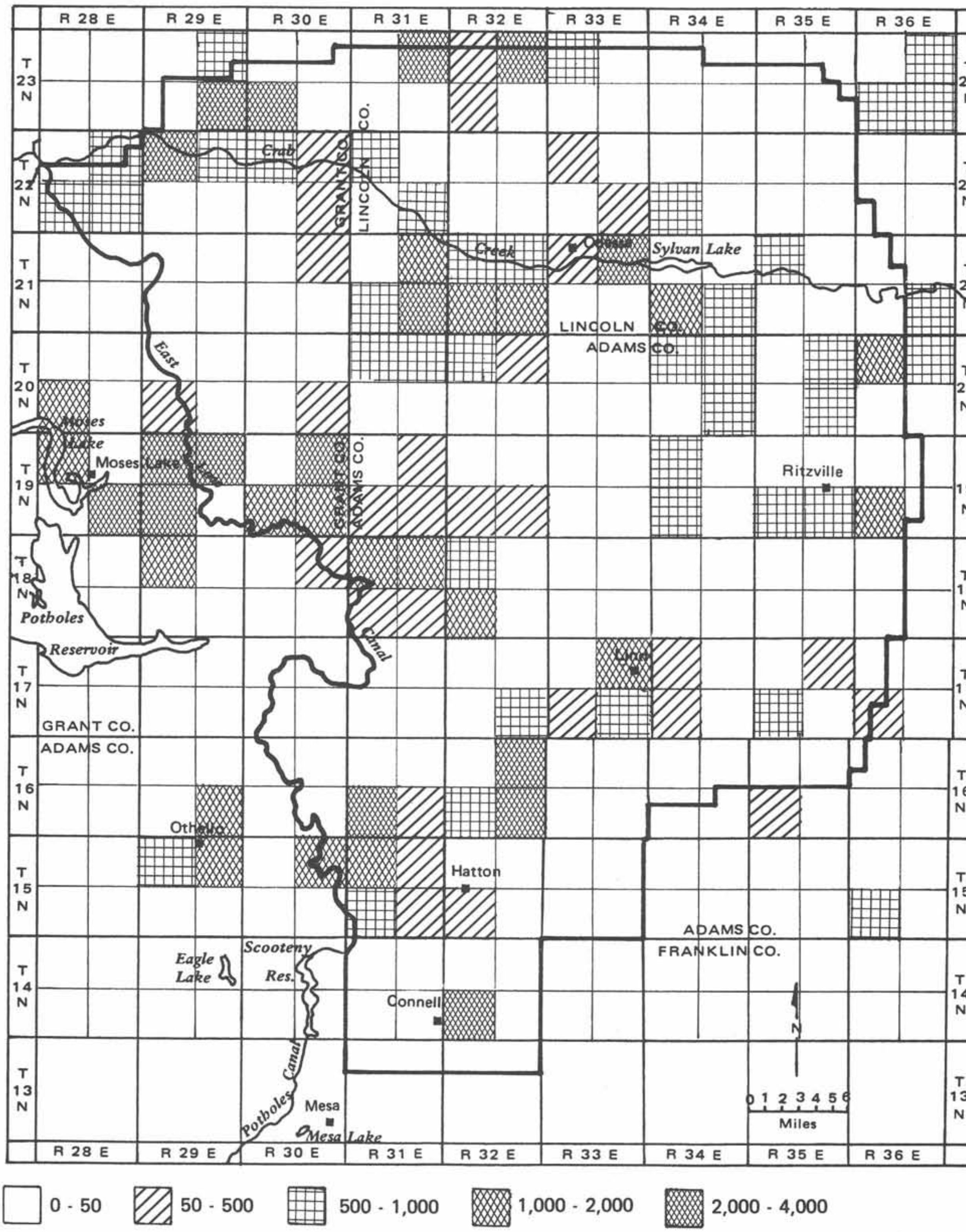


Figure 5. 1967 ground-water pumpage, in acre ft.

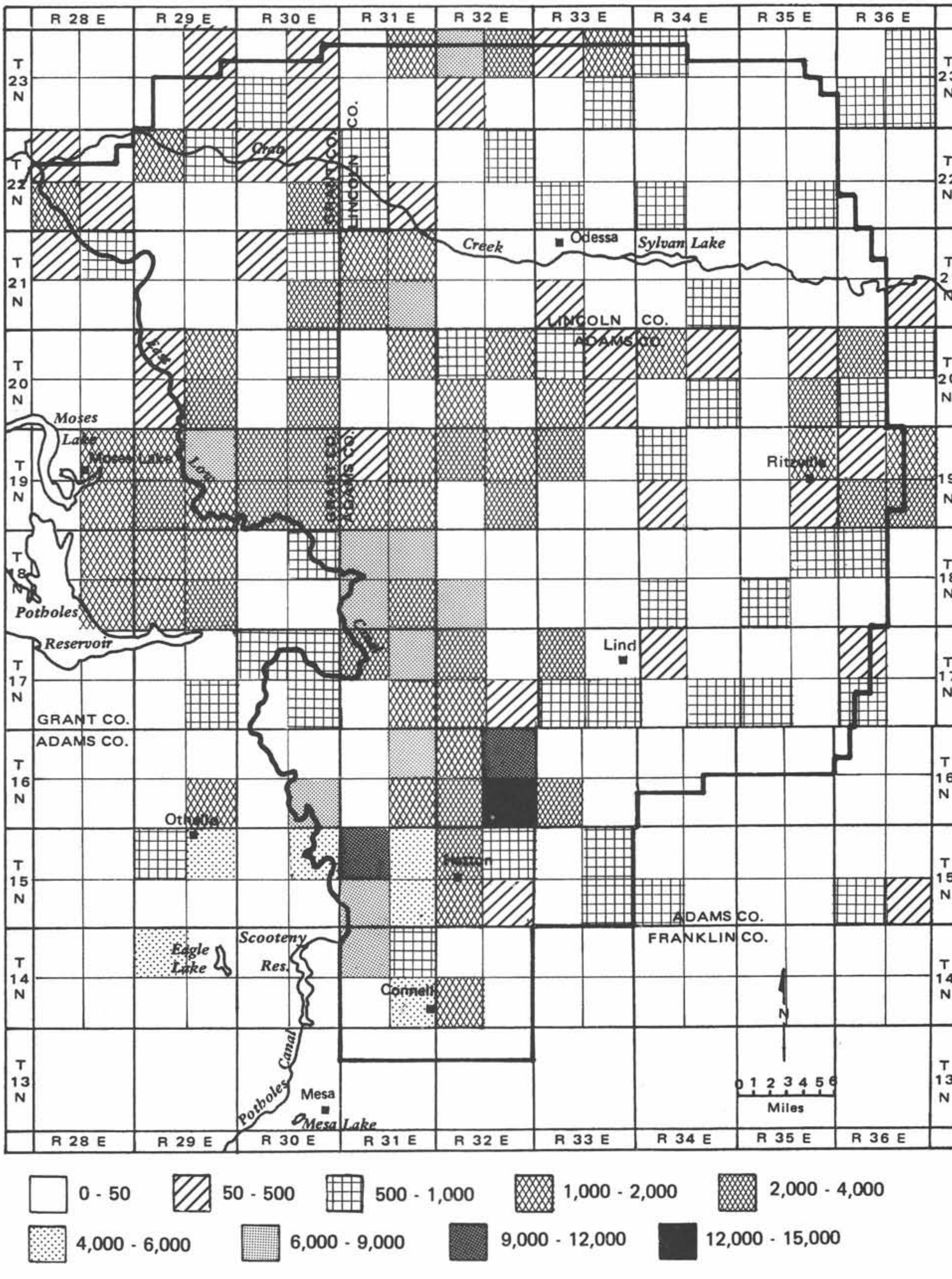


Figure 6. 1977 ground-water pumpage, in acre ft.

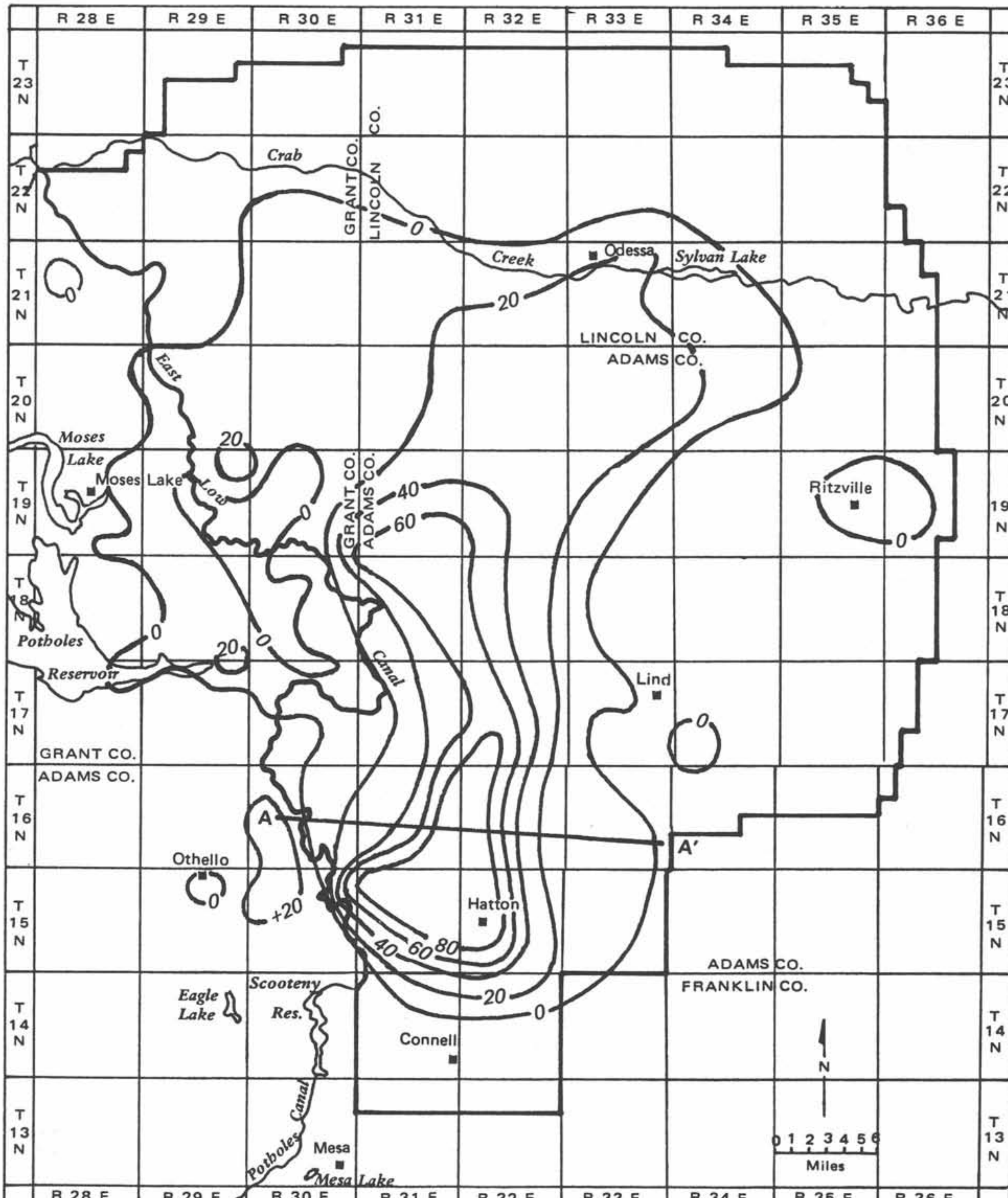


Figure 7. Ground-water level declines in wells tapping the Wanapum Basalt, 1968-1978 (contours in ft).

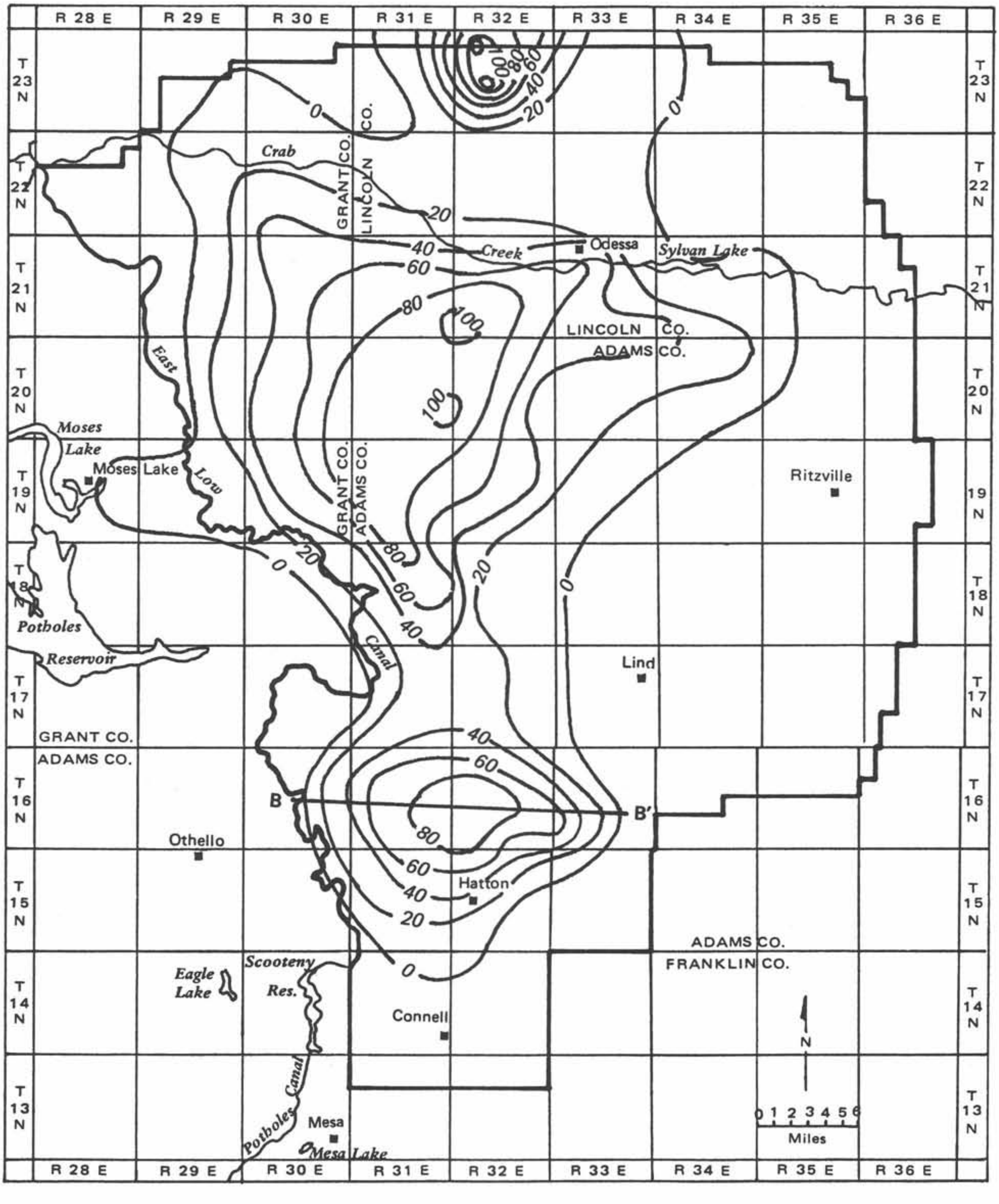


Figure 8. Ground-water level declines in wells tapping both the Wanapum and Grande Ronde basalts, 1968-1978 (contours in ft).

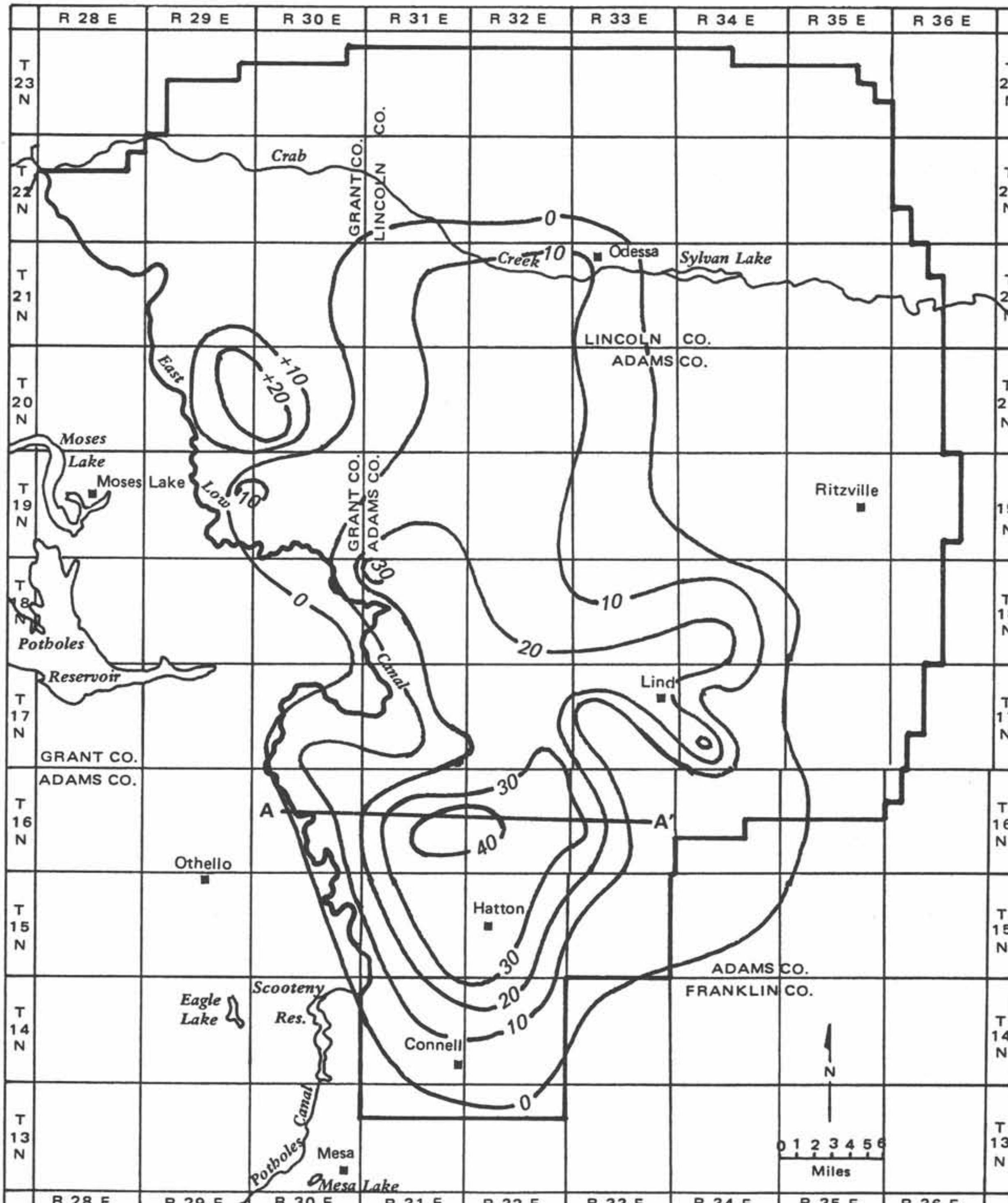


Figure 9. Ground-water level declines in wells tapping the Wanapum Basalt, 1978-1981 (contours in ft).

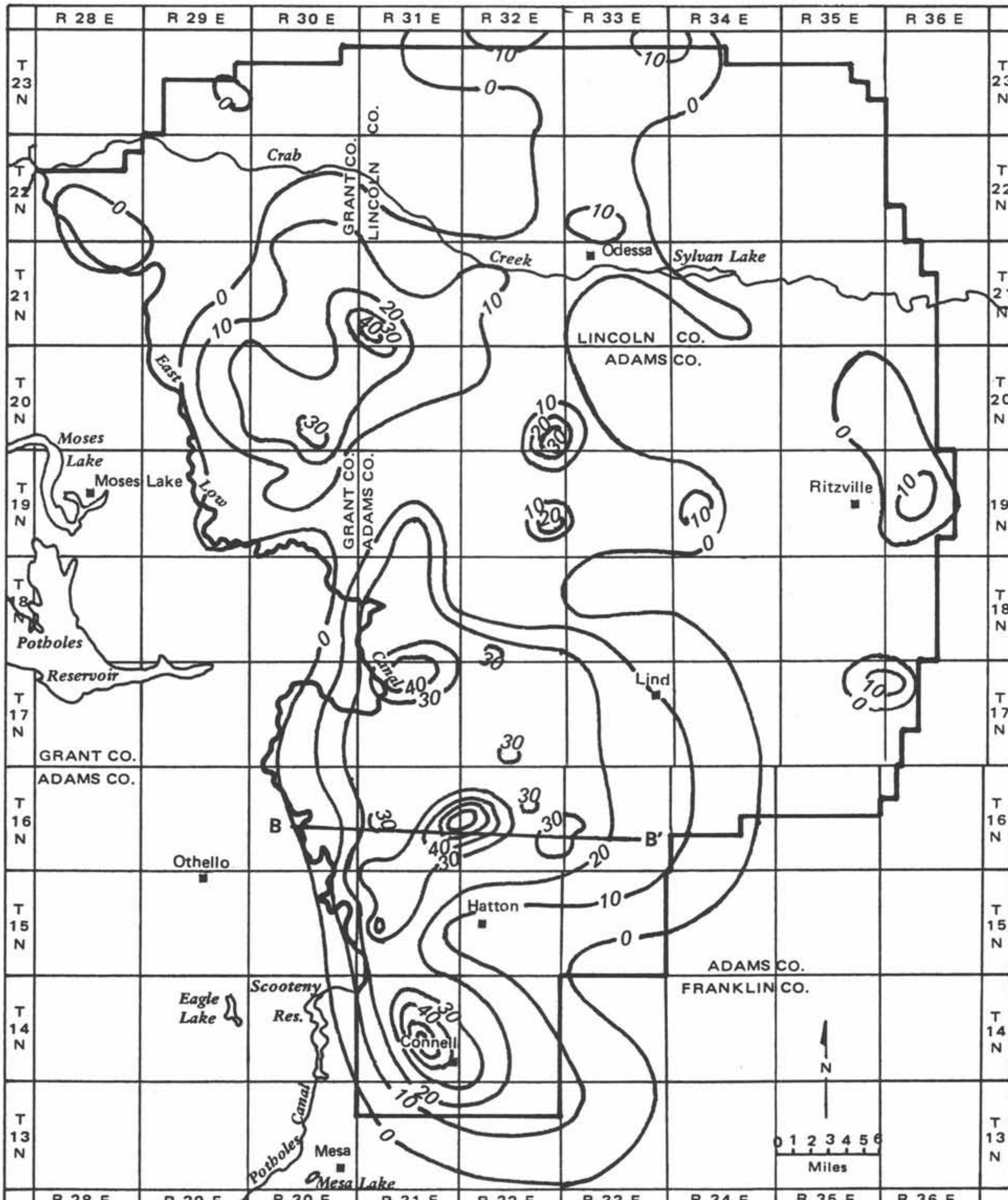


Figure 10. Ground-water level declines in wells tapping both the Wanapum and Grande Ronde basalts, 1978-1981 (contours in ft).

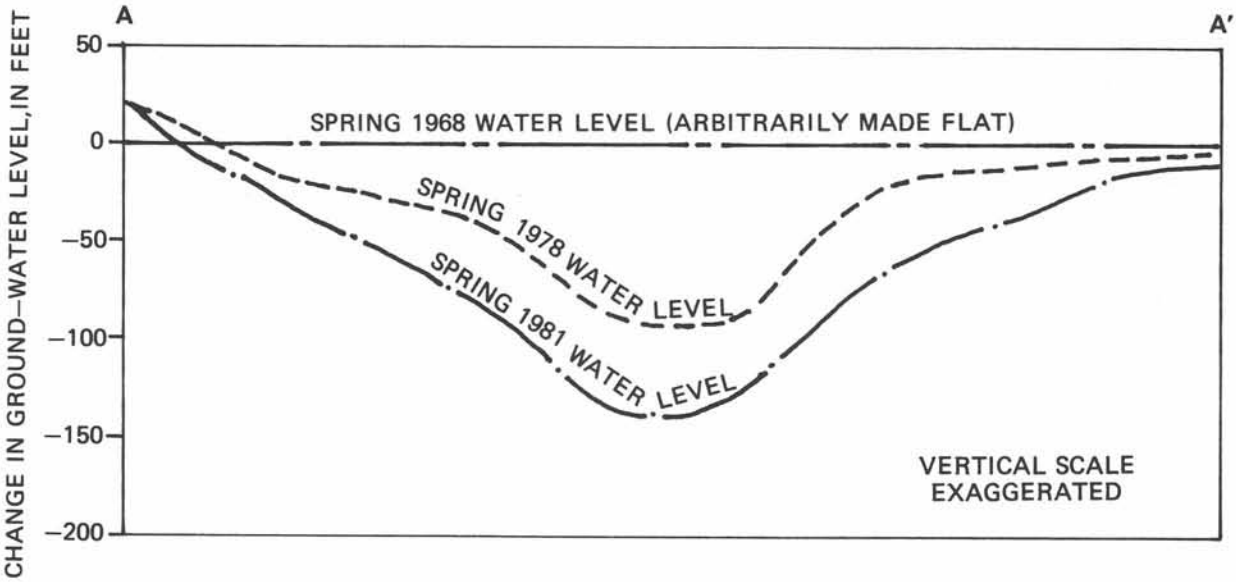


Figure 11. Ground-water level changes in wells tapping the Wanapum Basalt from spring 1968 to spring 1981.

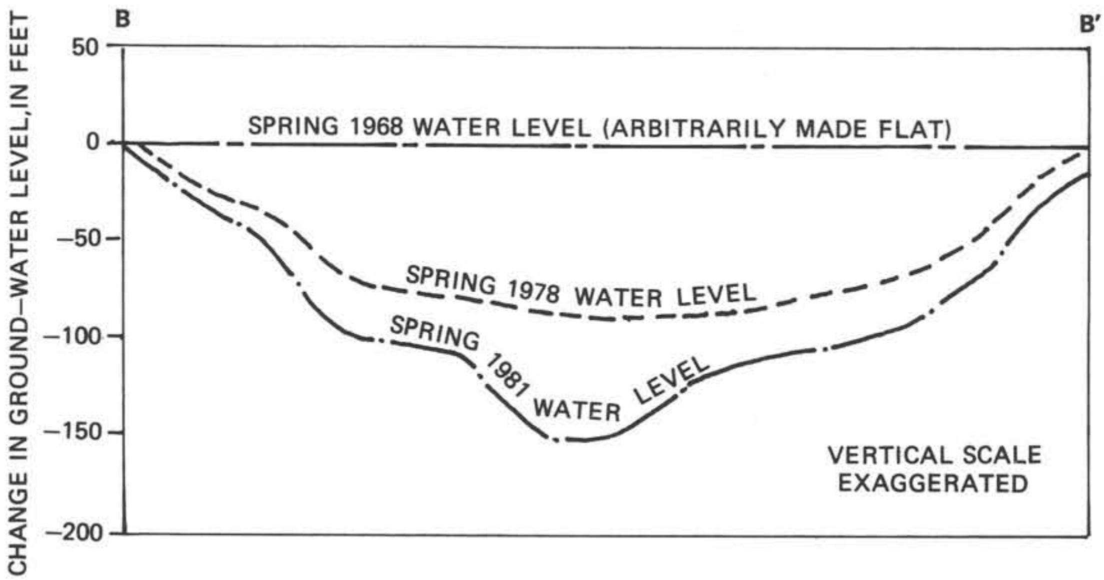


Figure 12. Ground-water level changes in wells tapping both the Wanapum and Grand Ronde basalts from spring 1968 to spring 1981.

several observation wells to provide data regarding individual aquifer systems within the basalt sequence. The recorded long-term trends in water-level change indicate that the aquifers with the greatest stress from irrigation withdrawal exhibit the greatest annual and long-term decline (Figure 16). Wells with total depths in excess of 500 to 700 ft show the most dramatic declines because they penetrate the zones with greatest pumpage.

The installation of piezometers in eastern Washington wells has assisted the Department in monitoring changes in water levels. Some piezometers have been equipped with continuous recorders to accurately define rate of decline with pumping stress during the irrigation season. A typical installation is shown on Figure 17. Piezometers were also installed in an abandoned exploratory oil well; the water-level data are shown on Figure 18. From this hydrograph, it is readily apparent that the intensely pumped zone from 755 to 1,480 ft reflects the greatest decline, and that the 1,498-to-2,300-ft zone shows essentially no effect from pumping and has a head higher than all other aquifer zones.

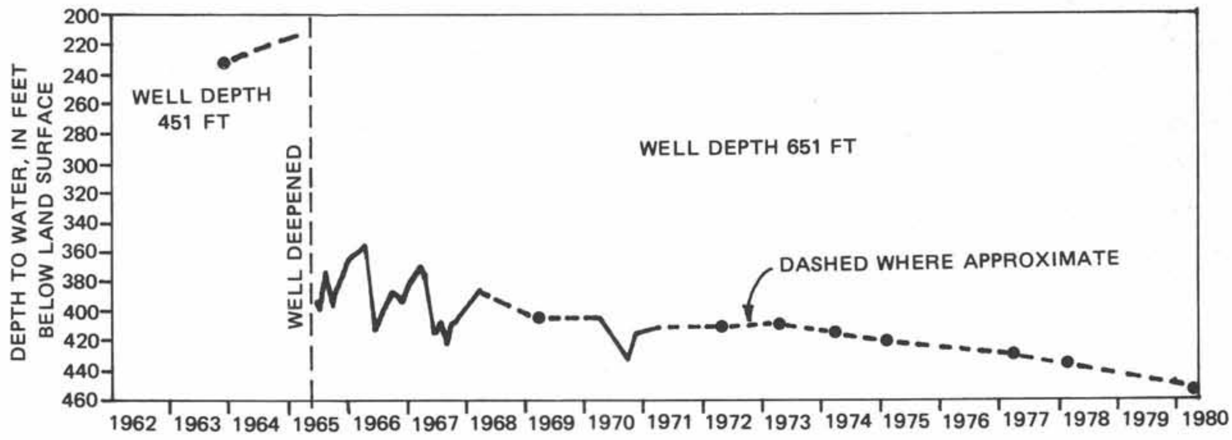


Figure 13. Ground-water level changes in well 21/30-3E1, tapping the Wanapum Basalt.

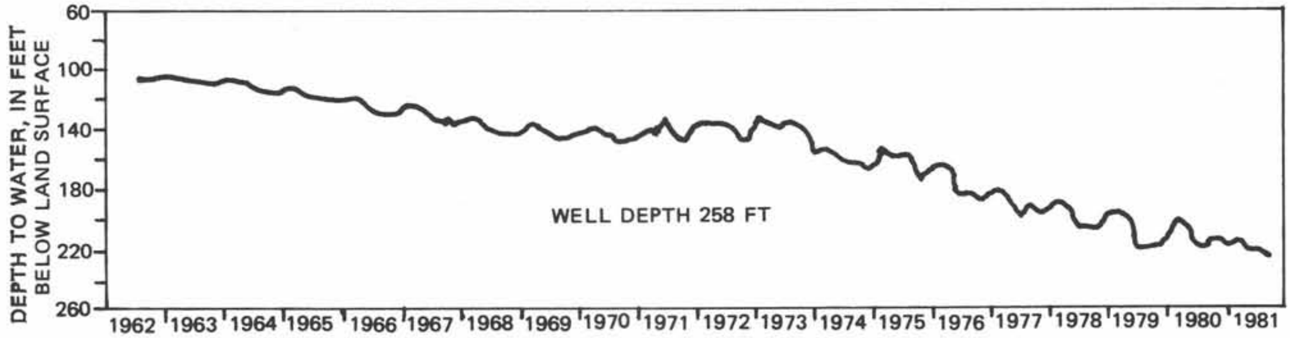


Figure 14. Ground-water level changes in well 17/32-19E1, which was deepened.

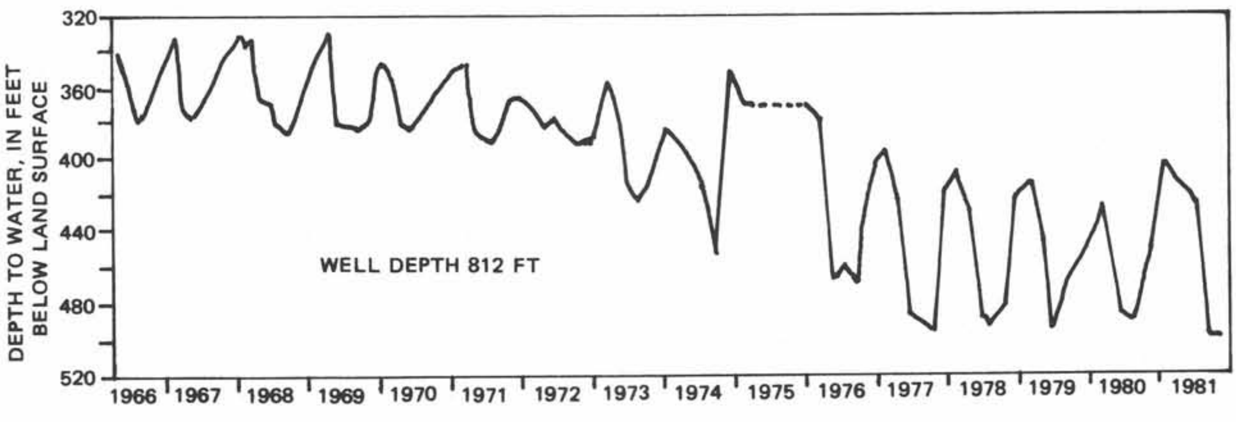


Figure 15. Ground-water level changes in well 16/32-25A1, tapping both the Wanapum and Grande Ronde basalts.

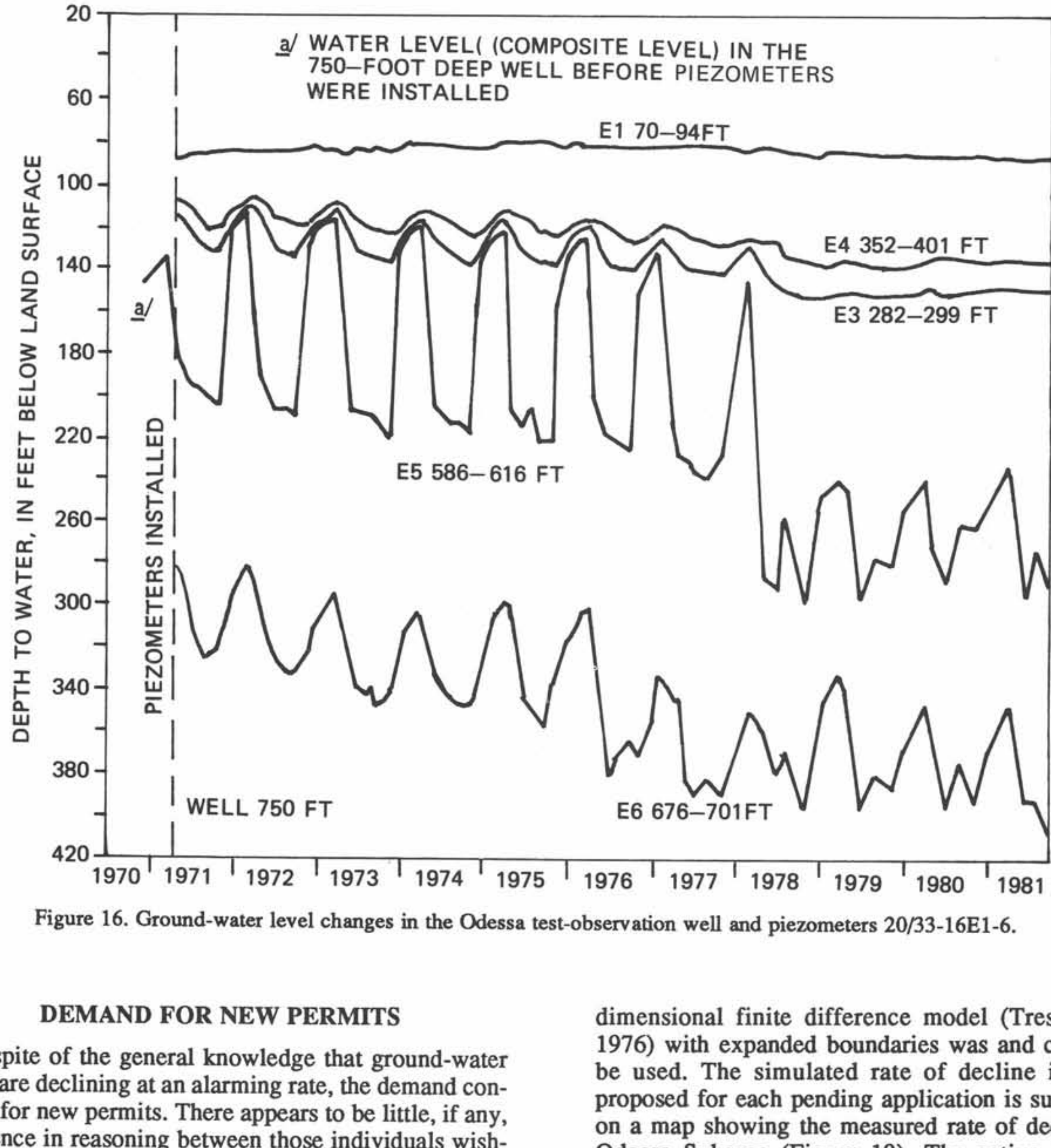


Figure 16. Ground-water level changes in the Odessa test-observation well and piezometers 20/33-16E1-6.

DEMAND FOR NEW PERMITS

In spite of the general knowledge that ground-water levels are declining at an alarming rate, the demand continues for new permits. There appears to be little, if any, difference in reasoning between those individuals wishing to expand irrigation capacity of existing systems and those converting from dry land practices to irrigation other than expectation of increased profit. The water-level decline, associated with increasing costs of power, may dictate extent of future development. Some projects are currently incurring water costs of as much as $50.00/acre-ft in the southern part of the subarea.

Because of the continued demand for new permits, in 1974 the Department decided to process more than 100 ground-water applications which were being held for priority purposes only during the moratorium. The computer program, developed by the U.S. Geological Survey during the 1967-1972 moratorium, was not used then because the model boundary needed to be expanded and dependable pumping data were not available. Instead, the U.S. Geological Survey two-dimensional finite difference model (Trescott et al., 1976) with expanded boundaries was and continues to be used. The simulated rate of decline in the well proposed for each pending application is superimposed on a map showing the measured rate of decline of the Odessa Subarea (Figure 19). The active part of the model includes Townships 13 through 34 and Ranges 28 through 37 and is bounded by constant head nodes. The model boundary extends beyond the subarea boundary to minimize the effect of the constant head boundary on the predicted declines. The transmissivity and storage values are modified slightly from the original 1972 U.S. Geological Survey model data to reflect additional data gathered since that time. Starting with a flat water surface, each well in order of its application priority date is simulated as being pumped for 150 continuous days at a rate equivalent to the annual acre feet requested, and then the simulated water level is allowed to recover for 215 days to complete one irrigation year. The computed water-level decline is printed in map form at the end of the recovery period of the third irrigation year.

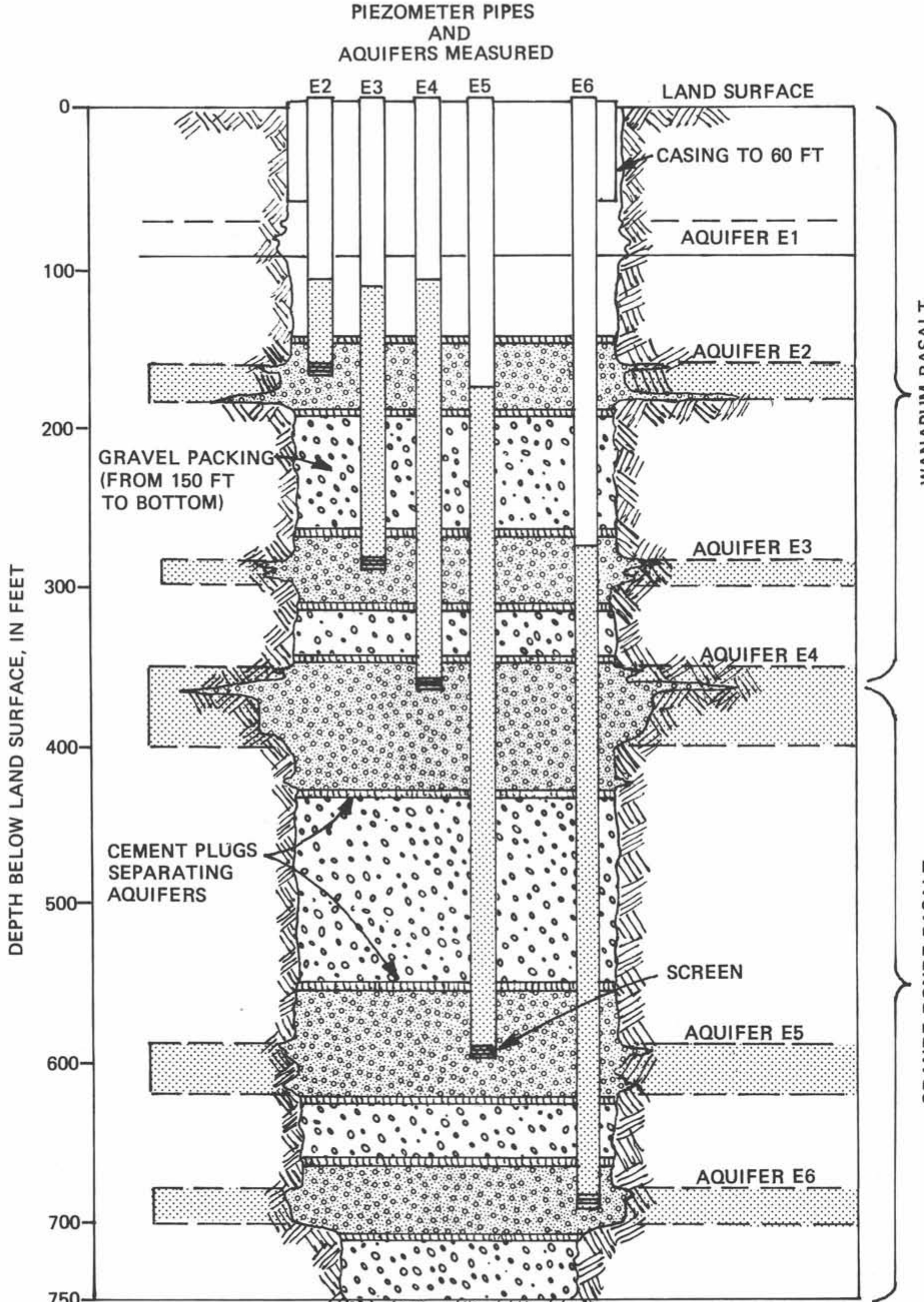


Figure 17. Diagrammatic section through Odessa test-observation well 20/33-16E1-6 showing piezometer pipes and aquifer zones.

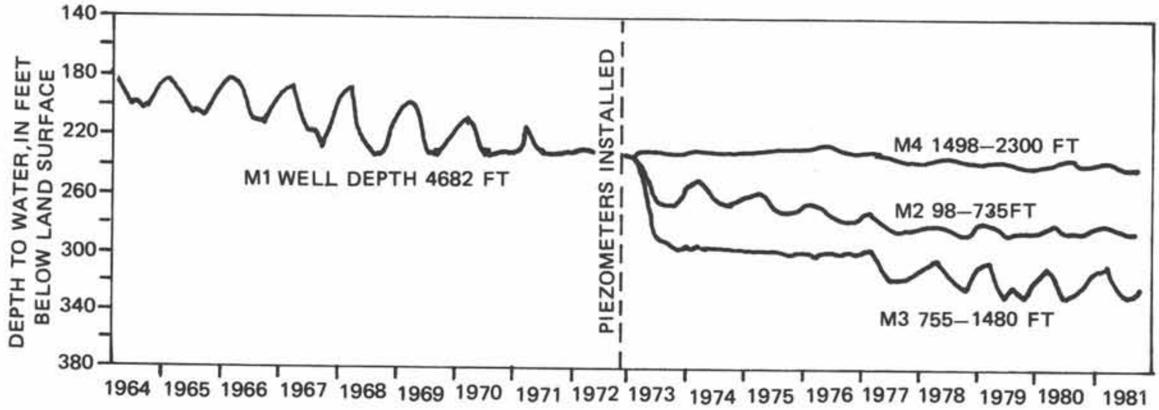


Figure 18. Ground-water level changes in the Basalt Explorer oil test well and piezometers 21/31-10M1-4.

The total water-level decline for the period 1977-1982 was plotted and contoured for those wells penetrating both the Wanapum and Grande Ronde basalts. A contour interval of "50" represents an average decline rate of 10 ft/yr, a "40" contour 8 ft/yr, and so on. (Figure 19). For convenience, the scales of the measured and computed decline maps are the same.

The contour map of current annual decline rates is overlaid on the computer-produced decline map, and the measured and the computed values are matched. An application for a well whose predicted decline plus existing decline rate is within the limit of decline permitted (30 ft in 3 yr) is accepted. Once accepted, the well remains as part of the cumulative pumping pattern consisting of all previously accepted applications. Applications exceeding the limit of decline are withdrawn from further processing, and the permit is denied. A total of 129 applications were processed and 10 permits for 594 acres were approved through 1982.

MANAGEMENT FOR THE FUTURE

Recognizing the intent of the Water Resource Act of 1971 (RCW 90. 54), that is, that the allocation of public water is to be based upon securing the maximum net benefits to the people of the State of Washington and that there is a limited supply of unappropriated public water, the State is faced with some difficult decisions, the results of which will have far-reaching implications.

One readily apparent solution to the problem of water-level declines is to deny permits to all future applications. In effect, this will end the development of irrigated agriculture in a large part of eastern Washington and have serious economic consequences. An alternative is to use computer modeling. With the continuing collection of data on water levels and pumpage, modeling techniques will be increasingly useful and more accurate in predicting effects of new wells.

Because of the continuing demand for permits to irrigate new lands and the opposition of non-irrigators, the State legislature has taken an interest in the problem and has drafted legislation aimed at the problem of declining water levels. Changes in the State water code have also been suggested as a vehicle to better management. Proposals include statewide adjudication of surface and ground water rights to more precisely account for the uses and quantities of public waters; a clear definition of the term "public interest" as used in the Water Resource Act of 1971; and a clear definition of the phrase "reasonable and feasible pump lift" as it is used in the ground-water code (RCW 90. 44. 070, 1947). Additional suggestions include: prioritization of water uses and issuance of permits accordingly, for example, domestic use over irrigation use; issuance of a term permit, as opposed to water rights in perpetuity; and establishment of an applicant's financial ability to complete the project on schedule to discourage speculation in water-short areas.

These alternatives are currently in the discussion stage within the Department of Ecology and other interest groups. The goal is a reasonable solution which is acceptable to the majority of the citizens of the State of Washington.

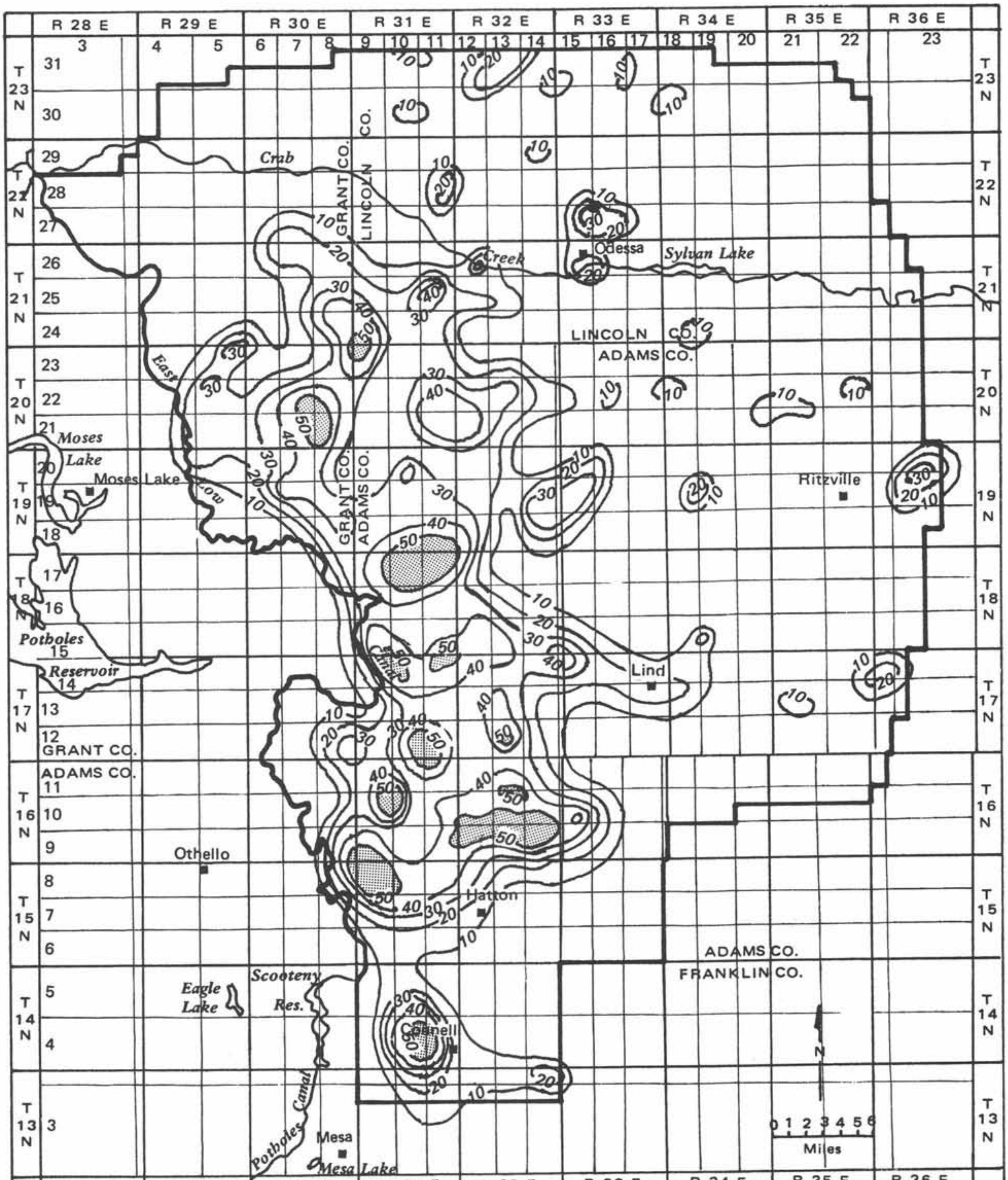


Figure 19. Contour map of ground-water level decline in the Odessa Subarea, 1977-1982 (contours in ft).

REFERENCES

Garrett, A. A., 1968, *Ground Water Withdrawal in the Odessa Area, Adams, Grant and Lincoln Counties, Washington*: Washington Department of Water Resources Water Supply Bulletin 31, Olympia, WA, 84 p.

Luzier, J. E. and Burt, R. J., 1974, *Hydrology of Basalt Aquifers and Depletions of Ground Water in East-Central Washington*: Washington Department of Ecology Water Supply Bulletin 33, Olympia, WA, 53, p.

Luzier, J. E. and Skrivan, J. A., 1975, *Digital Simulation and Projection of Water Level Declines in Basalt Aquifers of the Odessa-Lind Area*: U.S. Geological Survey Water Supply Paper 2036, 48 p.

Swanson, D. A.; Anderson, J. L.; Bentley, R. D.; Beyerly, G. R.; Camp, V. E.; Gardner, J. N.; and Wright, T. L., 1979, *Reconnaissance Geologic Map of the Columbia River Basalt Group in Eastern Washington and Northern Idaho*: U.S. Geological Survey Open-File Report 79-1363, 12 sheets, scale 1:250,000.

Trescott, P. C.; Pinder, G. F.; and Larson, S. P., 1976, *Finite-Difference Model for Aquifer Simulation in Two Dimensions with Results of Numerical Experiments*: U.S. Geological Survey Techniques of Water Resource Investigations, Book 7, Chapter C1, 116 p.

Revised Code of Washington (RCW) 90.44.070, 1947, Regulation of Public Ground Waters

Revised Code of Washington (RCW) 90.44.130, 1947, Regulation of Public Ground Water

Revised Code of Washington (RCW) 90.54, 1971, Water Resources Act of 1971 [Washington Administrative Code (WAC) 173-128A, 1982, Odessa Ground Water Management Subarea]

Washington Administrative Code (WAC) 173-130A, 1982, Odessa Ground Water Subarea Management Policy.

A van with a logging machine panel. Borehole geophysical logging may include natural gamma, spontaneous potential, and resistivity. Photograph courtesy of Golder Associates, Redmond, WA.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Ground Water Management for Renton, Washington: Development of an Aquifer Protection Area

STUART M. BROWN and JEFFERY H. RANDALL
CH2M Hill, Inc.

INTRODUCTION

The City of Renton, Washington, relies on ground water for approximately 85 percent of its water supply. Ground water is withdrawn from the Cedar River aquifer by five wells capable of producing 14 million gpd. Figure 1 shows the general location of the City of Renton and its well field.

Historically, the well field has produced high-quality water that consistently exceeds State of Washington Department of Social and Health Services (DSHS) and the federal Environmental Protection Agency (EPA) quality standards for public water supplies.

The Cedar River aquifer, however, is vulnerable to contamination because ground water is relatively shallow and there are a number of potential sources of contamination close to the well field. Ground water occurs under water-table conditions at a depth of approximately 20 ft below the ground surface; the City of Renton production wells are screened at depths ranging from 35 to 105 ft. As Figure 1 shows, the central business district and several major transportation corridors (particularly Interstate Highway 405 and State Route 169) are near the well field. These and other potential sources of contamination pose a significant threat to the aquifer. The threat is likely to increase in the future because of increased urban and commercial development in the area and proposed highway expansions.

This paper briefly reviews an aquifer protection program initiated by the City of Renton in 1983 and then focuses on one phase of the program: the Well Field Monitoring Study. This study involved monitoring water-level fluctuations and ground-water quality in the vicinity of the well field to provide information on the rates and directions of ground-water movement under different pumping conditions. The paper describes the monitoring activities conducted during the study and how the information was used to delineate an aquifer protection area (APA) for the well field.

AQUIFER PROTECTION PROGRAM OVERVIEW

To date, the City of Renton aquifer protection program has been conducted in three phases (Figure 2):

- Phase 1 – Well Field Protection Study
- Phase 2 – Well Field Monitoring Study
- Phase 3 – Ordinance Development

A more detailed description of each phase is provided in Brown and Randall (1987).

Phase 1 – Well Field Protection Study

Phase 1, the Well Field Protection Study (CH2M Hill, Inc., 1984), involved:

(1) Characterization of the hydrogeology of the Cedar River aquifer and potential contaminant migration pathways,

(2) Inventory of potential sources of contamination,

(3) Development of preventive measures for different types of potential sources, and

(4) Initiation of a public information program.

Hydrogeologic Characterization

The hydrogeologic characterization involved a review of the following information: Water Resources Bulletin 28 (Luzier, 1969), boring logs for the City of Renton production wells, and a hydrologic analysis of Well 9.

On the basis of this information, it was determined that the Cedar River aquifer is a 70- to 90-ft-thick delta and alluvial deposit at the mouth of the Cedar River valley. Following the retreat of the last glaciation, the Cedar River eroded a channel into the existing glacial drift plain and deposited a delta fan into a marine embayment that occupied the valley. The fan deposits consist of coarse gravel and cobbles near the mouth of the valley and grade to sands and silty sands radially outward from the mouth. Overlying the fan deposits are more recent alluvial deposits of the Cedar River.

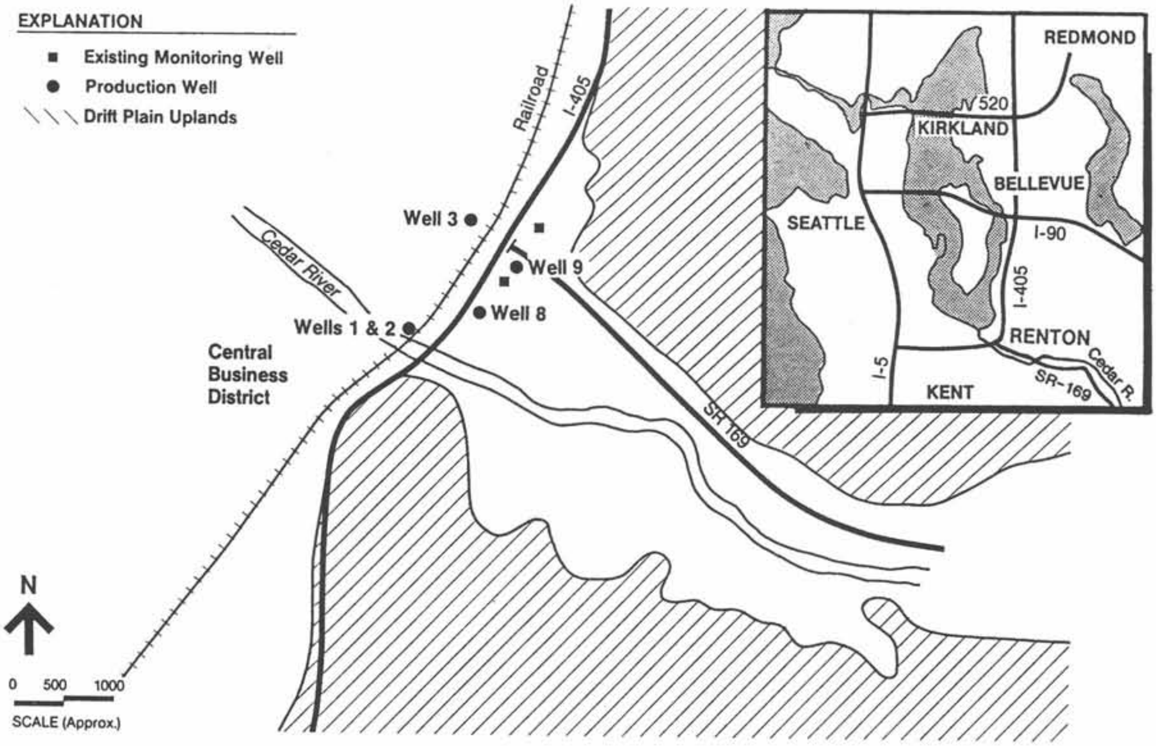


Figure 1. City of Renton well field area.

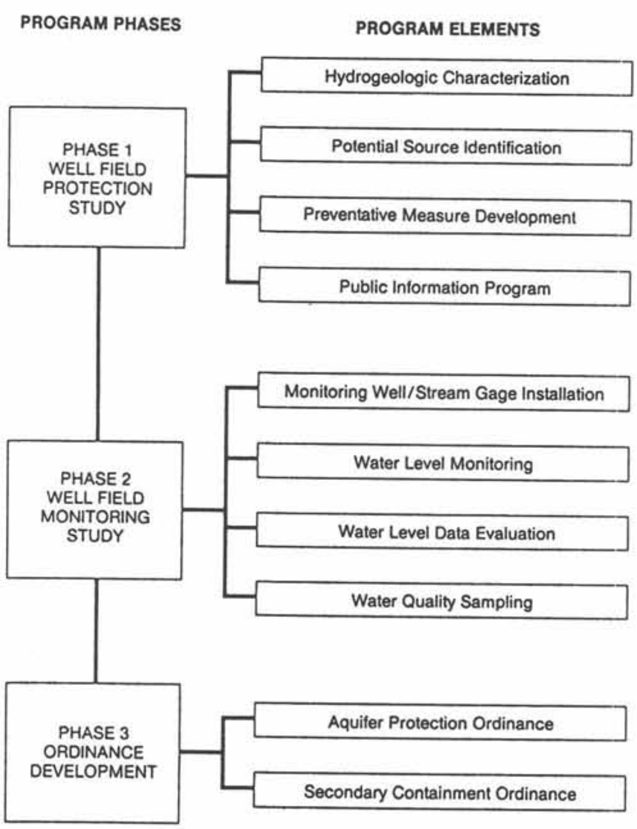


Figure 2. City of Renton Aquifer Protection Program phases and elements.

Ground water occurs under water-table conditions at a depth of approximately 20 ft below the land surface. Regionally, ground water moves westward, down the Cedar River valley (Figure 1). Locally, ground-water movement is influenced by well field pumping.

The probable lateral extent of the aquifer is shown in Figure 3. To the northeast and southeast of the Cedar River, the aquifer is bounded by the drift plain uplands. To the southeast, the aquifer extends beyond a bedrock narrows located about 4,000 ft from the well field. The western boundary is defined as the approximate extent of coarse sand and gravel materials associated with the delta deposit.

Identification of Potential Contaminant Sources

A four-step process was used to inventory potential sources of contamination. The first step was to identify existing land uses within the limits of the Cedar River aquifer and its recharge areas that could be potential sources of contamination. Incidents that could lead to a contaminant release to the aquifer were also identified (for example, spills and sewer overflows). The second step was to divide the potential contamination sources into five general categories: subsurface, surface, river, transportation, and general. The third step in the process was to characterize each potential source in terms of the following key factors:

(1) Nature of the hazard posed by the source,

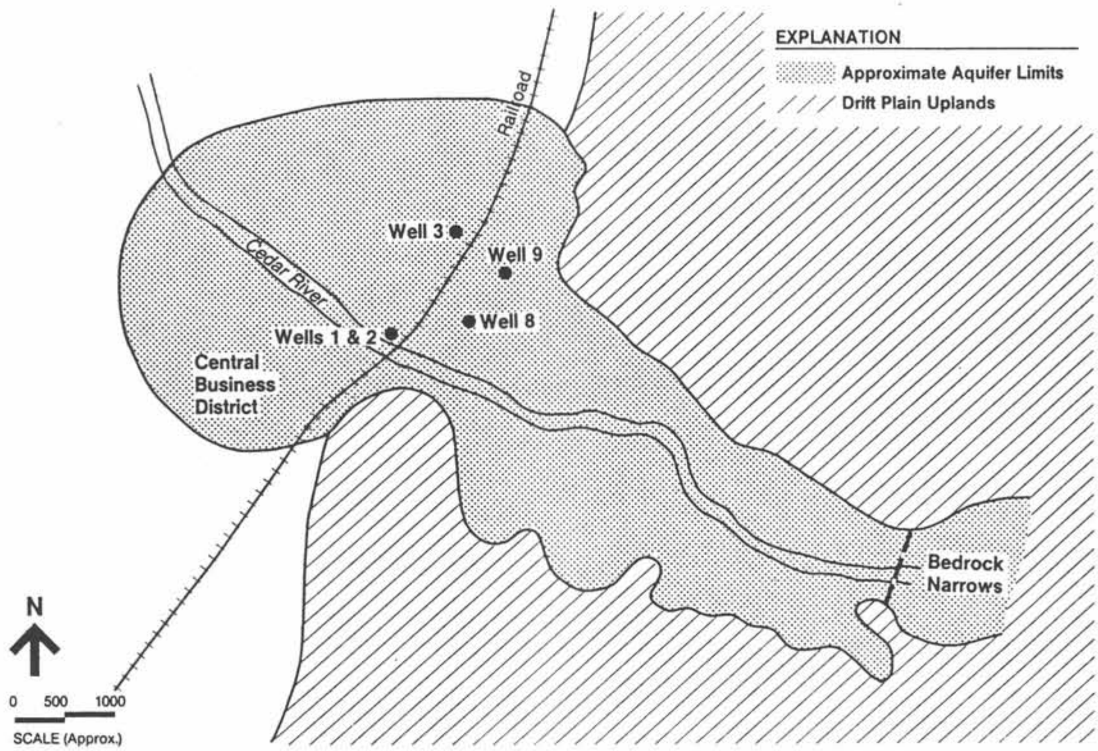


Figure 3. Approximate limits of Cedar River aquifer.

(2) Source location with respect to the well field and probable direction of ground-water movement,

(3) Quantity of chemical,

(4) Probability of occurrence of a release,

(5) Potential for chemical attenuation because of adsorption, precipitation, degradation, and dilution, and

(6) Ability to detect a release and prevent migration.

The final step was to qualitatively rank each source (for example, high, medium, or low) according to its potential for impacting the aquifer. The six factors listed above were used to develop a qualitative ranking.

Development of Preventive Measures

Measures for preventing contamination were developed for those potential sources that were ranked as high or medium. It was decided that preventive measures were probably not necessary at this time for sources that ranked low. Two types of preventive measures were developed: (1) general measures applicable to a number of sources and (2) measures applicable to specific sources. The general preventive measures that were developed are summarized in Table 1. Preventive measures for specific sources are presented in CH2M Hill, Inc. (1984) and Brown and Randall (1987).

Table 1. Summary of general preventive measures

Develop policies that limit land use within the aquifer recharge area. Such policies include appropriate zoning to limit or eliminate commercial activities that are potential contaminant sources and the acquisition of such properties for conversion to park, greenbelt, or another noncontaminating use.
Increase participation by the City of Renton in resolution of regional issues that may impact aquifer protection. These issues include I-405/I-90 and other highway planning, construction, and traffic restrictions; continued use of and hauling of waste to the Cedar Hills landfill; and use in the river basin east of the city limits; sewerage of outlying areas; and maintenance of minimum stream flows in the Cedar River.
Petition of EPA to have the Cedar River aquifer declared a sole-source supply.
Monitor water-table elevations in the aquifer area to confirm ground-water and contaminant flow paths.
Monitor water-quality of both well (aquifer) water and river water to observe trends in contaminant levels.
Develop an emergency response plan to deal with possible aquifer contamination incidents.

Public Information Program

In an effort to inform the public of the need to protect ground-water quality, the City of Renton prepared a public information leaflet. The leaflet discusses the importance of protecting ground-water quality and presents a series of do's and don'ts for the handling and disposal of potential contaminants (for example, paints, solvents, lubricating oils, household cleaners, and antifreeze). The City of Renton distributes the leaflet to developers, contractors, engineers, and local citizens.

Phase 2 – Well Field Monitoring Study

One of the major findings of the Well Field Protection Study was that rates and directions of ground-water movement in the vicinity of the well field and the zone of potential capture for the well field could not be determined from the available hydrogeologic information. Thus, additional hydrogeologic information needed to be collected to provide a defensible basis for delineating an APA.

For this reason, the City of Renton initiated a well field monitoring study. As Figure 2 illustrates, the Well Field Monitoring Study consisted of four major program elements:

(1) Monitoring well/stream gage installation,

(2) Water-level monitoring,

(3) Water-level data evaluation, and

(4) Water-quality sampling.

A more detailed description of each program element is presented in the next section.

Phase 3 – Ordinance Development

The Well Field Protection Study recommended that the City of Renton implement administrative restrictions to control land uses and activities that could impact the well field. The City decided to implement these restrictions through an aquifer protection ordinance. The Well Field Protection Study also recommended that restrictions be placed on underground storage facilities, particularly in the vicinity of the well field. A separate secondary containment ordinance was drafted, with special provisions for existing underground storage facilities located in the aquifer protection area. Brown and Randall (1987) provide a description of both ordinances.

WELL FIELD MONITORING STUDY

The original objective of the Well Field Monitoring Study was to determine rates and directions of ground-water movement near the well field to determine the zone of potential capture under different pumping conditions. This objective was subsequently expanded to include two more objectives:

(1) Delineation of the boundaries of an APA for the well field to satisfy the provisions of the City of Renton aquifer protection ordinance.

(2) Ground-water sampling to obtain additional information on existing water-quality conditions in the Cedar River aquifer.

Water-Level Monitoring Activities

To meet these objectives, a monitoring network consisting of 11 ground-water monitoring wells and three Cedar River stage gages was designed. The location of each monitoring well and stage gage, as well as the location of the five production wells that constitute the City of Renton well field (PW1, PW2, PW3, PW8, and PW9) are shown in Figure 4. Except for MW8 and MW9, all monitoring wells shown in Figure 4 were installed during the Well Field Monitoring Study. MW8 and MW9 are observation wells installed during the construction and testing of PW9. The three Cedar River stage gages installed during the Well Field Monitoring Study are also shown in Figure 4. City of Renton staff recorded water levels in the monitoring wells and production wells and at the Cedar River stage gages 21 times between March 1986 and March 1987.

In June of 1987 a well-field pumping test was conducted by the City of Renton as part of a water rights evaluation study. The study consisted of an 8-hr shutdown of the well field to allow the aquifer to recover, followed by two 24-hr periods of pumping. Pumping during the first period was at the current water right of 11,500 gpm; pumping during the second period was at an increased rate, 15,000 gpm. This test provided an opportunity to collect additional water-level data under controlled pumping conditions. Water levels were measured in all of the monitoring wells at the end of the 8-hr recovery period and at the end of each 24-hr pumping period. Continuous recordings of water levels were made prior to and during the test in monitoring wells MW1, MW5, and MW10 (Figure 4).

All of the water-level data were analyzed by contouring water levels to obtain potentiometric maps and by plotting water-level variations with time at each well or stage gage to obtain hydrographs. On the basis of the potentiometric maps and hydrographs, the zone of potential capture for the well field was defined by determining:

(1) Probable directions of ground-water movement, and

(2) Cedar River-aquifer interactions.

Directions of Ground-Water Movement

A potentiometric map (Figure 5) shows ground-water elevations and probable directions of ground-water movement under a no pumping condition (that is, none

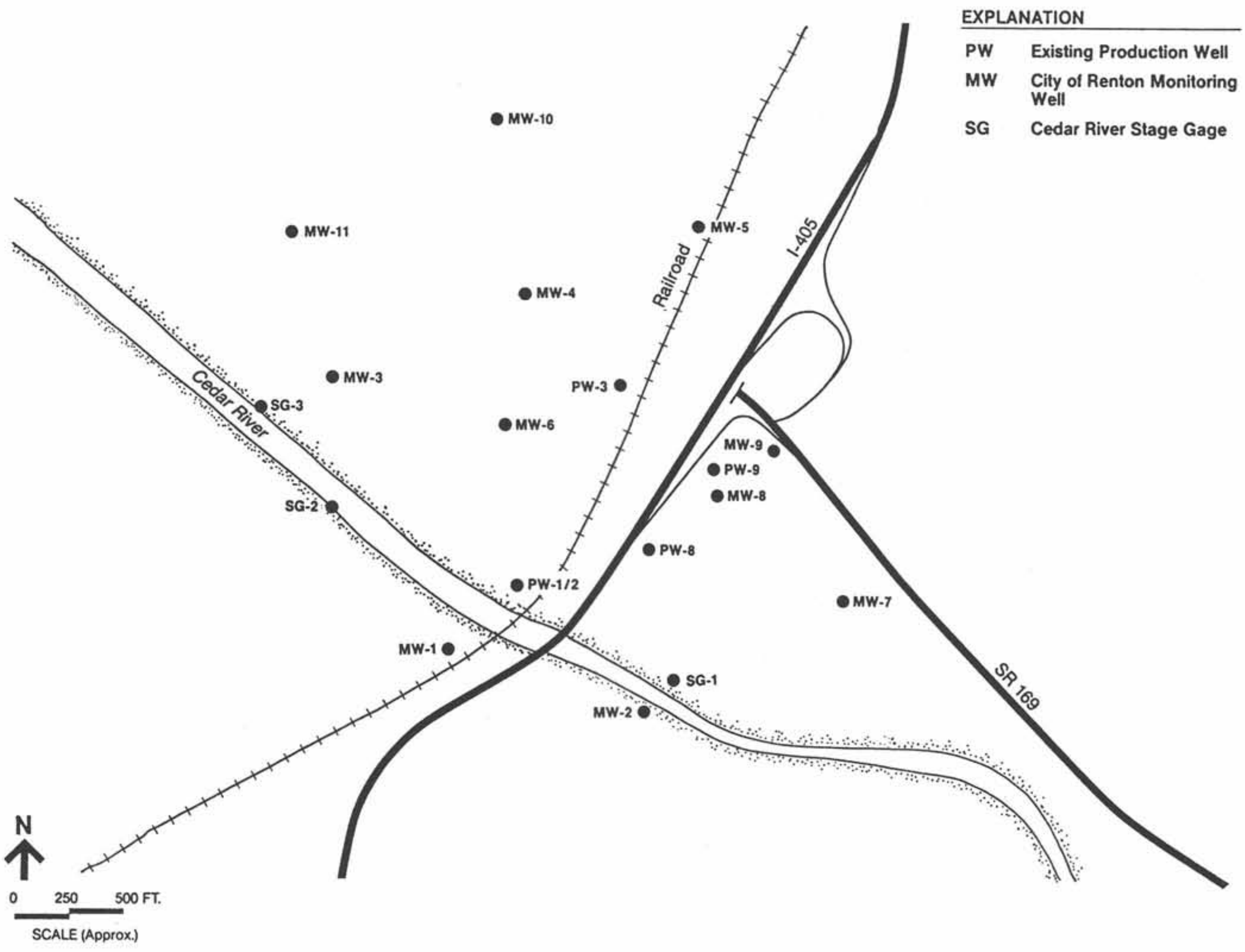


Figure 4. Location of wells in monitoring network.

of the wells are in operation). This potentiometric map indicates that the regional direction of ground-water movement is to the west.

When one or more of the wells is pumped, a cone of depression forms around the well(s), causing ground water to flow toward the well. Figure 6 is a potentiometric map that illustrates this condition.

The boundary between the portion of the Cedar River aquifer in which ground-water movement continues in the regional direction and the portion in which ground-water movement is back towards the well field is referred to as a ground-water divide. The ground-water divide defines the boundary of the well field zone of potential capture. As will be discussed later, the location of the divide defines part of the boundary of the well field aquifer protection area. Its approximate position on September 16, 1986, when PW8 was in operation, is shown as a dashed line in Figure 6. The results of the Well Field Monitoring Study indicate that the zone of potential capture expands and contracts depending upon well field pumping and regional ground-water flow conditions. The maximum extent of the zone of potential capture occurs during the summer when well field pumping is at its maximum and regional ground-water elevations are low.

Cedar River-Aquifer Interactions

Monitoring of ground-water elevations across the Cedar River from the well field found that pumping of PW1 and PW2 influences ground-water movement south of the river. Thus, the zone of capture extends to the south of the river. This influence was clearly observed at monitoring well MW1 during the June 1987

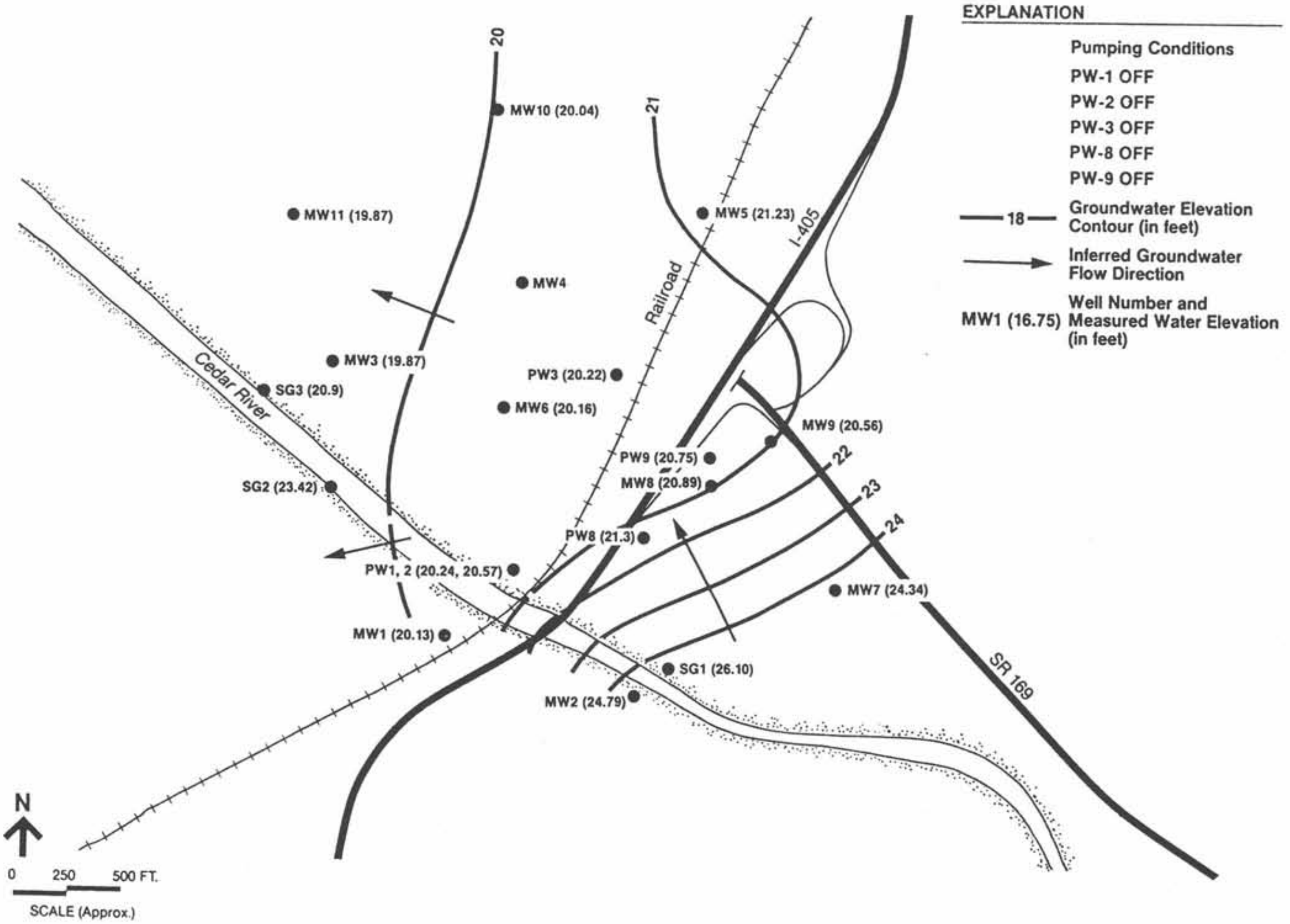


Figure 5. Ground-water elevations, January 23, 1987.

well-field pumping test. From the available data, pumping of PW3, PW8, or PW9 does not appear to influence ground-water movement south of the river.

Monitoring of river and ground-water elevations near the Cedar River indicates that the river contributes limited recharge to the aquifer in the vicinity of the well field. The results of the June 1987 well-field pumping test indicate that the magnitude of the river recharge is small in comparison to the well-field pumping rate. Monitoring of stream flows upgradient and downgradient of the well field during the pumping test did not detect any measurable change in flow rate.

Delineation of the Well Field Aquifer Protection Area

The results of the Well Field Monitoring Study and Well Field Protection Study provided a basis for delineating an APA for the well field to satisfy the provisions of the City of Renton aquifer protection ordinance.

According to the ordinance, an APA can be divided into two zones. Zone 1 is defined as the area between the 365-day ground-water travel-time contour and the well field. Zone 2 is defined as the area between the 365-day travel-time contour and the recharge area for the well field.

Probable ground-water velocities in the Cedar River aquifer under different pumping conditions were calculated to determine the extent of the 365-day travel-time contour. Velocities were estimated from hydraulic conductivities obtained from pumping test data, an assumed effective porosity of 0.25, and gradients obtained from potentiometric maps. The resultant velocities were converted into probable ground-water travel times.

From the calculated travel times, the boundary for Zone 1 was delineated as follows: The regional downgradient boundary of Zone 1 was generally defined as the extent of the zone of potential capture under current water right pumping conditions (Figure 7) because

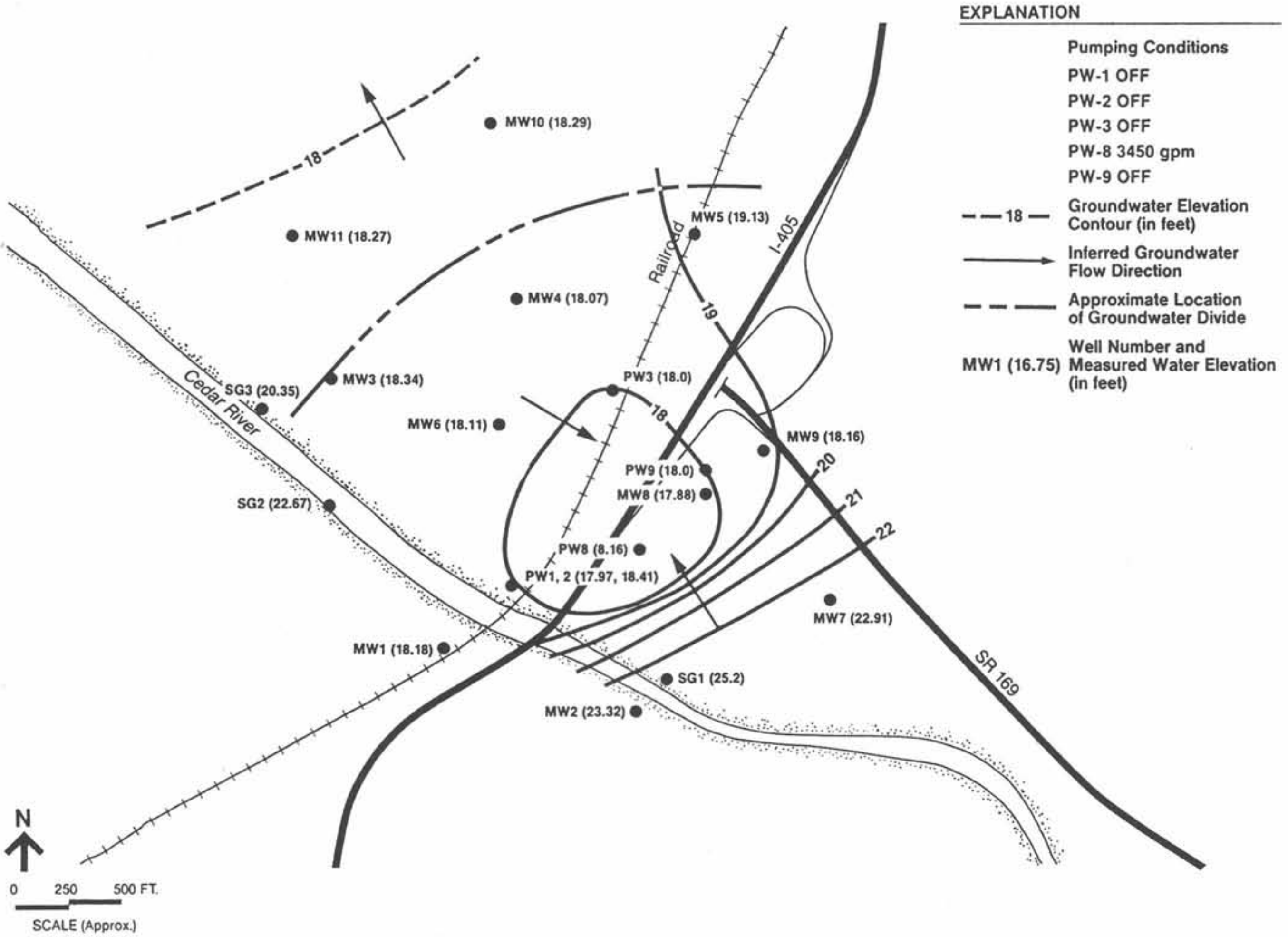


Figure 6. Ground-water elevations, September 16, 1986.

calculated travel times from the ground-water divide were less than 365 days. The only exception is in an area immediately north of the well field. In this area, the zone of capture extends beyond the coarse sand and gravel materials commonly associated with the Cedar River aquifer into less permeable silt and peat materials associated with Lake Washington deposits. Because ground-water velocities in the silt and peat deposits are low, the boundary for Zone 1 does not extend as far as the ground-water divide. Where the ground-water divide intercepts the uplands north and south of the well field, the boundary of Zone 1 proceeds regionally upgradient (that is, to the east) along the walls of the Cedar River valley past the bedrock narrows (Figure 7). These portions of the Zone 1 boundary correspond to the northern and southern limits of the Cedar River aquifer. The upgradient (or eastern) boundary of Zone 1 transects the Cedar River valley approximately 6,000 ft from the well field. This distance corresponds to a 365-day ground-water travel time.

Zone 2 encompasses upland areas north and south of the Cedar River valley that contribute recharge to the Cedar River aquifer (Figure 7). The boundary of Zone 2 was delineated by mapping the surface drainage area for the Cedar River east of where the ground-water divide intercepts the uplands north and south of the well field. The eastern boundary of Zone 2 corresponds to the Renton city limits.

Ground-Water Quality Monitoring

The Well Field Monitoring Study also consisted of sampling ground water from four monitoring wells. Priority pollutant analyses were conducted on the samples to obtain supplemental data on the quality of water in the Cedar River aquifer. As is shown in Table 2, ground water in the Cedar River aquifer satisfies current and proposed maximum contaminant levels (MCL) specified by the EPA for drinking water.

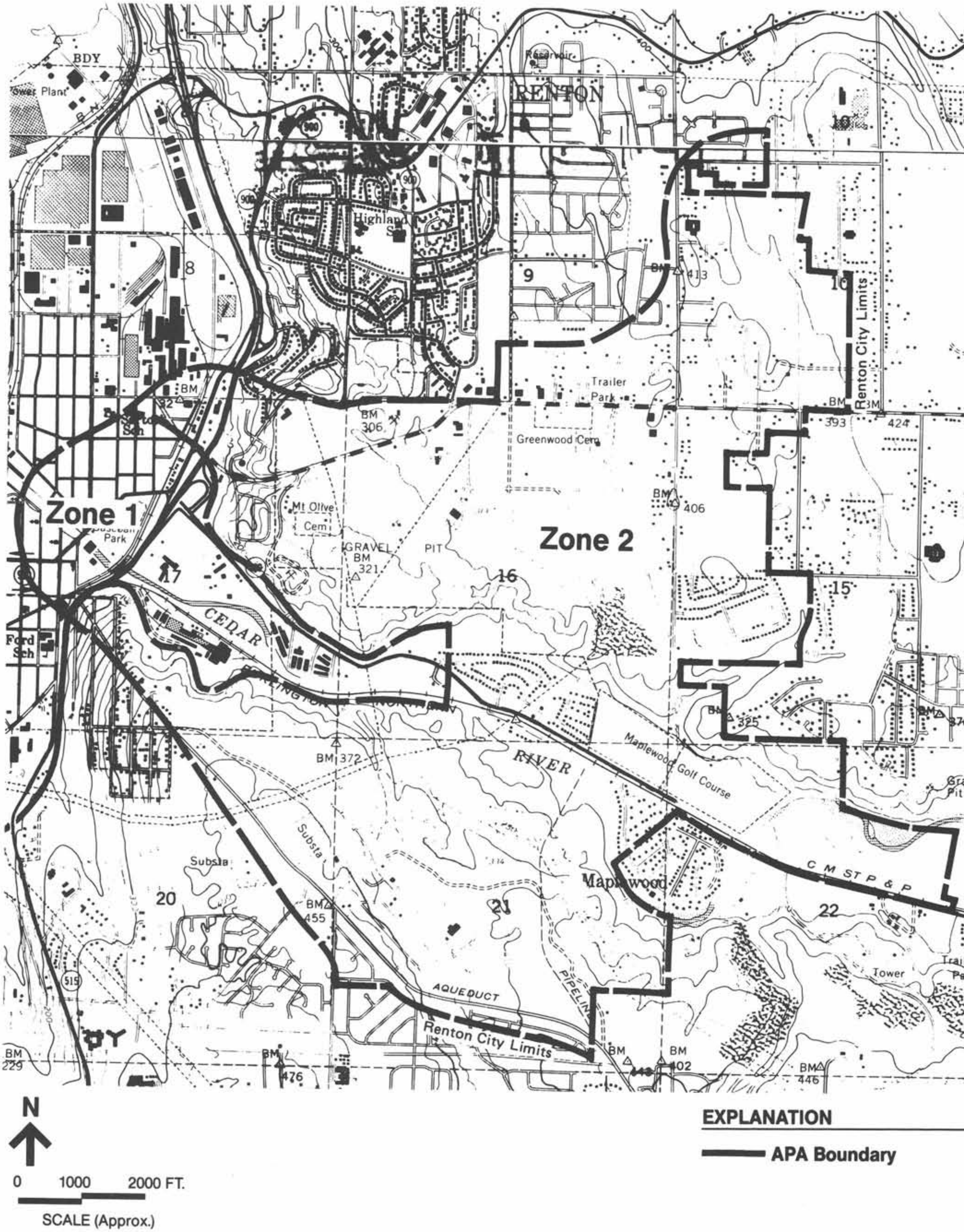


Figure 7. Well-field Aquifer Protection Area.

Table 2. Concentrations (μg/l) of selected inorganic and organic constituents, City of Renton monitoring wells, June 12, 1986; MCL, maximum contaminant levels (μg/l), U.S. Environmental Protection Agency, September 1986; ND, not detected

Constituent	MCL		Sampling Results				Detection Limit
	Current	Proposed	MW1	MW4	MW5	MW7	
Inorganic							
Arsenic	50		ND	ND	ND	ND	5
Cadmium	10		ND	ND	2	2	1
Chromium	50		1	1	3	2	1
Selenium	10		ND	ND	ND	ND	5
Lead	50		ND	ND	ND	ND	10
Organic							
Endrin	0.2		ND	ND	ND	ND	0.04
Lindane	4		ND	ND	ND	ND	0.02
Methoxychlor	100		ND	ND	ND	ND	0.1
Toxaphene	0.5		ND	ND	ND	ND	5
2,4-D	100						
2,4,5-TP silvex	10						
Benzene		5	ND	ND	ND	ND	1
Carbon tetrachloride		5	ND	ND	ND	ND	1
1,2-Dichloroethane		5	ND	ND	ND	ND	1
1,1-Dichloroethylene		7	ND	ND	ND	ND	1
p-Dichlorobenzene		750	ND	ND	ND	ND	1
1,1,1-Trichloroethane		200	ND	ND	ND	ND	1
Trichloroethylene		5	ND	ND	ND	ND	1
Vinyl chloride		1	ND	ND	ND	ND	1

CONCLUSIONS

A major element of most ground-water management programs is the delineation of an APA. Available hydrogeologic information rarely provides a defensible basis for delineating such an area. For this reason, a ground-water monitoring study will generally be required to generate additional hydrogeologic information. The elements of the monitoring program will depend upon site-specific hydrogeologic conditions, well or well-field operations, and ground-water management program needs (for example, ordinance requirements).

One year of monitoring of ground water and Cedar River elevations provided the additional information required to delineate an APA for the City of Renton well field. The water-level data collected during the Well Field Monitoring Study were used to determine probable directions of ground-water movement and Cedar River-aquifer interactions. Both were required to determine the extent of the zone of potential capture under different pumping conditions. The data were also used to calculate ground-water travel times for purposes of dividing the APA into two zones requiring different levels of protection.

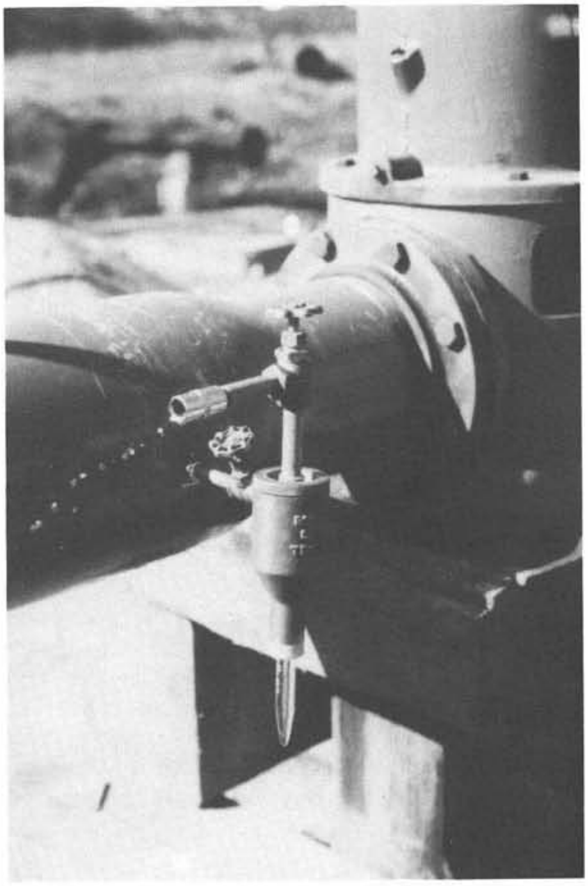
REFERENCES

Brown, S. M. and Randall, J. H., 1987, Aquifer protection–One Washington city's experience. In *Proceedings of the Focus Conference on Northwestern Ground Water Issues*, Portland, OR, May 5-7, 1987: National Water Well Association, Dublin, OH, pp. 25-46.

CH2M Hill, Inc., 1984, *Well Field Protection Study, City of Renton, Washington*: Prepared for City of Renton, WA, 66 p., 7 figures.

Luzier, J. E., 1969, *Geology and Ground Water Resources of Southwestern King County, Washington*: Washington Department of Water Resources Water Supply Bulletin 28, Olympia, WA, 260 p., 3 plates.

Pumping test of an 8-in.-diameter test well at approximately 450 gpm at the site of a proposed fish hatchery on the Nisqually River near McKenna, WA. Photograph courtesy of Hart Crowser Inc., Seattle, WA.



A sand testing device mounted in the pump discharge line for the pumping test of a municipal supply well near Renton. Photograph courtesy of CH2M Hill, Inc., Bellevue, WA.

Waste Disposal and Ground-Water Contamination

Larry West and James S. Bailey, Chapter Editors

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Waste Disposal and Ground Water Contamination: Introduction

LARRY WEST
Sweet-Edwards/EMCON, Inc.

ISSUES AND CONCERNS

Waste disposal has emerged as one of the paramount geotechnical issues of the 1980s in terms of both public awareness and as steady employment for the geotechnical profession. The recent and increasing attention placed on waste disposal bodes well for our society, for, as most major social issues go, it is a relatively unglamorous, economically depressing, and generally dirty (literally and metaphorically) subject to deal with. There is little argument that the increasing amounts and complexity of the waste our society generates are a direct reflection of our prosperity and technological advancement. However, it can be argued that the increasing amounts and complexity of our waste are also a reflection of society's failure to efficiently utilize our natural and manmade resources. Also, the numerous ground-water contamination problems occurring across the country are indicative of society's failure to properly dispose of its waste.

Our heightened awareness of waste and contaminated ground-water problems are also a direct product of our technological advancement. The ability of scientists to monitor changes in our environment has increased by orders of magnitude. A scant few years ago we had trouble measuring chemical parameters in our soil and water in the parts-per-million range. Now, routine analysis in the parts-per-trillion range is an everyday occurrence. Likewise, health and medical advances have taught us what to look for. Fifteen years ago, ethylene dibromide (EDB) was applauded as an effective antiknock additive for gasoline and helped our cars run better. EDB also proved to be an excellent nematicide, increasing the yield and quality of our own Northwest strawberries and raspberries. Now we know EDB as a particulary persistent carcinogen that has contaminated ground-water supplies in several Washington farming areas.

The state of Washington is relatively fortunate in that its youth, low population density and environmental awareness have resulted in relatively few waste-disposal and ground-water contamination problems. Nevertheless, problems do exist, but, as the case studies presented in this chapter illustrate, a considerable amount of human, technological, and economic effort has been and continues to be expended to address and alleviate these problems.

In order to provide the proper setting or context for these case studies, the reader may find useful the following overview of major factors influencing hydrogeologic investigations of waste-disposal and ground-water contamination sites in the state of Washington. These factors include: waste definition, problems associated with waste disposal, the hydrogeologic environments unique and common to western and eastern Washington and, equally important, the regulatory environment.

REGULATORY ENVIRONMENT

With few exceptions, government regulation is the driving force behind most of the effort in developing sound waste-disposal practices and identifying and cleaning up existing ground-water contamination. Regulations now dictate siting, design, operation, and monitoring of waste disposal facilities. They also dictate the approach and, in many cases, the methodology of conducting hydrogeologic investigation of existing ground-water contamination problems. Consequently, practicing hydrogeologists must have, in addition to their scientific skills, an understanding of the laws and regulations governing the waste-disposal industry. In some situations adherence to regulations during the course of an investigation is a relatively simple "cookbook" type approach. However, more often than not (particularly in existing contamination situations), scientific investigations as well as engineered solutions are guided by the complicated legal manipulations of lawyers and the power of the courts. This is the direct result of the liability involved for both industry and consultant, the enormous cost involved in ground-water investigation, monitoring, and cleanup, as well as the numerous, often conflicting and overlapping federal, state, and local regulations.

Solid Waste

Prior to 1972, waste disposal in Washington was virtually unregulated beyond state requirements for permitting by local health departments. In 1972 the State adopted Minimum Functional Standards (MFS) for Solid Waste Handling, Chapter 173-301 Washington Administrative Code (WAC). While these standards provided for the inclusion of ground-water pollution controls in waste disposal site development, they were relatively limited and interpreted on a case by case basis. From a ground-water perspective, the only elements included in the 1972 MFS were provision for leachate control and a separation equivalent to 4 ft of impervious soil between the bottom of the solid waste and highest ground water.

The 1972 MFS required design reports, but throughout the early and mid 1970s, the State lacked the resources (money and expertise) to adequately implement the MFS. It was also during the early to mid 1970s that most of the existing waste disposal sites were established. By the time the solid waste industry and the regulatory agencies (primarily local health departments and the Washington Department of Ecology) were consistently interpreting and applying the MFS, the federal government, through the Environmental Protection Agency (EPA), had adopted and was enforcing the 1976 Resource Recovery and Conservation Act (RCRA), which provided for the regulation of solid and hazardous waste disposal.

Under agreement with EPA, the Department of Ecology is responsible for implementing the federal regulations and in response, after several years of development, adopted in 1985 a new set of MFS (WAC 173-304). The new MFS are detailed and comprehensive, covering nearly every aspect of solid-waste disposal from initial siting to long-term post-closure monitoring.

Hazardous Waste

Its emotionally charged names as well as its environmental and health consequences have focused much of society's attention and resources on hazardous waste. Consequently, prior to 1986, the regulatory emphasis was much greater with respect to hazardous waste than to solid waste. However, with time and increased enforcement activity, solid-waste disposal facilities are being treated more like hazardous-waste disposal sites. These actions are due to the unknowing (in most cases) disposal of hazardous wastes in rural and municipal landfills and an increasing body of information indicating that leachates from municipal solid waste (previously thought benign) commonly contain hazardous substances. By and large, however, most ground-water contamination is due to improper handling or disposal of hazardous waste at industrial sites, private sewage drainfields, and the agricultural use of pesticides and herbicides. Nearly 400,000 tons of hazardous waste are generated in Washington every year (Kruger, 1986). However, at present, there is no authorized hazardous-waste disposal site in Washington. All hazardous waste as well as contaminated soils must be transported to disposal sites in Oregon or Idaho.

There are numerous federal, state, and local laws governing the regulation of hazardous waste. The first and foremost is the RCRA. RCRA was amended in 1980 and again in 1984. The most relevant part of RCRA was Subtitle C - Hazardous Waste Management. Subtitle C provided for the identification and listing of hazardous waste as well as standards for hazardous-waste generators, transporters, and owners and operators of hazardous-waste facilities (storage, treatment, and disposal). Subtitle C also provides for enforcement of the law, and in Washington this function has been delegated to the Department of Ecology by the EPA.

The initial response by the state was the 1980 implementation of its own Dangerous Waste Regulations (Chapter 173-303, WAC). These regulations covered most of the hazardous-waste provisions of RCRA, but they specifically excluded radioactive wastes.

Equally important as RCRA in driving the search for and cleanup of contaminated sites is the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) passed by Congress in 1980. CERCLA, otherwise known as Superfund, established the liability and funding for contaminated site cleanup. Furthermore, it established the National Priority List (NPL), under which EPA targets the most seriously threatening contamination sites for early cleanup. Washington contains 23 NPL sites. Only 10 other states have a greater number of NPL sites. This implies that Washington has a greater contamination problem than many other parts of the country, or that EPA Region X is more diligent and/or zealous in identifying NPL sites. While Superfund has played a major role in stimulating hydrogeologic investigation in Washington, the actual success rate of Superfund was rather dismal. Within the first 5 yr of Superfund, only 15 of the more than 1,500 NPL sites across the country had been cleaned up, and cleanup costs increased from \$2.5 million to \$8.3 million per site (Atkeson et al., 1986). The poor success rate was in part due to the inadequacies of the Superfund law itself, as well as to the reluctance of potentially responsible parties to engage in such costly cleanup activities. Consequently, President Reagan signed into law the Superfund Amendments and Reauthorization Act of 1986 (SARA). SARA was designed primarily to prevent litigation from influencing the rate of NPL site cleanup. Also, it provides for a much greater role for the Washington Department of Ecology in implementation of Superfund. In accord with the provisions set forth in SARA, the Washington legislature passed its own superfund law in October 1987, which, through industrial taxes, provides additional funds for site cleanup. SARA also provides for cleanup of federal facilities on the

NPL, including McChord Air Force Base and Fort Lewis in Pierce County.

One of the more subtle elements of SARA that has major implications for the geologic practioner is the section that eliminates the liability of "innocent landowners" who have purchased contaminated property. However, the innocent landowner must not have had knowledge after appropriate inquiry of the contamination at the time of acquisition. Appropriate inquiry includes taking into account specialized expertise (Marvin, 1986). This expertise falls into the domain of the hydrogeologist and means that more and more bankers and developers will require environmental audits or contamination investigations prior to the transfer of property. While such environmental audits have become commonplace in the Southwest and Northeast, there has been little demand for them in Washington. With the implementation of SARA and correlative state legislation, the geotechnical industry is besieged by last minute requests for soil and ground-water testing necessary to finalize property sales. It is important to note, too, that the demand for environmental audits applies not only to active industrial properties, but also to cow pastures, woodlands, and farms.

The impacts of regulation are significant. Adherence to the regulations over the long term will ensure high-quality ground water for future generations; however, the costs will be enormous. The regulatory environment which currently prevails will also ensure the accumulation of sufficient high-quality data. The regulations in some instances advance the waste industry's state of the art. Without a doubt, the hydrogeologists' role becomes more comprehensive as well as more demanding. They are responsible not only for protecting the environment and seeking cost-effective solutions to problems, but also for ensuring that the plethora of complex and sometimes conflicting regulations are not erroneously or improperly applied.

WASTE DEFINITION AND GROUND-WATER CONTAMINATION

Generally, waste is broken down into two major classifications: solid waste and hazardous waste. This classification is primarily a result of the federal and state regulations governing the generation and disposal of waste.

Solid waste as defined by the federal government in the Code of Federal Regulations (CFR) 40, part 241.101, includes "garbage, refuse, sludges, and other discarded solid materials resulting from industrial and commercial operations and from community activities". The State of Washington has adopted a more detailed and comprehensive view of solid waste which is defined in WAC 173-304 as

> "all putrescible and nonputrescible solid and semi-solid wastes, including but not limited to garbage, rubbish, ashes, industrial wastes, swill, demolition and construction wastes, abandoned vehicles or parts thereof, and discarded commodities. This includes all liquid, solid and semi-solid, material, which are not the primary products of public, private, industrial, commercial, mining and agricultural operations. Solid waste includes but is not limited to sludge from waste water treatment plants and seepage, from septic tanks, woodwaste, dangerous waste, and problem wastes."

This relatively all-encompassing definition governs the manner for waste disposal and consequently the costs of disposal. The inclusion of "dangerous waste" (a classification unique to Washington) and "problem wastes" tends to blur the definition for solid waste because dangerous and problem wastes often are included in the definition of hazardous wastes. This is an issue typically debated among scientists, lawyers, and regulators.

While solid waste is defined by the type of waste, hazardous waste is defined by its effect. Hazardous waste is defined in CFR 40 241.101 as

> "any waste or combination of wastes which pose a substantial present or potential hazard to human health or living organisms because such wastes are non-degradable or persistent in nature or because they can be biologically magnified, or because they can be lethal, or because they may otherwise cause or tend to cause detrimental cumulative effects."

The EPA further classifies hazardous waste by characteristic into eight groups:

(1) Ignitability	(5) Radioactivity
(2) Corrosivity	(6) Infectiousness
(3) Reactivity	(7) Phytotoxicity
(4) Toxicity	(8) Teratogenicity and mutagenicity

With respect to ground-water contamination, the toxicity group receives the most attention. This is due primarily to the ability to test for contaminants in this group. No doubt, as testing and investigative procedures advance, the other hazardous-waste groups will receive greater attention.

The most common hazardous wastes include a wide variety of chemicals ranging from heavy metals such as lead, arsenic, and chromium, to simple and complex manmade organic chemicals such as solvents, herbicides, pesticides, explosives, and radioactive materials.

PROBLEMS ASSOCIATED WITH WASTE DISPOSAL

A number of common cliches immediately come to mind when considering waste disposal: "Fine, but not in my back yard", or "out of sight, out of mind". Cliches are a common response to major issues or problems that seem to lack simple solutions, and waste disposal certainly falls into that category. Fortunately, as the case studies in this chapter amply illustrate, the waste-disposal industry has moved well beyond the cliche stage and is actively pursuing technologically sound solutions to the problems of waste disposal.

In general, the problems associated with waste disposal can be divided into those that are primarily social in nature and those that are primarily technical.

Social Problems Associated with Waste Disposal

First, there is the problem of an ever increasing volume of both solid and hazardous waste throughout Washington, clearly a problem falling into the social category. Consequently, this first and foremost of waste-related problems has been addressed primarily by political bodies (Congress and the State legislature). In its effort to stem the tide of increasing solid-waste accumulation, the Washington legislature has adopted a fairly well defined direction for implementing all solid-waste management policy. This policy includes in order of descending priority: (a) waste reduction; (b) waste recycling; (c) energy recovery or incineration; and (d) landfill.

Similar policy has been established for hazardous wastes. In line with these policies, landfilling is the least preferred course of action. However, most waste in the state is disposed of in landfills. And, barring any major technical breakthroughs, landfilling will continue to be the principal method of disposal over the next decade. Therefore, maintaining and operating the existing waste-disposal sites, as well as finding new disposal sites, present the most pressing social and technological challenges to the waste-disposal community. Refer to the accompanying paper by K. Rattue and S. Sagstad on the Snohomish County regional landfill siting for a discussion of this situation.

The major social problems result from the "not in my backyard" syndrome and, equally important, the ever-increasing costs of siting and operating waste-disposal sites. For example, in King, Pierce, and Snohomish counties, dumping fees for solid waste increased three- to fourfold between 1985 and 1988. In 1987, tipping fees increased from $26/ton to $46/ton at the King County Cedar Hills Landfill solely from the county's efforts to maintain compliance with Department of Ecology MFS (Deborah P. Lambert, King County Solid Waste, personal communication). This same pattern is repeated throughout the state as county, municipal, and private landfill operators implement new State-mandated standards for solid-waste disposal.

Technical Problems Associated with Waste Disposal

Identifying and solving the technical problems associated with waste disposal are the primary focus of the papers presented in this chapter. Those problems with which the engineering geologist is most involved are typically environmentally related and include ground-water contamination, leachate generation, and gas migration. While all of these problems are of concern in most waste-disposal situations they vary in severity and nature from site to site depending on geologic, hydrologic, and climatic conditions. As such, the problems of waste disposal and the solutions to these problems fall into the domain of the geologist and in most cases, more specifically, the hydrogeologist.

Because problems due to improper siting, design, operation, and disposal of waste occur in virtually every part of the state, the hydrogeologist must address all of the hydrogeologic phenomena the state has to offer. Although infinitely varied throughout the state, these phenomena and the types of associated waste-disposal problems/solutions can generally be separated into those occurring in western Washington environments and those occurring in eastern Washington environments.

WESTERN WASHINGTON HYDROGEOLOGIC ENVIRONMENTS

Within the context of waste disposal, the hydrogeologic environment of western Washington is distinguished by generally high but varied rainfall, numerous surface water bodies, shallow ground-water occurrence, complex geology dominated by highly transmissive glacial deposits, and few or no true clay deposits.

Precipitation west of the Cascades ranges from 15 to 120 in./yr. With the exception of a few areas protected by the Olympic Mountains (northwest Olympic Peninsula, Whidbey Island and the San Juan islands), rainfall is typically in excess of 30 in./yr. This high precipitation results in significant ground-water fluctuations (as much as 30 ft/yr) and high rates of local recharge, both of which contribute to increased rates of leachate generation at landfills.

The great number of surface-water bodies (streams, creeks, rivers, and lakes) are also a direct result of the high precipitation rates west of the Cascades. These surface-water bodies contribute to ground-water recharge, but, in many areas associated with waste-disposal sites, they are more commonly discharge points for ground-water systems passing through or beneath landfill sites.

Due to the shallow ground waters of western Washington and the relatively high population densities, ground-water production, for both municipal and domestic use, is quite high; well densities in some areas (for example, Pierce County) reach 50 wells per square mile. With the intense surface- and ground-water usage, it is rare to find an existing waste-disposal site that is not upgradient of some beneficial uses. This condition is not unique to the population centers of the state; it also is present in more rural environs, such as Island County. This is well illustrated by an evaluation of the pollution potential at eight waste disposal sites in Island County presented later in this chapter.

We find western Washington waste-disposal sites underlain by a variety of geologic materials, including marine sediments along the coast, fluvial and estuarine deposits along rivers, and even the occasional landslide or volcanic mudflow. However, past landfill siting has, for the most part, favored glacial sedimentary environments. The typical glacial sequence consists of a till having low permeability (10^{-4} to 10^{-7} cm/sec) sandwiched between highly transmissive recessional and advance outwash sand and gravel deposits. As many as five glacial sequences have been superimposed upon one another; some extend as far south as Olympia. Determining which glacial sequences are present and their hydrologic relationship to a waste disposal site is usually the first challenge the hydrogeologist is faced with in a site investigation.

The design, operation, and closure of a waste facility is also dependent upon the availability of suitable or select geologic materials. Fine-grained low-permeability materials are required for liners and caps, whereas permeable coarser materials are sought for drainage, gas control blankets, and daily and final cover of waste.

It is a rare site indeed where earth materials are readily available in sufficient quantities for all the required applications. Commonly, costly manmade impermeable geomembranes are necessary to adequately construct or close out a waste-disposal site. Due to the types of parent rock and the erosional and depositional history of western Washington, there is a significant absence of true clay deposits. Although glacial till possesses low *in-situ* permeabilities, this is primarily a function of compaction by the glacial ice rather than of material type (usually silty sand or gravelly silt). Due to the lack of sufficient clay fraction in tills, it is commonly difficult or impractical to achieve, through recompaction, the required 10^{-6} or 10^{-7} cm/sec permeability necessary for applications at waste disposal facilities.

Due to western Washington's climate and geology, and in part due to ignorance, past waste-disposal siting practices often consisted of finding a nearby deep gravel pit where the till had been stripped away to get at the sand or coarse aggregate of an advance outwash deposit. Many of these pits were excavated down to the ground-water level, then abandoned. Invariably, the gravel pits were selected for waste disposal in July or August when ground water was at its lowest level, and the pit was filled over succeeding years. Consequently, infiltrating precipitation and high ground water saturated the waste, generating leachate that then migrated through the highly transmissive gravels and in places contaminated ground-water supplies.

EASTERN WASHINGTON HYDROGEOLOGIC ENVIRONMENTS

While precipitation in western Washington is one of the principal factors leading to ground-water contamination, it is of minor concern in eastern Washington where total precipitation rarely exceeds 20 in./yr. However, the unique hydrogeology of eastern Washington presents its own challenges with respect to waste disposal. The central and southern parts of eastern Washington are dominated by scablands geology where intense glacial flooding has stripped the surface of most sediments, leaving exposures of the Columbia River basalt. The northern part of eastern Washington is dominated by igneous and metamorphic rocks, which like basalt, results in minimal soil development and a hard-rock base (commonly highly fractured) underlying most landfill sites.

As a result of the "hard-rock geology", past landfill siting and operation in eastern Washington usually consisted of finding a small canyon or a topographic depression, scraping off the limited soil accumulation, filling the low area with waste, and covering that with whatever residue was available. In most instances, the low population densities of eastern Washington yield relatively insignificant waste accumulation. This, coupled with the low precipitation rates, has spared most of eastern Washington the ground-water contamination problems associated with western Washington landfills. However, problems occur where large populations are present (for example, Spokane). In addition, the intense agricultural activity in eastern Washington has typically led to the disposal of pesticides and herbicides in many small rural landfills. Intense agriculture also leads to raised water tables which can saturate the base of a previously dry landfill, increasing the potential for leachate generation.

Where problems do occur, the fracture flow and basalt interflow hydraulics pose unique challenges to the hydrogeologist, including: locating representative monitoring wells, identifying the uppermost aquifer(s), determining the direction of ground-water flow, identifying downgradient beneficial uses, and establishing aquifer interconnection.

These challenges are compounded in tectonically disturbed areas where thrust faulting may make it possible to penetrate the same aquifer (basalt interflow zone) twice in the same borehole. Lateral and vertical faulting creates subsurface dams or conduits, diverting the direction of ground-water flow.

Like those in western Washington, the typical eastern Washington landfill site rarely possesses readily available earth materials for proper landfill operation and construction. Although low-permeability clay is more prevalent in eastern Washington, it is commonly uneconomically distant from a site, and sufficient suitable cover material is always at a premium.

CONCLUSION

Despite our advances in waste technology and the death of that proverbial cliche "out of sight, out of mind", which has been the root of traditional public awareness, we still face some major challenges with respect to waste disposal, ground-water contamination and ground-water cleanup. However, the waste and ground-water industries, in a remarkably short period of time, have responded aggressively and, in most cases successfully, to the challenges. Five years ago, a major pipeline leak would have gone unnoticed or, at best, been patched and forgotten. The resulting impacts to health and environment would possibly have been disregarded. Now, teams of experts are immediately dispatched, the problem identified, analyzed, and solved. Virtually all of the state's major landfills are currently under hydrogeologic investigation, and where problems have been identified, remedial measures are being implemented. The solutions are not always simple, cheap, or successful. The effort, however, is there and the successes far outnumber the failures. The ever-increasing number of geologists employed in the waste-related industries is evidence of the enormous efforts being expended. The critical shortage of experienced ground-water specialists is drawing on the professional resources of a number of related disciplines, somewhat alleviating the depressing slack in the mining, petroleum, and other energy-related industries.

Under stringent regulatory, liability, and economic pressures, a diverse range of professionals, with geologists at the forefront, is advancing the state of ground-water science to a new and higher standard. This advance includes new technologies such as subsurface microbial remediation and computer-assisted analysis and interpretation. We have also advanced our methodologies and instrumentation to better observe our Earth and its myriad of geologic, hydrologic, physical, and chemical phenomena. Compared to a scant 10 yr ago when hydrogeologists were just beginning to grapple with the vagaries of nitrate movement in the subsurface, they are now characterizing the fate and transport of numerous complex organic chemicals that have polysyllabic names and which change form and composition in the subsurface environment.

The case studies presented in this chapter provide a diverse overview of the talent and effort expended on waste-disposal and ground-water contamination problems occurring in Washington. Many of the challenges faced by the hydrogeologist specializing in waste-related problems are a direct result of the complexity of subsurface contaminant behavior. Consequently, the following paper by Gerritt Rosenthal on contaminant characteristics should provide the reader with an overview and appreciation of the range and scope of the environmental problems and creative solutions addressed in this chapter's case studies.

REFERENCES

Atkeson, T.; Goldberg, S.; Ellrod, F. E. III; and Connors, S., 1986, An Annotated Legislative History of the Superfund Amendments and Reauthorization Act of 1986 (SARA): *Environmental Law Reporter*, Environmental Law Institute, Washington, DC, 10,369 p.

Kruger, D. M., 1986, *1984 Hazardous Waste Annual Report Summary*: Washington Department of Ecology, WDOE 86-3, Olympia, WA, 22 p.

Lambert, D. P., 1986, Personal communication, King County Solid Waste Division, Seattle, WA.

Marvin, M. J., 1986, CERCLA As Amended—A Section-by-Section Commentary: *Environmental Law Reporter*, Environmental Law Institute, Washington, DC, 10,400 p.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

Introduction to Hazardous Waste Characteristics and Subsurface Behavior of Contaminants in Washington State

GERRITT ROSENTHAL
Sweet-Edwards/EMCON, Inc.

INTRODUCTION

Hazardous waste behavior in the subsurface environment is extremely complicated, combining the various aspects of ground-water hydrology and mineral and organic contaminant chemistry, all in an environment that is less known and understood than that of surface-water regimes. An understanding of these systems is critical, however, to meaningful discussions of ground-water contamination. This is particularly true since technical approaches often rely on simplifications of the actual situation, and these simplifications must be well grounded to provide any degree of adequate response to difficult contamination situations. It is insufficient and incorrect to deal with ground-water contamination from either the purely hydrologic or geologic aspect since the chemistry of the contamination is usually the critical element affecting downstream health and environmental risks.

Factors to be considered in the evaluation of hazardous wastes in the subsurface environment include: subsurface temperature; absence of light; absence of oxygen (aerobic/anaerobic); physical and chemical properties of the constituents; soil/contaminant interactions; biological processes; and ground-water hydrology.

More specifically, regarding the physical conditions in the subsurface regime, the subsurface environment is characterized by an absence of light and thus an absence of photochemical reactions; it is generally partially or completely deoxygenated and thus the reactions are not those that will occur in the surface environment; and coincident with this, electromotive potentials (chemical reactivity potentials) are greatly different than in the surface environment. A simplifying factor is the uniformity of temperatures, which are generally moderated between 35° and 55° F in the shallow aquifer environment.

Regarding the physical behavior of the contaminant, the most important parameters to consider are the melting and boiling points, the vapor pressure, the water solubility, and the octanol/water partition coefficients. The last measures the ability of the chemical to sorb to organic material in soils. For mineral constituents, the cation exchange capacity (CEC) of the soil (the ability of the soils to adsorb positively charged mineral ions) is a key factor in retardation and attenuation.

The biological behavior of subsurface contaminants is probably the least understood of the attenuation factors and may vary locally, regionally, and seasonally. The potential for anaerobic and/or aerobic transformations and breakdowns must be considered along with the availability of energy sources sufficient to stimulate the microbial population. In addition, both the chronic and acute toxicities of the subsurface contaminants are significant because these toxicities will influence the ability of organisms to metabolize contaminants. Included in this complexity is the potential for synergism (that is, the combined effects of multiple contaminants). Finally, there are some indications that both the type and matrix characteristics of the soil are capable of causing or catalyzing additional transformations of both a biological and non-biological nature. These interactions are complex and poorly understood.

Superimposed on this contaminant complexity is the behavior of the ground water and its movements under an almost limitless array of natural hydrologic and geologic conditions. Because of this bewildering array of factors influencing contaminant movement, this paper will only outline the major factors that must be considered and some of the simplifications that are possible.

SUBSURFACE REGIMES AND INFLUENCES ON CONTAMINANT TRANSPORT

As noted in the introduction, there is a wide geologic variety of subsurface environments in Washington. Broadly speaking, however, aquifers can be characterized either by true or approximate porous media flow or by fractured rock and/or channelized flow. The former situation is accessible to general theories of aquifer behavior and contaminant transport, even though these general theories are difficult or impossible to match to specific conditions without (and in many cases even with) an extensive data base. In cases of fractured or channelized flow, the interpretations are largely geologic and governed by the knowledge of the degrees and directions of fracturing. As a result, the degree to which the flow, or portions of the flow, can be approximated with general porous media descriptions is based on geologic considerations.

In each geologic setting, the important parameters to consider include: grain-size distribution, anisotropies in hydraulic characteristics, thickness and porosity of the media, presence or absence and the tightness of layers (that is, the existence of aquicludes and aquitards), the distance to the water table, the degree of saturation, the anion/cation exchange capacity of the soil material, soil organic content, and, in some cases, the presence or absence of specific natural contaminants (for example, arsenic, mercury) or mineral catalytic agents. In some instances, the acid/base structure of the soil also comes into play, for example, in the dissociation and movement of weak organic acids such as pentachlorophenol where the solubility depends on soil pH as well as the CEC level.

Each of the above parameters could provide the subject material for an individual text. For this volume, only the key issues and considerations will be highlighted.

CONTAMINANT TRANSPORT CONTROL PARAMETERS

There are many reference books to turn to for detailed explanations of the types and/or importance of specific forms of modeling appropriate to various types of contaminant transport. From the general standpoint of this paper, the most significant elements are an understanding of the types of aquifer and contaminant parameters that drive these models and a formulation of the necessary conceptual schematic models to help simplify and categorize the behavior of subsurface contaminant migration. The following parameters are of greatest interest in modeling of subsurface contamination in all porous media.

Ground-water Velocity

The specific hydraulic gradients, porosity, and hydraulic conductivity determine ground-water velocity according to Darcy's Law, which is generally valid for porous media flow but fails to apply in extremely coarse, cobbly, or bouldery deposits or in channelized flow as may be observed in recessional glacial outwash deposits or in unconsolidated mountain alluvium. Ground-water flow velocities (typically 0.1 to 20.0 ft/day) in excess of 95 ft/day have been observed in the Steilacoom gravels of central Pierce County, and similar velocities are not atypical in areas such as the upper Methow Valley of Okanogan County or in the basalt aquifers of eastern Washington.

Flow Direction

Also determined by gradients, flow direction is further influenced by local channelization and the general rule that water will flow via the path of least resistance. Flow direction will determine the major pathway of dissolved contaminant migrations, but it may not necessarily control contaminants that volatilize or liquids that are insoluble and denser than water. Dense, non-aqueous phase liquids (DNAPLs) are influenced primarily by geology and gravity. Investigations in the Kent valley and in Clark County have shown that deep, artesian aquifers are not necessarily protected against DNAPLs or deep contaminant movement even though they are overlain by shallow aquifers with discharging flow.

Retardation

The retardation of contaminants is generally of two types, mineral and organic. In the former, ionic inorganic mineral or ionic organic contaminants of any type are adsorbed and/or exchanged with charged materials (usually calcium and magnesium) in the soil. This causes a low migration tendency for heavy metal ions such as cadmium, lead, and chromium. Organic retardation of contaminants depends on the amount of organic material in the soil and the relative partition of the contaminant between the organic phase and ground water as measured by the octanol/water partition coefficient. High retardation is common in clay soils (ionic contaminants) found in the Ellensburg Formation of eastern Washington, organic-rich mud and debris flows (organic contaminants) of the Kent valley and northeastern Pierce County, or in lacustrine deposits and buried embayment soils along the coast.

Dispersion

One of the major processes by which contaminants spread in the subsurface environment is advective dispersion, a key factor in the classical-theoretical equations governing contaminant migration. Dispersion is measured in the subsurface environment by a factor referred to as dispersivity, which is dependent on soil type and grain size, on ground-water velocity, and, most problematically, by the size of the plume and its distance from its origin (so called "scale" factors). Approximations for dispersion are usually employed, on the basis of experimentally measured dispersion factors for unconsolidated soils of a general porous nature. To complicate the situation, dispersion is generally much greater, usually by a factor of 5 to 20, in the direction of flow than vertically or horizontally perpendicular to flow. Also, as with other soil properties, dispersion is not isotropic but varies with layering and soil particle orientation. Since these factors are usually impossible to determine in a field setting, they are subsumed under the general estimation of uncertainty for dispersivity.

Dispersion in fractured flow is also quite varied, depending on whether the fracturing is simple and regular or highly varied and widespread.

Dissolution and Solubility

The behavior of a compound in the subsurface and/or ground-water regime will depend on its solubility and ability to dissociate and move with water. Nearly all materials are at least slightly soluble and so the behavior of even "insoluble" contaminants will consist of two components, that of the insoluble portion and that of the leached or soluble material. Insoluble liquids will tend to be influenced by gravity flow and either sink through the ground water or float on the surface of the uppermost water layer. Insoluble solids generally do not migrate but may leach via the action of ground water or rainfall infiltration.

Volatilization

Some materials, especially a small class of both insoluble and soluble organic contaminants (solvents and fuels) are sufficiently volatile that they produce gaseous vapors that migrate away from the ground water and through the unsaturated soil. Gases are also formed by chemical reactions. Examples include the production of methane at landfills (for example, Midway landfill, Seattle) or cyanide gas in acid mine areas (rare in Washington). Gaseous materials also migrate under the influence of gravity, but, depending on the gas density, their path may be opposite the direction of ground-water flow. Gases lighter than air (for example, acetone vapor, methane) will generally migrate upward, while dense gases (vinyl chloride) may disperse downward where capped by structures or paved areas.

Decay and Degradation

Decay and degradation are important processes to consider in modeling, especially in the behavior of organic contaminants. Both bacteriologic and autocatalyzed degradative processes have been invoked, and aerobic degradation is often used to model remedial treatment methods that may involve the re-injection of oxygenated ground water. In many cases of organic contamination, the bacterial decay process is the single most important factor governing contaminant spread and attenuation. It is also the least well characterized since it is virtually impossible to study *in situ* without changing those conditions. Decay is usually approximated by estimating contaminant half-lives based on an assumed first order exponential decay. Sensitivity analysis is then used to detail the range of expected impacts of varying decay rates on the contaminant migration model.

Decay is not applied to certain "conservative" inorganic contaminants such as nitrate, heavy water, sodium, chloride, and certain other mineral salts. These "tracers" are assumed to be "conservative" (that is, not decaying or adsorbing) and are modeled without decay or retardation. Their migration prediction is often used to define the maximum possible rate of migration for other non-conservative materials.

CONCEPTUAL MODEL OF CONTAMINATION MIGRATION

Before attempting to categorize specific types of contamination and provide for some generality to the types of migrations that occur, it is important to develop a conceptual framework or model of contaminant migration.

Figure 1 is a schematic diagram of one such model. This diagram is an oversimplification, but the major patterns are relatively clear, and understanding this framework provides a useful context in which to view near-surface contamination situations occurring in alluvial/glacial aquifers typical of Washington.

As shown in Figure 1, there are two major modes in which contamination enters the subsurface environment: as solid or as liquid. The solid form of entry is shown as presenting a division into three types of contamination, that which does not migrate or leach to any significant extent, that which leaches slowly (slow plume), and that which leaches rapidly to produce a short, concentrated pulse plume. In reality, there are virtually no materials that are so insoluble such that, given a sufficiently high toxicity, a plume of some concentration of concern is not possible. Examples of this type of plume may be mining or metal reprocessing slag piles which weather and leach slowly.

Regarding liquid contaminations (Figure 1), it is important to note the two basic types or forms of contamination—aqueous phase, and pure liquid products, including mixtures of non-aqueous liquids.

The aqueous liquids produce two extremes of contamination on a continuum determined by soil interaction. These extremes are referred to as conservative and non-conservative. Very few materials are entirely conservative (that is, move with ground-water flow and are not adsorbed), and few are entirely immobilized. Nitrate, chloride, and sulfate solutions are often treated as conservative contaminants, as are tracers such as bromide and iodide, but the only strictly conserved materials are the isotopic forms of water ($H^2{}_2O$, $H^3{}_2O$, or H_2O^{18}).

Non-conservative aqueous contaminants include soluble nutrients such as phosphate; ionic constituents such as potassium, nitrite, and ammonia; and strong acids, strong bases, and dissolved organic liquids and solids such as sugars, salts, and organic acids (for example, sodium acetate, benzoate).

Among the non-aqueous contaminants, there are three major forms, soluble, light insoluble (low density), and dense insoluble. Examples of soluble organic liquids include acetone, alcohol, formaldehyde, ethyl acetate, and glycols. Regarding the "insoluble" forms, it should be noted that "chemical insolubility" is usually measured at levels on the order of 0.01 to 0.1 percent; that is, anything more soluble than 0.1 percent = 100

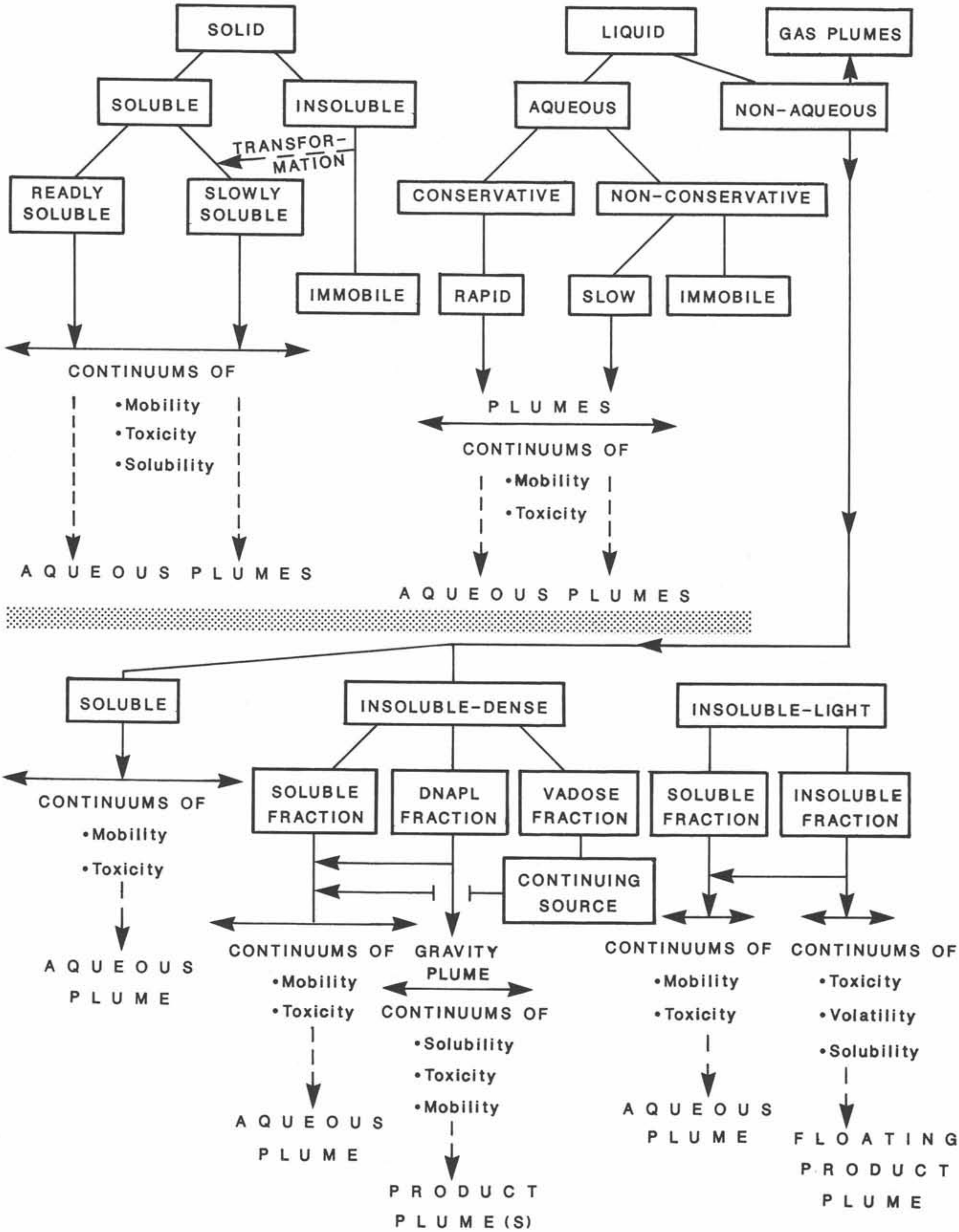


Figure 1. Contaminant plume generation schematic.

mg/100 ml is considered "soluble". On the other hand, contamination at the part per billion (0.00001%) level is easily measured and often of concern. There are then, for practical purposes, no non-aqueous liquids that are sufficiently insoluble so as not to produce a leachable plume. As a result, density is usually the remaining factor of greatest concern in dealing with liquid phase contaminants.

As may be inferred from Figure 1, the so-called "insoluble" liquids are of the greatest concern in the subsurface environment because, in addition to factors associated with dispersion, degradation, and mobility, they produce multiple forms of contaminant plumes, including non-aqueous liquid plumes, aqueous phase plumes, and, in some cases, gaseous plumes. From the diagram, the material types of the greatest concern are the DNAPLs since they are capable of migration through aquifers and aquitards and in directions determined by stratigraphy and not hydrology. As a result, they frequently pose threats to both shallow and deep aquifers and may be of concern even in areas where the water-supply source lies below significant clay, silt, or till aquitards.

Overlain on these general behavioral categories are the specific chemical types as defined and described in the next section. The above classifications are useful in the evaluation of these categories of chemical type.

CATEGORIES OF HAZARDOUS MATERIALS

The situation of contaminant behavior, although hopelessly complicated, can be simplified for practical purposes by the categorization of wastes into several general types, bearing in mind the previous distinction of aqueous and non-aqueous solids and liquids. This simplification takes into consideration the material type, in particular its toxicity and behavior in the environment, as well as key physical parameters. The following categories of subsurface contaminants are identified:

- Metals
- Acids and Caustics
- Organic Solvents
- Petroleum Products
- Pesticides (see Other Organics)
- Nutrients/Anions
- Other Organics

These categories are discussed in detail below.

Metals

This category includes "heavy" metals in either solid or dissolved aqueous forms. Metal cations (dissolved inorganic chemicals with positive [+] charges) can be grouped into two general categories: naturally occurring ground-water metals whose excessive concentrations cause nuisance problems; and "heavy" metals, significant concentrations of which can result in significant exposure hazard.

Iron, manganese, zinc, barium, and copper fall in the first, natural, category. These metals are present in most waters and natural soils in concentrations varying with the mineralogy. Iron and manganese, particularly, can reach high concentrations under anaerobic ground-water conditions such as in deeper glacial outwash and alluvial sands. Anthropogenic contributions of these metals are associated with landfill and woodpile leachates and other sources of mildly acid and reducing leachate waters. Excessive concentrations of these materials may also be found at industrial slag metal sites. In general, these minerals will rapidly oxidize and precipitate from pumped waters and surface seeps with a characteristic red iron-oxide staining.

The second category of metals, the heavy metals, includes those for which Primary Drinking Water Standards exist, such as arsenic, cadmium, lead, mercury, chromium, barium, selenium, and silver. Arsenic is of widespread occurrence both naturally as well as from a variety of industrial sources. Areas naturally high in arsenic include the upper Skagit River valley and streams draining east slopes of the North Cascades. Arsenic also occurs naturally in volcanic-deposit aquifers in western Washington. Arsenic is generally not susceptible to transport modeling. The most notable industrial sources are historical smelting activities in the Tacoma area and sites used for Copper-Chromium-Arsenic (CCA) wood preserving treatment. The distribution of arsenic in the Tacoma area is part of a regional pattern since the waste slags were used for fill and road ballast in many Pierce County ares.

Arsenic is of particular concern both because of its toxicity and carcinogenicity as well as its relative solubility in both ground and surface waters. Concentrations of higher than 100 times the drinking water standard of 0.05 ppm (parts per million) (that is, 5.0 ppm) have been noted.

Lead, cadmium, chromium, and mercury are associated with metal, wood preserving (CCA), battery production or reprocessing, and other metals-related industries. Mercury contamination may be associated with chlorine bleach operations at paper plants. These metals may be found in lesser quantities associated with hazardous waste and other landfills. This group of "heavy" metals differs from arsenic in that the metals are not generally soluble, except under highly reducing, very low pH, very high pH, or other unusual ground-water conditions. (For example, mercury and some other metals are more soluble in the presence of high chloride concentrations due to the formation of soluble complexes.) These metals tend to be readily removed from ground water by ion exchange or precipitation reactions with soil minerals (especially clay).

Although the "heavy" metals are routinely tested for in the shallow alluvial and glacial aquifers, their occurrence in large concentrations is usually confined to areas immediately beneath or adjacent to anthropogenic sources of contamination. These metals are not generally modeled since the levels of attenuation are very high (due to chemical reaction and/or ionic exchange) and the data needed to model these migration processes are rarely available.

Of the remaining metals, barium is quite soluble but largely of only a nuisance concern and is not widely occurring in industrial processes. Silver and selenium both may occur in trace levels in natural, mineralized waters as well as in areas of contamination. They do not travel significant distances in normal alluvial or glacial aquifers due to the formation of insoluble chlorides, sulfates, and carbonates.

Acids and Caustics

Acids and caustics are characterized by extremes of pH (pH $\leq$ 3.5; pH $\geq$ 10.0) and can result from a wide variety of industrial processes common in Washington. Acid conditions may be generated by pickle liquors, associated with both metal and, to a lesser degree, food processing. Acid wastes are also associated with wood processing and metal plating and etching. Caustics (alkaline wastes) are often associated with cement production, chlorine/lime bleach operations, and areas of lime or caustic soda production. Acid or caustic contamination generally occurs as an aqueous leachate but is generally of little more than a localized ground-water problem since these solutions tend to react rapidly with the soil environment and become neutralized within fairly short distances from sources. The more common acids and caustics (hydrochloric and sulfuric acids and lime and sodium hydroxide), when neutralized, produce non-toxic components such as sulfates and chlorides (acids), and calcium, sodium, and potassium (caustics).

Exceptions to this general statement include nitric and hydrofluoric acid wastes (excess nitrate and fluoride levels) or situations where the ground-water flow is very rapid and the water has little acid/base neutralizing capacity, such as in coarse and poorly sorted gravels and cobbles. Glacial outwash channels and highly transmissive recessional outwash such as the Steilacoom gravel of central Pierce County or the Spokane/Rathdrum Prairie Aquifer are particularly vulnerable to this type of contamination.

Nutrients/Anions

Nutrients are a small class of non-metal inorganic constituents such as ammonia, nitrate, phosphate, sulfate, and chloride. For the sake of convenience, all common anions may be considered together in this category. Of these materials, only nitrate is of general concern because of its widespread occurrence from waste disposal, septic tank leachate, fertilizer, and other high-nitrate waste solutions. Most forms of nitrogen contamination produce nitrate plumes after biological transformation process. With the exception of a few "conservative" tracers (chloride, nitrate, sulfate), these nutrient species are readily attenuated or transformed, and contaminant plumes are not generally observed. Conservative contaminant movement is indicated in Figure 2.

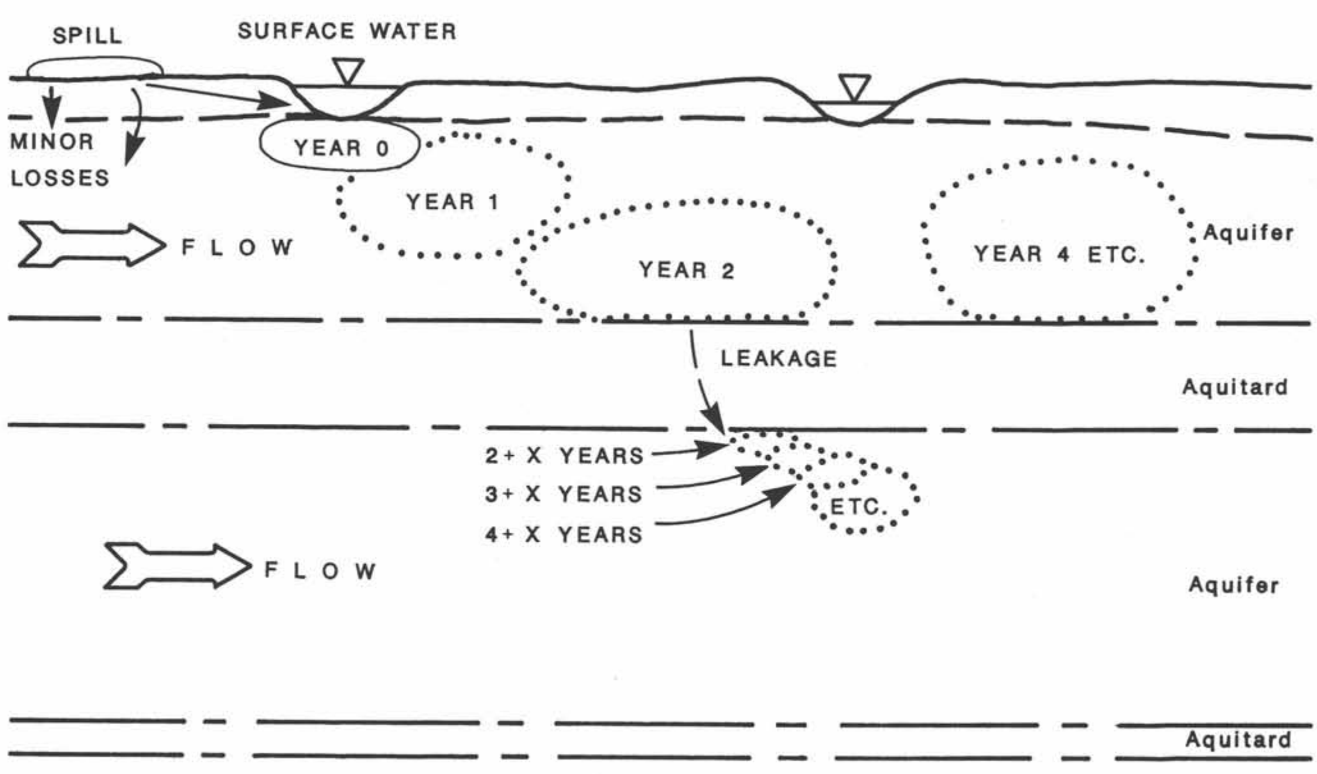


Figure 2. Diagram of water coincident contaminant migration.

Organic Solvents

Organic solvents are a widespread ground-water contaminant and can be roughly subdivided into two major types, the halogenated solvents and the non-halogenated solvents. This division also corresponds closely with the characterization of solvent plumes as dense (sinking) or light (floating).

Some typical examples of halogenated solvents in western Washington ground water include the trihalomethanes, trichloroethene (trichloroethylene), perchloroethene (PERC), 1,1,1 trichloroethane (TCA), bromodichloromethane, and other similar chlorinated, brominated, and fluorinated solvents including freons. These compounds are widespread in the ground water in trace and larger concentrations throughout the industrial as well as residential and commercial areas of the state. They have been identified as a significant concern in the glacial aquifers of Pierce County where their presence has resulted in the shutdown of high-yield municipal wells in Tacoma and Lakewood. The problems with halogenated solvents are widespread and are distributed from the Kent valley to the Spokane, Vancouver, Yakima, and Pasco Basin alluvial aquifers. Their widespread occurrence is directly tied to their many uses including metal degreasing, solvent washing for the electronics industry, septic tank degreasing, drycleaning, automobile degreasing (repair shops), and the like.

The physical and toxicological characteristics of the halogenated solvents make them the ground-water contaminant group of greatest concern. As a group they are generally volatile liquids (a few, such as vinyl chloride) are volatile gases) which are slightly soluble in water and, with a few exceptions, are heavier (more dense) than water. As a result of these properties and their interaction with the soil matrix, they produce a variety of plumes including a dissolved fraction plume, a dense non-aqueous pure liquid product plume, a residual soil (vadose zone) plume, and in many places a vapor plume. These plumes are illustrated conceptually for the Troutdale aquifer system of Clark County in Figure 3.

In addition, many of these halogenated compounds have been observed to produce breakdown products and breakdown product plumes which are of equal or greater toxicity. Maximum acceptable concentrations range from 1 to several thousand parts per billion (ppb), and many of these compounds are of significant concern at levels near detection limits of 1 ppb.

Because chlorinated solvent contamination occurs in such a wide variety of situations and because past waste disposal practices were undocumented, there are very few shallow developed aquifers in Washington in which at least traces of contamination will not be found. Past disposal of quantities as little as 1 quart of used degreaser is sufficient to contaminate an aquifer area one half the size of a football field and 10 ft thick to a level of 1,000 ppb, a concentration 200 times the drinking water criteria level for trichloroethylene (TCE). Traces of these solvents may even appear in the relatively pristine alluvial valley aquifers of the east slope (for example, Methow, Entiat, Naches rivers) as a result of their use as septic system degreasers.

A second class of solvent contaminants includes the more water-soluble solvents associated with paint, var-

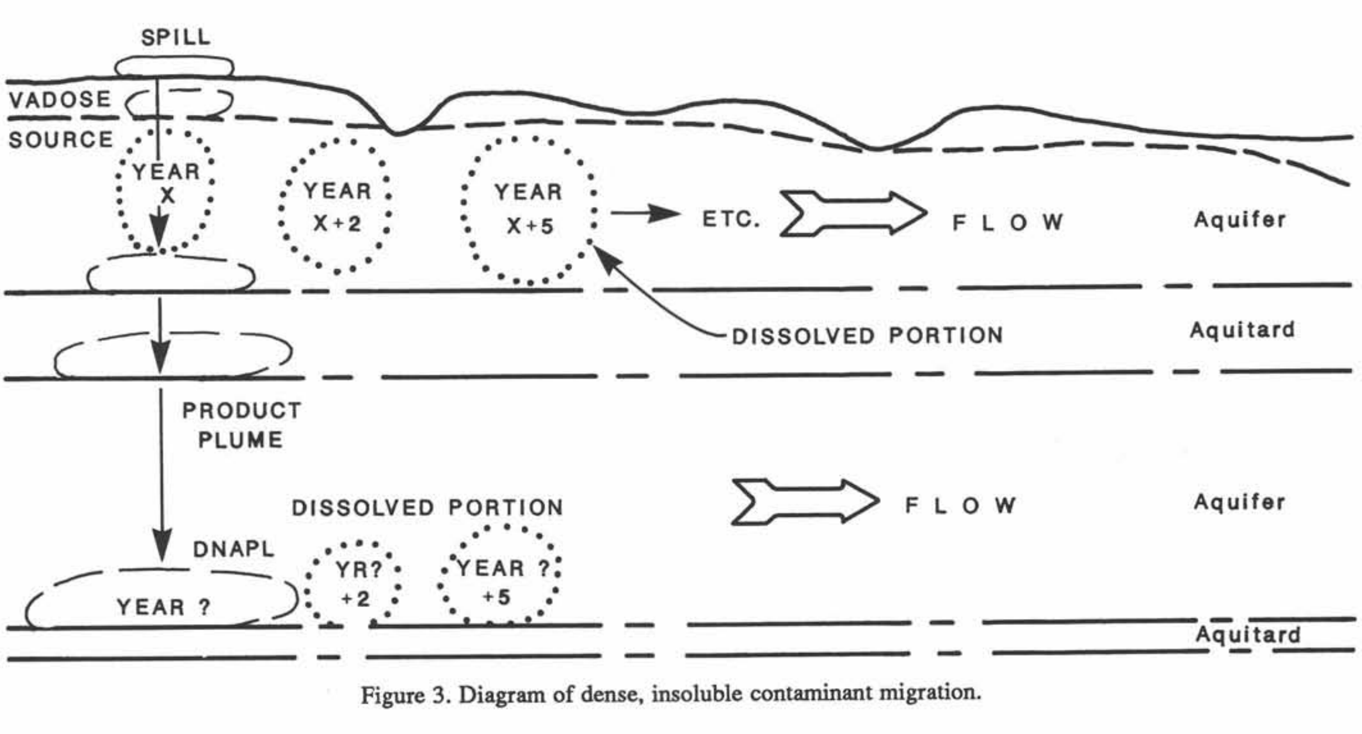


Figure 3. Diagram of dense, insoluble contaminant migration.

nish and wood-treatment manufacture, and degreasing activities. Many of these solvents (for example, acetone) have widespread home usage and so are found in landfill waste streams. These solvents are generally less dense than water and include such non-chlorinated solvents as acetone, various ketones (MEK, MIBK), tetrahydrofuran, DMSO, hexane, pyridine, benzene, toluene, and xylenes. These last three chemicals (the BTX group) also fall under the category of petroleum derivatives and are discussed in the next section.

As a general rule (benzene being an exception), the non-halogenated solvents are of less a concern because of their lower toxicity, greater solubility, and a more rapid biological breakdown to non-toxic products such as carbon dioxide and water. Also, in many cases, these solvents have taste and odor thresholds at lower levels than their toxicity and so are detected readily in contaminated water without elaborate detection programs. The major red flag of concern, particularly for the ketonic solvents, is the fact that their higher solubility means that concentrations of tens to thousands of parts per million may occur in waste disposal areas or areas of industrial manufacturing (for example, the Duwamish valley silts) and may persist for some distance downgradient. Generally, however, these materials do not migrate over long distances because of dispersion and biological breakdown.

Petroleum Products

Another widespread contaminant group throughout areas accessible to combustion engines is the petroleum derivatives, including gasoline, oil, kerosene, and other similar materials. These materials are associated with petroleum refining, fuel, oil storage, and service stations. Historical practice has been to store these materials in underground containers, of which a substantial number have leaked in nearly all developed environments in the state, especially in areas of periodically wet but unsaturated soils characteristic of western Washington.

Although generally referred to as "insoluble", most of these materials are sufficiently soluble to produce pure product and dissolved product plumes. They are of less concern than the insoluble and dense organic solvents since contaminant plumes are generally confined to floating product at the surface of the aquifer plus a smaller dissolved fraction in the aquifer. Figure 4 illustrates the movement of these plumes. They are also generally less toxic than many of the chlorinated organic solvents, with benzene as a notable exception, and often have lower taste thresholds. This means that the risk of hazardous exposure is generally reduced and that taste detection in water supplies usually occurs at levels at which there is limited danger from toxic effects. Unfortunately, this also implies that water supplies may readily become unpleasant or unpalatable.

The presence of petroleum product contamination is general throughout the industrial and, to a lesser extent, other developed areas of the state. Leaking underground storage tanks are a widespread problem both relating to refinery activities as well as to fleet or individual service station storage. Contamination is usually limited to the shallowest aquifers.

Other Organics

Other organic chemicals and feedstocks are lumped into a catchall group which include the following diverse members: PNAs (polynuclear aromatics); PCBs (pentachlorobiphenyl); pesticides; process chemicals (for example, phenol, formaldehyde, methanol); industrial chemical feedstocks; resins or polymer precursors; exotic chemicals (including alkaloids, peptides, drugs, antibodies) such as may be used in drug manufac-

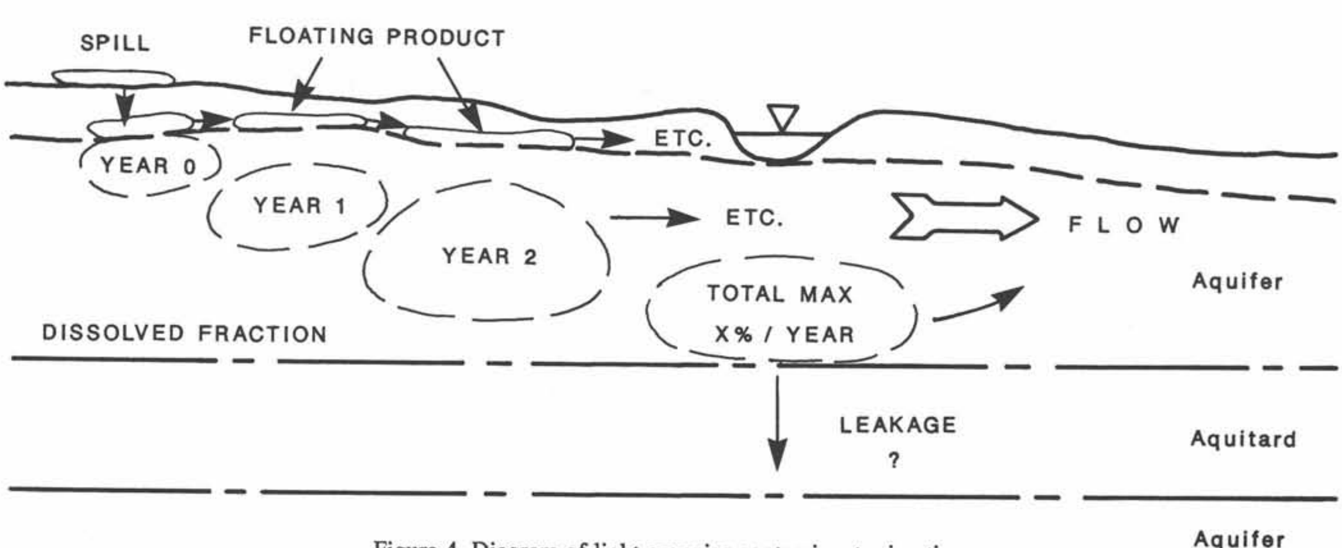


Figure 4. Diagram of light organics contaminant migration.

ture or are hospital by-products; explosives (for example, trinitrotoluene); wood preserving agents such as pentachlorophenol and the creosote chemicals; and food process chemicals (for example, organic acids, oils, and BHA, or butylated hydroxyl anisole). The list of potential chemical contaminants, especially organic chemicals, is nearly infinite, ranging from acetic acid used in food processing to dibenzofurans and dibenzodioxins which are by-products of other processes such as the manufacture of pentachlorophenol. It is impossible to detail the broad range of these materials, but a few broad outlines are possible.

PCBs are well known contaminants due to their high toxicities and persistence which have resulted in an enhanced public awareness of their occurrence in the environment. The most significant sources appear to be power and transformer facilities, plus used and waste oil collection, treatment, and disposal. PCBs do not, as a rule, migrate significantly, and they pose a generally higher threat from their presence in soil than from ground-water contamination.

Pesticides as a category include herbicides, insecticides, fungicides, rodenticides, and other pest killers. Their primary common attribute is a toxicity to one or more plant or animal groups. Chemicals in this category range from soluble to insoluble and from gaseous to solid. Although many of them are highly toxic, as a group they do not migrate readily with ground water due to a susceptibility to adsorption on target organisms, adsorption on organic material in soils, or breakdown by natural or atmospheric processes. A noteworthy exception to this is ethylene dibromide (EDB), which may also be classed with the halogenated solvents. More than 20 wells in the Skagit River valley as well as a number of wells in Whatcom and Thurston counties have been contaminated by EDB.

Soluble pesticides tend to break down more readily than oil-carrier pesticides. Pesticides are found most commonly in ground water in porous soils in areas of intense agriculture and high rainfall (Skagit valley) or areas of heavy irrigation (Yakima and Walla Walla valleys).

Feedstock chemicals are a roughly defined grouping of low to moderate toxicity—chemical production feedstocks such as methanol, formaldehyde, urea, furan, ethylether, aniline, and pyridine. The more common of these chemicals tend to be rapidly attenuated by biodegradation and soil adsorption processes, although the high levels of usage and/or production (for example, of acetone, methanol) provide for sporadic occurrence of low levels of these compounds in many shallow aquifers.

Biological chemicals (from laboratories, hospitals, pharmaceutical manufacture, and the like) show such a wide variability in both receptor sensitivity and toxicity that generalizations are difficult. In general, biological chemicals are removed by microbiological decay and/or by soil adsorption and attenuation before they reach ground water . The impacts from these materials are also low due to the isolated nature of the sources and to cost factors that encourage limited use, recycling, and a thorough material supply tracking.

Finally, food and food products constitute another large category of chemicals (such as oils, sugar, weak acids, food additives, and preservatives) that is of minimal concern due to their rapid degradation and low toxicity. These materials tend to stimulate aerobic degradation by providing energy sources for bacterial populations.

CONTAMINANT BEHAVIOR OVERVIEW

The situation is not as bleak as it would first appear, and the reasons for this lie in the consideration of the physical, chemical, and biological characteristics of the different groups of chemical species. The contaminant transport parameters may be reconceptualized in a somewhat simpler form as four major characteristics: mobility, stability, solubility, and toxicity.

Mobility

As discussed previously, mobility is a combination of velocity, solubility, and attenuation, and is determined by adsorption and ionic exchange interactions between the contaminant and the soil and by the rate and characteristics of ground-water flow. Most of the materials previously discussed have strong limits placed on their mobility by ionic exchange reactions (for metal cations and some anions) or by adsorption onto clay or organic materials in the soil column through which the contaminated water passes. In general, pesticides, herbicides, most polynuclear aromatics, PCBs and similar materials, plus many dissolved metals are strongly adsorbed onto the soil and have little potential for migration beyond the immediate vicinity of the contaminated area, especially under neutral pH conditions.

The primary classes of compounds of concern, from a mobility standpoint, are the conservative nutrients (anions such as nitrate, chloride, and sulfate), soluble organics (such as methanol, acetone, formaldehyde, and furfural), the dissolved portions of the organic solvent plumes (particularly the halogenated solvents such as trichloroethylene), and the light petroleum product plumes. Figures 2, 3, and 4 illustrate the migration behavior of the most mobile of each of these contaminant types.

Stability

Chemical stability is of equal (and in many cases greater) importance to mobility in the attenuation of contamination. Stability is the resistance to degradation by biological, atmospheric, or soil catalytic breakdown processes as well as resistance to other chemical reactions. Many of the more esoteric and toxic chemicals are relatively unstable (owing their toxicity to vigorous reactions with biological systems) and will break down on exposure to soil microbial populations. Many non-chlorinated pesticides, most acids and caustics, reactive chemical feedstocks such as phosgene or arsine gas solutions, and computer industry liquids such as silanes fall into this reactive category. Acid and caustic materials are susceptible to hydrolysis with the consequent liberation of neutral products, making their contamination locally intensive but not usually far reaching. Nutrient materials (for example, nitrate, nitrite, and phosphate) and many of the non-halogenated solvents and industrial feedstocks also have the capacity of being rapidly biodegraded or metabolically consumed in the near-surface and shallow subsurface environments. This is also true of such chemicals as methanol, acetone, ethyl acetate, urea, ethanol, furfural, benzoic acid, and, to a lesser extent, toluene, pyridine, and many petroleum products. This limitation on longevity in the soil also applies as a general rule to the non-halogenated pesticides and herbicides, such as the carbonates and thio- and azo- compounds.

Intermediate instability is exhibited by compounds such as halogenated solvents (TCE, PERC, 1,1,1-trichloroethane, EDB, and others), certain complex pesticides, and many chlorophenolics. The breakdown of these materials is not well understood but appears to vary with soils and specific locality, as well as with the degree of soil saturation. These degradation processes may yield products that are more toxic than the starting compound. For example, vinyl chloride is a common breakdown end product (for example, from TCE) and its formation appears to occur anaerobically (which is usually much slower than aerobic degradation) with a half-life on the order of several months to several years. The degradative production of vinyl chloride has been noted for TCE and similar solvents in the silty, shallow aquifer soils of the Kent valley, the outwash gravels of Pierce County, and in the Troutdale silty soils of Clark County.

Although nearly all chemical contaminants are degraded to some extent, half-lives of tens to hundreds of years are postulated for compounds such as PCBs, dioxins, and certain pesticides (for example, DDT, DDE, and Mirex). These materials are considered essentially stable. Metals, of course, do not degrade but are reactive to ion exchange. Arsenic is of particular concern since it is stable and less susceptible to ion-exchange stabilization.

Solubility

Solubility is, as noted previously, a significant factor in subsurface behavior of contaminants, although there are very few materials that are so insoluble as to not produce a dissolved contaminant plume. Nearly all so-called "chemically insoluble" compounds are soluble to levels from 0.01 up to the 10-100 ppm range (for example, dioxins, PCBs, and pentachlorophenol) and hence, from the standpoint of contamination, which is usually measured in parts per billion (1 ppb = 0.001 ppm), are quite soluble. This is true of most of the pesticides, the petroleum derivatives, organic solvents (many of which are soluble to thousands of parts per million), most wood waste products and, of course, caustics, acids, and many of the more common chemical feedstocks. It is also true of PCBs, dioxins and other carcinogens such as EDB, benzene, and vinyl chloride.

The most important influence of solubility on liquid product contamination is that it determines whether a contaminant will produce one or two (water coincident and insoluble) plumes. For solids, the concern is whether the plume will be produced by rapid dissolution or by slow leaching of product.

Toxicity

Toxicity does not affect the behavior of the chemical contaminants in the ground water, but it does adjust our level of concern for their fate. The chlorinated solvents are of great concern, and their fate is of great importance since they are both mobile and toxic. The conservative nutrients, on the other hand, although by definition mobile, are of limited concern since their toxicity is generally much lower (for example, drinking water criteria of 10,000 ppb for nitrate versus 1 ppb for vinyl chloride). Standards are non-existent for many nontoxic or low-toxicity materials such as chloride, sulfate, phosphate, ethanol, and acetone. Conversely, the pesticides and herbicides are of great concern due to high toxicity, as are the heavy metals cations (for example, lead, chromium, and cadmium), but they are often of reduced practical concern because of their lowered mobility due to attenuation and degradation. The contaminants that are both toxic and somewhat mobile (for example, pentachlorophenol, other phenols, feedstocks such as urea and formaldehyde, and the halogenated solvents) are also of significant concern. The conclusion is that toxicity considerations are largely specific to each chemical class and that their evaluation depends highly on the previously discussed characteristics of mobility, stability, and solubility.

SUMMARY

In summary, the fate and behavior of contaminants in the ground water are as varied as the chemicals that are available. Several specific chemical categories have been found to be of widespread concern in the shallow ground waters of Washington, particularly the alluvial and glacial aquifers used for drinking water supply. These categories are:

- Chlorinated liquid solvents (TCE, PERC, vinyl chloride, EDB)
- Chlorinated wood preservative chemicals (pentachlorophenol and dioxins)

- Polynuclear aromatic chemicals (anthracene, napthalene, chrysene)
- Pesticides and herbicides (particulary chlorinated species such as aldrin, endrin, chlordane)
- Other organic solvents; feedstocks (methanol, urea, acetone, phenol, pyridine)
- Heavy metals (arsenic, lead, chromium)
- Nutrients plus common metals (nitrate, nitrite, chloride, iron, manganese)

The behavior of these materials is varied, as discussed previously, but in brief (and not without exception) the following generalizations are useful:

- The chlorinated solvents move readily, degrade to other toxic products, persist in the environment, and may be present as dense plumes, soluble plumes, and residual soil contamination.
- The chlorinated wood preservatives are not as mobile as the solvents, are somewhat less toxic, break down slowly due to their toxicity to microorganisms, and are usually present only as soil contamination and dissolved phase plumes.
- Polynuclear aromatic chemicals are generally insoluble and have densities similar to that of water. They are quite immobile and generally moderately to highly toxic; they persist in the environment, usually primarily as soil contamination.
- Petroleum materials float on top of the water table and produce both a dissolved phase in the ground water as well as pure product plumes. They are generally not highly toxic and are broken down by microorganisms to volatile or innocuous products. The primary concern here is the volume in which they may exist and the taste and odor nuisance considerations. Benzene is a noteworthy exception, being carcinogenic and hence of great concern due to high toxicity.
- Pesticides and herbicides are generally either readily broken down by microorganisms or are adsorbed strongly to the soil matrix and are rarely found far from contamination sources. They do, however, tend to be highly toxic. They are found chiefly as contaminated soil residuals or as limited ground-water plumes. Significant exceptions are presented by EDB and similar solvent pesticides which are moderately soluble, highly toxic, and only moderately attenuated.
- Other organic feedstocks and solvents are typically highly soluble and hence would migrate great distances except for their biodegradability. Their toxicity is usually low to moderate, but due to high volume usages, they may exist locally in large quantities, either as pure product plumes or as relatively concentrated, soluble, aqueous plumes.
- Dissolved heavy metals are generally immobile, arsenic being an exception. These metals are also, to variable extents, naturally occurring, and, in many cases, also quite toxic. Their soil adhesion properties make them of only limited concern at significant distances from a source of contamination.
- Nutrients and common metals are of generally lower concern because of low toxicities or nuisance characteristics. They generally will migrate with the ground water and so are common in low concentrations and are naturally occurring. For these ground-water constituents, the question of concern is a matter of degree and not occurrence per se.

Although each case of chemical contamination in Washington deserves special and unique consideration, the situation is not hopeless since, as has been described, many of these incidents fall within recognizable patterns. The potential variety of problems is limited by both hydrologic and chemical factors.

A more thorough understanding of both the individual subregional aquifer situations, as well as the number and extent of these areas of contamination, will take a great deal of commitment on the part of the state, the regulatory agencies, and the business community.

SELECTED REFERENCES

Freeze, R. A. and Cherry, J. A., 1979, *Groundwater*: Prentice Hall, Engelwood Cliffs, NJ, 604 p.

National Symposium on Aquifer restoration and Ground Water Monitoring [4th, 5th, 6th], [1984, 1985, 1986], *Proceedings*: National Water Well Association, Columbus, OH.

National Water Well Association, 1985, *Petroleum Hydrocarbons and Organic Chemicals in Ground Water–Prevention, Detection and Restoration; Conference Proceedings, 1984*: National Water Well Association, Columbus, OH. [Proceedings of this annual conference are available for other years]

Rogoshewski, P.; Bryson, H.; and Wagner, K., 1983, *Remedial Action Technology for Waste Disposal Sites*: Noyes Data Corporation [NDC Pollution Technology Review 135; under contract to U.S. Environmental Protection Agency], 497 p.

Sax, I., and others, 1979, *Dangerous Properties of Industrial Materials*, 5th Edition: Van Nostrand-Reinhold, New York, NY, 1,118 p.

Schwille, Friedrich, 1988, *Dense Chlorinated Solvents in Porous and Fractured Media*: Lewis Publishing, Chelsea, MI, 146 p.

Windholz, Martha, et al. (editors), 1983, *The Merck Index—An Encyclopedia of Chemicals, Drugs, and Biologicals*, 10th Edition: Merck & Co., Rahway, NJ, 1 Vol.

Drilling a methane extraction well. Photograph by Greg Mack, 1988.

Cable tool drilling of a borehole for installation of a ground-water monitoring well at an industrial site in Tacoma. Photograph by Denis E. Mills.

Engineering Geology in Washington, Volume II
Washington Division of Geology and Earth Resources Bulletin 78

A Hydrogeologic Assessment of Cedar Hills Regional Landfill, King County, Washington

DENISE E. MILLS and DONALD A. CORDELL
Sweet-Edwards/EMCON, Inc.

INTRODUCTION

After the City of Seattle was forced to close the Kent-Highlands Landfill at the end of 1986, Cedar Hills Regional Landfill has served as the principal solid waste disposal facility for both King County and the municipality of Seattle. It is owned and operated by King County. The landfill was opened for solid waste disposal in 1964 and, today, approximately 3,500 tons of refuse are accepted daily. At roughly 920 acres, the Cedar Hills landfill is the largest in the Northwest.

The Cedar Hills landfill is located approximately 3.5 mi south of the town of Issaquah (Figure 1). It is situated on the east side of the Puget Sound lowland, at the foothills of the Cascade Range. Northeast of the landfill, Issaquah Creek flows north toward Lake Sammamish and the Cedar River drainage basin lies to the south.

In 1964, when the landfill began operating, few regulations regarding landfill siting and operations were in effect. During the more than 20 yr of operation, King County has modified the landfill in an effort to meet state and federal regulatory requirements relevant to operations, air quality, and water quality. Knowledge of existing conditions at the site has been aided by installation of 31 ground-water monitoring wells around the landfill perimeter and 9 leachate-monitoring wells in the solid waste. Notable improvements over the life of the facility include construction of a leachate collector and sewer interceptor system, leachate pretreatment facilities, and a sewer line connecting to a trunk line that feeds into the Renton sewage treatment plant where leachate is treated and discharged (Sweet, Edwards & Assoc., Inc., 1986). Additional improvements include installation of scattered leachate surface breakout or nuisance seep collectors.

This paper discusses the geologic characteristics and ground-water flow regimes onsite relative to the site stratigraphy. This provides a basis for understanding the impacts of landfilling activities and mitigation measures at Cedar Hills. The paper concludes with a discussion of site improvement projects being developed to reduce the potential for future water-quality impacts at the facility.

SITE CHARACTERIZATION

King County has been conducting hydrogeologic studies at Cedar Hills for 14 yr. These studies have included geologic mapping, subsurface investigations, and collection of ground-water data to determine ground-water flow directions and water quality.

Field Investigations

The landfill site was mapped in 1984 and 1985 to locate exposures of the geologic units. The mapping was enhanced by excavations and concurrent subsurface exploration.

The stratigraphy of the Cedar Hills landfill has been characterized by extensive subsurface exploration. Since 1974, more than 75 exploratory borings and monitoring well borings as much as 360 ft deep have been completed at the site (Robinson and Noble, 1974, 1978; CH2M Hill Northwest, Inc., 1985; Sweet, Edwards & Assoc., Inc., 1984, 1985a). The shallow subsurface geology has been examined in more than 50 backhoe test pits (CH2M Hill Northwest, Inc., 1985; Sweet, Edwards & Assoc., Inc., 1984).

Since 1983, ground-water monitoring wells ranging in depth from 39 to 360 ft have been completed in 22 borings. Seventeen of these wells are completed in shallow ground-water zones perched within the Vashon till and upper advance outwash deposits; five wells are completed in the deep regional aquifer. Ground water is collected from the majority of these wells at quarterly intervals. These ground-water samples are tested for constituents specified by the Minimum Functional Standards for Solid Waste Handling in the State of Washington (WAC 173-304) and for additional inorganic and organic constituents.

Hydrogeology

This section describes the regional geologic setting, site stratigraphy and lithology, and occurrence of ground water within the geologic units identified onsite.

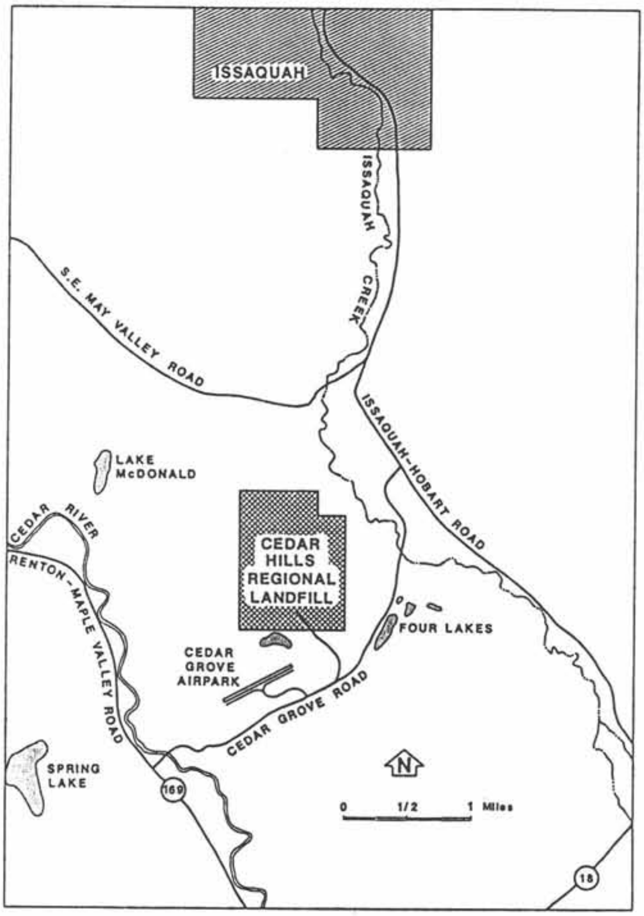


Figure 1. Location of Cedar Hills Regional Landfill.

This provides a basis for understanding the ground-water flow systems and potential impacts on water-quality related to solid waste disposal.

Regional Geology

The Cedar Hills landfill is located in the Puget Sound lowlands of western Washington, which consist of a structural trough between the Cascade Range and the Olympic Mountains. Knowledge of the structural geology and preglacial history is limited due to a cover of glacial deposits in the region (Figure 2). Well logs from the Cedar Hills region indicate that more than 350 ft of glacial sediments overlie bedrock (Sweet, Edwards & Assoc., Inc., 1984) (Figure 3). The bedrock appears to have numerous discontinuities where major structural blocks have been offset vertically. The exposures of bedrock closest to Cedar Hills are directly west in the Cedar River valley (Figure 2).

The landfill is underlain by Vashon till, advance outwash deposits, and undifferentiated pre-Vashon glacial sediments (Rosengreen, 1965; Livingston, 1971; Vine, 1962). Vashon till is very dense and concrete-like and is generally described as sparsely distributed pebbles, cobbles, and boulders in a fine-grained and structureless matrix. Glacial sediments identified at the site range from less than 1 to roughly 70 ft of lodgement till of Vashon age, underlain by outwash sands and gravels, and ice-contact deposits (Figure 3) and other undifferentiated sediments. These sediments include clay, silt, sand, and gravel and reflect the preglacial history of the area.

Site Stratigraphy and Lithology

The Cedar Hills landfill site and Queen City Farms to the south are underlain by alluvium and three types of glacial sediments (Hart-Crowser and Assoc., Inc., 1983; Livingston, 1971; Luzier, 1969; Rosengreen, 1965; Sweet, Edwards & Assoc., Inc., 1984, 1985a; Vine, 1962). These sedimentary units occur in the following sequence from youngest to oldest:

- recent alluvium
- Vashon till
- outwash sands and gravels, including younger ice-contact deposits.

Alluvium

Alluvium consisting primarily of sand and silt is present in the southeast-trending drainage south of the landfill. This alluvium extends onto the adjacent Queen City Farms waste disposal site and is locally underlain by both till and glacial outwash deposits (Hart-Crowser and Assoc., Inc., 1983).

Vashon till

Regionally, Vashon till mantles pre-existing topography, forming a blanket over older glacial sediments. Recent geologic mapping (CH2M Hill Northwest, Inc., 1985) and subsurface investigations at the landfill (Sweet, Edwards & Assoc., Inc., 1985a) show that the distribution of Vashon till is locally discontinuous. An isopach map for the till (Figure 4), constructed from current geologic data, indicates that the till is less than 10 ft thick toward the north and northwest portion of the landfill and thickest to the south.

Both weathered and unweathered till have been identified at the site. Oxidized (or weathered) till is light brown or grey mottled with brown. Unweathered till is blue-grey to grey. Weathered till at Cedar Hills is sandier, less dense, and more friable than unweathered till.

Several permeability tests have been conducted on unweathered till at the site and have indicated that the hydraulic conductivity ranges from 10^{-6} to 10^{-9} cm/sec (CH2M Hill Northwest, Inc., 1985; Sweet, Edwards & Assoc., Inc., 1984, 1985a). The permeability of weathered till was reported by Converse, Ward, Davis and Dixon (1980) to be 10^{-4} cm/sec. Ground water therefore is expected to move more quickly through the weathered zone than the unweathered zone. This is especially significant at the north end of the landfill where till is thinner and weathered till directly overlies the coarser grained outwash sediments.

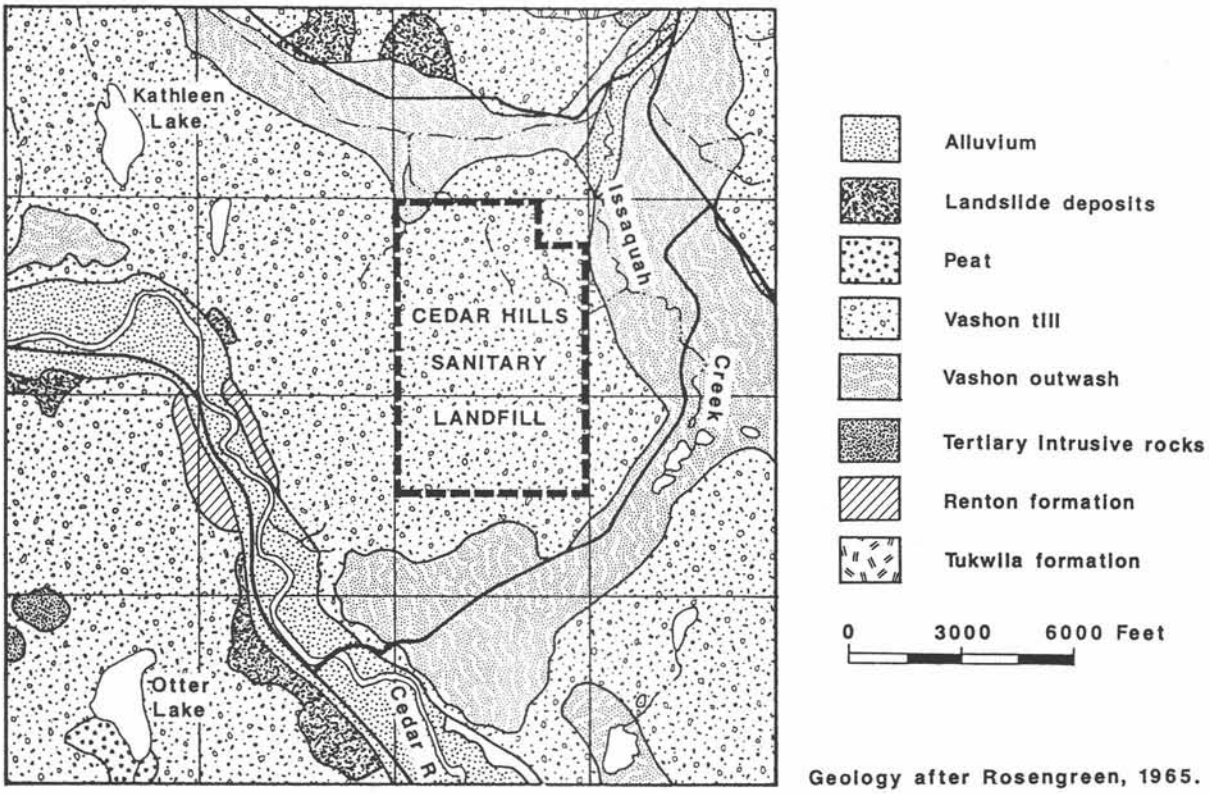


Figure 2. Geologic map of the Cedar Hills landfill area.

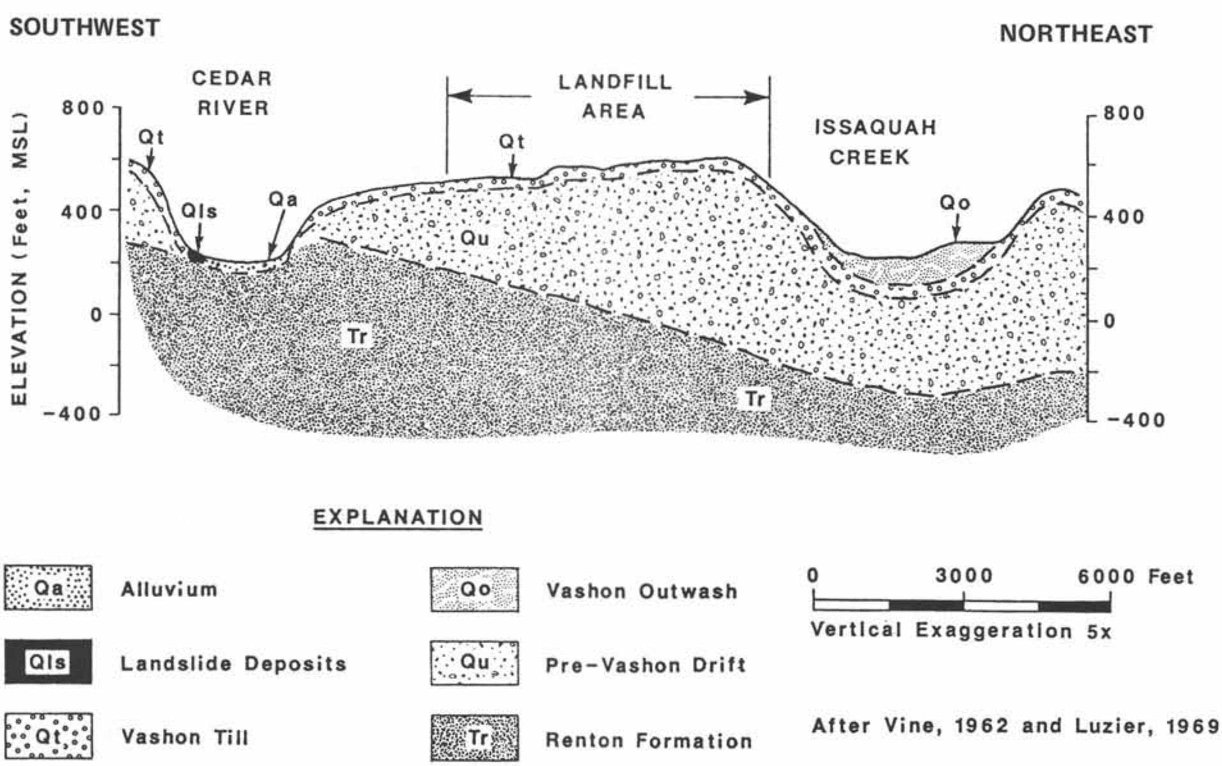


Figure 3. Geologic cross-section of the Cedar Hills landfill area.

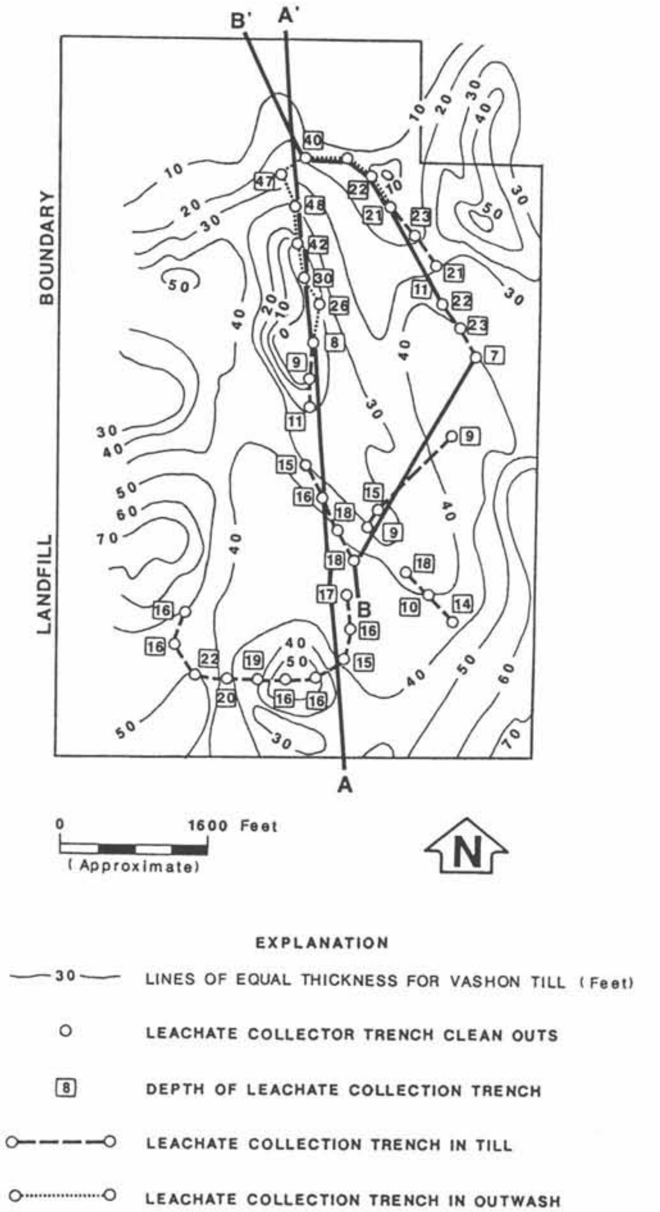


Figure 4. Isopach map of the Vashon till at the Cedar Hills landfill.

Advance outwash deposits

Advance outwash sediments deposited during the most recent glacial advance underlies the till. The outwash consists of various ratios of sand, silt, and gravel. The total thickness of the outwash deposits beneath the landfill is not known. Perched ground water has been observed at several depths, but these water-bearing zones are of limited extent and generally low yield (Sweet, Edwards & Assoc., Inc., 1985a).

A silt to silty gravel layer within the outwash has been observed in all of the deep borings completed at the landfill site (Sweet, Edwards & Assoc., Inc., 1985a) and at Queen City Farms (Hart-Crowser and Assoc., 1983). This layer is underlain by a confined aquifer, indicating it is extensive.

Hydraulic conductivity estimates for the outwash vary from 10^{-2} to 10^{-5} cm/sec. The permeability appears to vary according to the ratios of silt, sand, and gravel in the strata (Sweet, Edwards & Assoc., Inc., 1984).

Ground-Water Flow Systems

The ground-water flow systems of western Washington can be divided into regional, intermediate, and local flow systems. In general, the intermediate and regional recharge areas are the Cascade Range and adjacent foothills. These deep-seated flow systems discharge into the lower flood plains and terraces of the Puget Lowland. Local flow systems are superimposed on the regional and intermediate systems and are primarily controlled by local topographic and geologic conditions (Sweet, Edwards & Assoc., Inc., 1984, 1985a).

At the Cedar Hills landfill ground-water flow corresponds to three flow systems: Perched zones in the till are part of the local system; stratified drift and outwash sediments are part of the intermediate system; and the deep confined aquifer makes up the regional system. The deep aquifer is developed for domestic and other supplies (Sweet, Edwards & Assoc., Inc., 1984).

Percolating moisture recharges the local and intermediate flow systems. The recharge rates vary with local topographic and geologic factors. In areas blanketed by Vashon till, recharge to the local and intermediate flow systems is limited. Where till is absent and the more permeable stratified drift dominates the surficial geology, recharge may be more rapid (Sweet, Edwards & Assoc., Inc., 1984, 1985a). Local recharge-discharge flow regimes superimposed on the intermediate and regional systems are evidenced by discharge points such as springs and perched ground-water bodies, reflecting the relatively shallow nature of the local system.

Ground-water flow within the perched zones in the Vashon till most likely follows local topography. The direction of flow occurring in perched units within the upper part of the advance outwash is difficult to determine because of the variation of attitude of the perching layers and the wide range of permeabilities, which influence gradients, flow direction and rates.

Evidence of regional discharge is provided by water-level data from the wells completed in the deep aquifer (Sweet, Edwards & Assoc., Inc., 1985a). A potentiometric map of the regional aquifer (Figure 5) indicates that ground water in this system flows to the northeast.

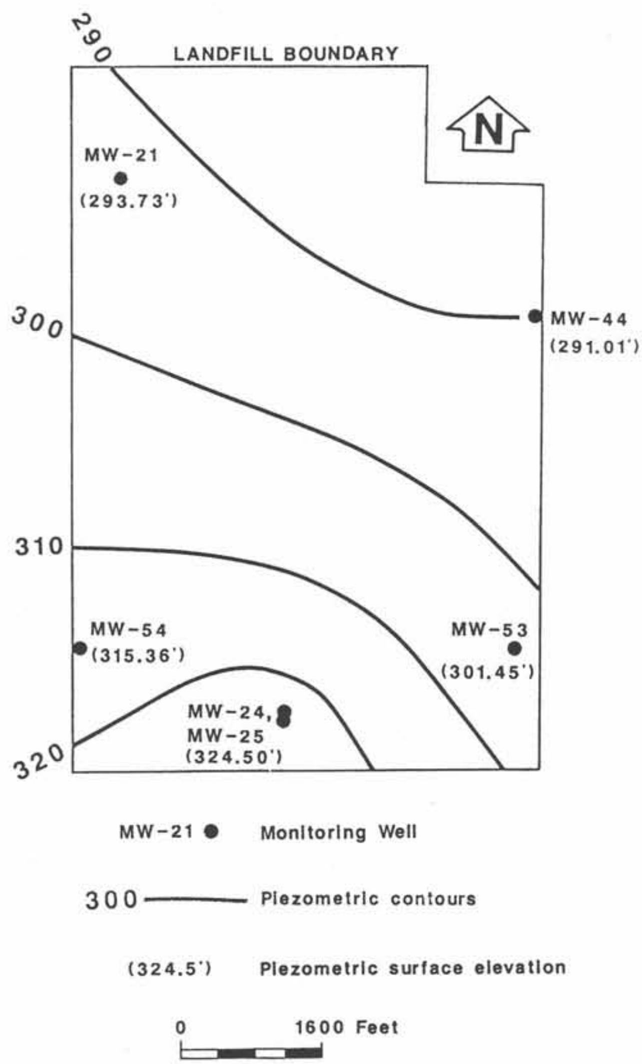


Figure 5. Ground-water contour map for the regional aquifer.

Surface Water

The existing storm-water collection system consists of naturally occurring streams, manmade drainage channels, and siltation ponds that convey storm-water flows away from developed areas at the site (Sweet, Edwards & Assoc., Inc., 1986). Generally, storm water flows to either the north or south. The north storm-water flow feeds tributaries of Mason Creek, which flows into Issaquah Creek. Storm water from the southern portion of the site flows south through the drainage system and leaves the site both at the southeast corner and through a drainage channel.

Water Quality

Quarterly monitoring of ground- and surface-water quality has been performed at the Cedar Hills Landfill since 1978. The results of the monitoring show that ground water perched in the till has been impacted by solid waste disposal activities. Evidence of impacts include elevated levels of iron, manganese, sulfate, nitrate, chloride, and specific conductance. Sporadic detections at very low levels of organic constituents do not permit definition of their distribution in the shallow aquifer.

Ground-water quality in the deep aquifer is much more difficult to assess regarding impacts from the landfill because:

(1) Ground water in the regional aquifer has higher levels of total dissolved solids relative to background levels because of its longer residence time.

(2) Water quality from deep wells in the vicinity shows a wide range of concentrations of naturally occurring constituents such as iron and manganese. It is difficult to assess whether impacts from the landfill are causing increases in iron and manganese concentrations.

(3) The Queen City Farms waste disposal site appears to be upgradient from the landfill on the basis of water levels measured in onsite wells completed in the regional aquifer. It is possible that if contamination of the deep aquifer is detected, Queen City Farms is a contributor.

(4) The potential for attenuation of contaminants by the 200 ft of unsaturated soils below the landfill makes interpretation of overall landfill impacts difficult.

Monitoring activities are continuing at the landfill in both the shallow and deep aquifers. An extensive suite of water-quality and geochemical parameters, both organic and inorganic, is being monitored; this should provide the information necessary to analyze potential landfill-related impacts on water quality. Quarterly evaluations of the water-quality data are completed to determine if ground-water information developed should alter the existing operation or design of the landfill.

GEOLOGIC EVALUATION OF THE LEACHATE COLLECTION SYSTEM

A system of subsurface trenches was completed in 1978 at Cedar Hills to collect leachate flows from near-surface geologic units and convey the leachate to an approved treatment facility. This system is one of the largest leachate collection and interceptor systems ever developed. The collector is constructed of perforated drain pipe and fine to medium gravel backfill. A plan view (Figure 4) of the depths of the leachate collector trenches superimposed on the isopach map of the Vashon till demonstrates the position of the collector with respect to the geologic units at the site.

Approximately 3,900 lineal feet of the collector at the north end of the solid waste disposal area are completed below the till and located in shallow advance outwash deposits (Figure 4). Cross-sections in Figure 6 and 7 show the leachate collector geometry east and west of the solid waste pile. At the south end of the site, most of the leachate collector trench is located in weathered till rather than unweathered till, which has lower permeability (Sweet, Edwards & Assoc., Inc., 1985a, 1986). Therefore, leachate discharge may be occurring from the south leachate collector.

The effectiveness of the leachate collection system completed in shallow outwash deposits and weathered till may be less than intended. There is no evidence that these systems are not functioning as designed, but it appears that conditions exist that allow leachate to escape the collection system and percolate into local and intermediate ground-water flow systems. This may partially account for some observed water-quality impacts at the site.

LEACHATE MOUNDING

The majority of the main solid-waste pile overlies till. Documented leachate seepage around the base of the main refuse area suggested that leachate was mounding in the waste overlying the low-permeability till. Investigations conducted by Sweet, Edwards & Assoc., Inc. (1985b, 1987) to characterize the occurrence of leachate in the solid waste verified the presence of a leachate mound within the main portion of the landfill. In addition to leachate heads within the waste that locally exceed 45 ft (Mills and Cordell, 1988; Sweet, Edwards & Assoc., Inc., 1987), landfill gas pressures to 12 psig have been measured. The excessive gas pressure contributes to the liquid head. The total combined head of approximately 75 ft increases the rate of leachate movement through the underlying till, allowing untreated leachate to enter the shallow ground-water flow system.

SITE IMPROVEMENTS

The hydrogeologic investigations of the Cedar Hills Regional Landfill have identified some impacts to ground- and surface-water quality at the site. Potential routes for leachate to affect water quality include nuisance seeps that primarily affect surface-water quality, the geometry of the leachate collector relative to the stratigraphic units at the site, and downward leachate migration from the leachate mound in the main solid waste pile. In this section, several proposed and/or implemented methods to reduce leachate impacts from these sources are discussed.

Surface-Water Quality Improvements

Surface breakouts of leachate occur where low-permeability interim cover intersects side slopes of the refuse pile. Surface breakouts or nuisance seeps on the landfill and shallow ground-water discharges have been cited as adversely impacting surface-water quality (Sweet, Edwards & Assoc., Inc., 1986).

An engineered system to intercept surface breakouts of leachate has been installed over areas of the landfill where leachate seepage has been identified. The system is a series of gravel-lined trenches that allow collection of surface breakouts. These interceptor trenches convey collected leachate to the onsite collector for treatment and disposal. Collection of leachate from nuisance seeps reduces the quantity of potentially impacted surface runoff from the solid waste areas, thus decreasing potential impacts to surface-water quality.

Ground-Water Quality Improvements

Information developed from hydrogeologic and geotechnical investigations at the Cedar Hills landfill suggests that leachate discharges may occur where the leachate collector is completed in the relatively permeable weathered till rather than in the low-permeability unweathered till. Ground-water quality data support this finding in that there appears to be impacted ground water onsite within the till south, east, and north of the landfill (Sweet, Edwards & Assoc., Inc., 1986).

As described previously, portions of the existing leachate collector are also founded in permeable advance outwash sands and gravels, allowing exfiltration of leachate from the collector system. Leachate leakage from the collectors completed in outwash can potentially impact water quality in the landfill vicinity.

The efficiency of the existing collection system can be improved in some areas by deepening the collector and locating the bottom of the trench in unweathered till. The county plans to complete this work in 1988. Realigning the leachate collection trench should mitigate impacts to shallow ground water within the till. In 1986, Sweet, Edwards & Associates, Inc. recommended construction of an inner trench in a configuration that would not allow leakage from the collector. Construction of an unperforated pipeline where the existing collector extends below the till/outwash contact and possibly a pump station to convey leachate to the interceptor system from the existing system were also recommended.

In-Waste Leachate Head Reduction

As previously mentioned, investigations of the occurrence of leachate in the main refuse area identified substantial leachate mounding and landfill gas pressures in the waste overlying low-permeability till. The combined head from leachate and landfill gas pressure is sufficient to cause leachate flow through the till. Reduction of the total liquid head acting on the till can decrease the potential for continued impacts on water quality around the landfill.

In 1987, Sweet, Edwards & Associates, Inc. conducted a study to assess the feasibility of in-waste leachate head reduction using horizontal drains and/or vertical extraction well. To assess if dewatering the main solid waste area is a feasible remediation option, drawdown and recovery "aquifer" tests were conducted

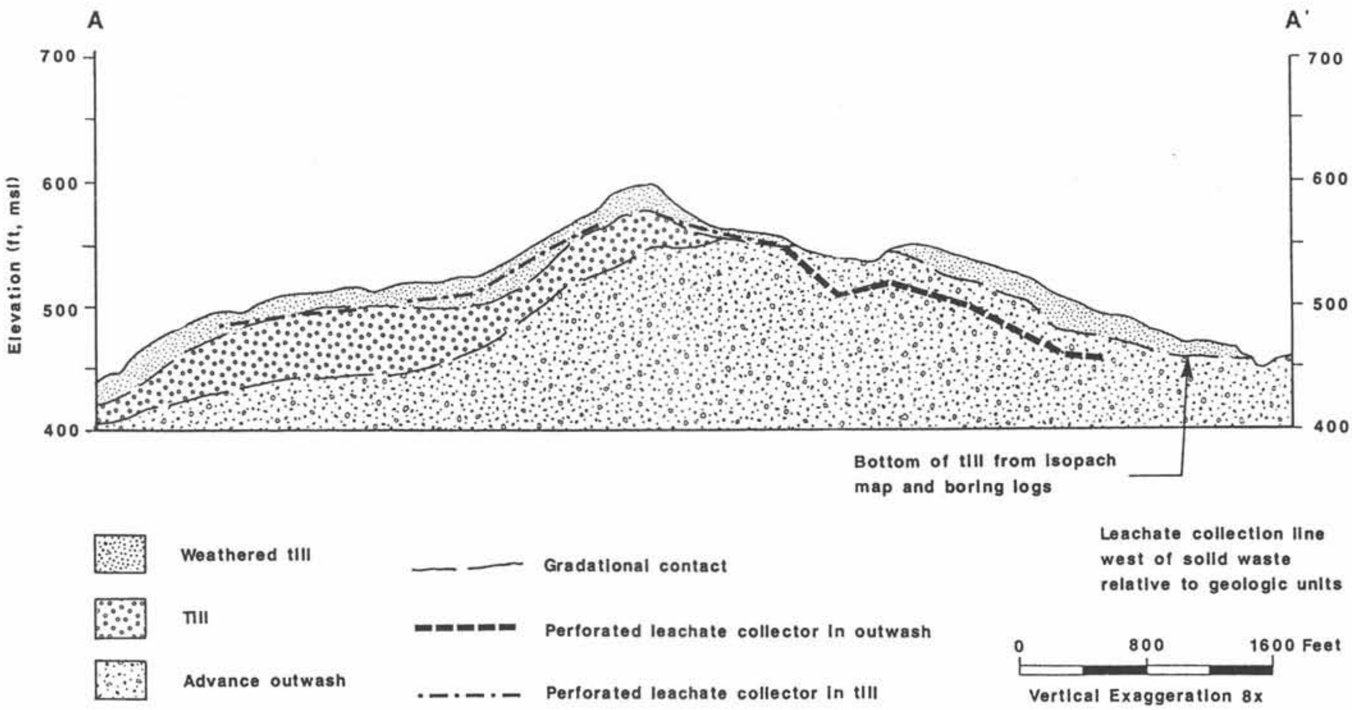


Figure 6. Cross-section A-A′ showing the position of the leachate collector relative to the geologic units at the landfill. See Figure 4 for cross-section location.

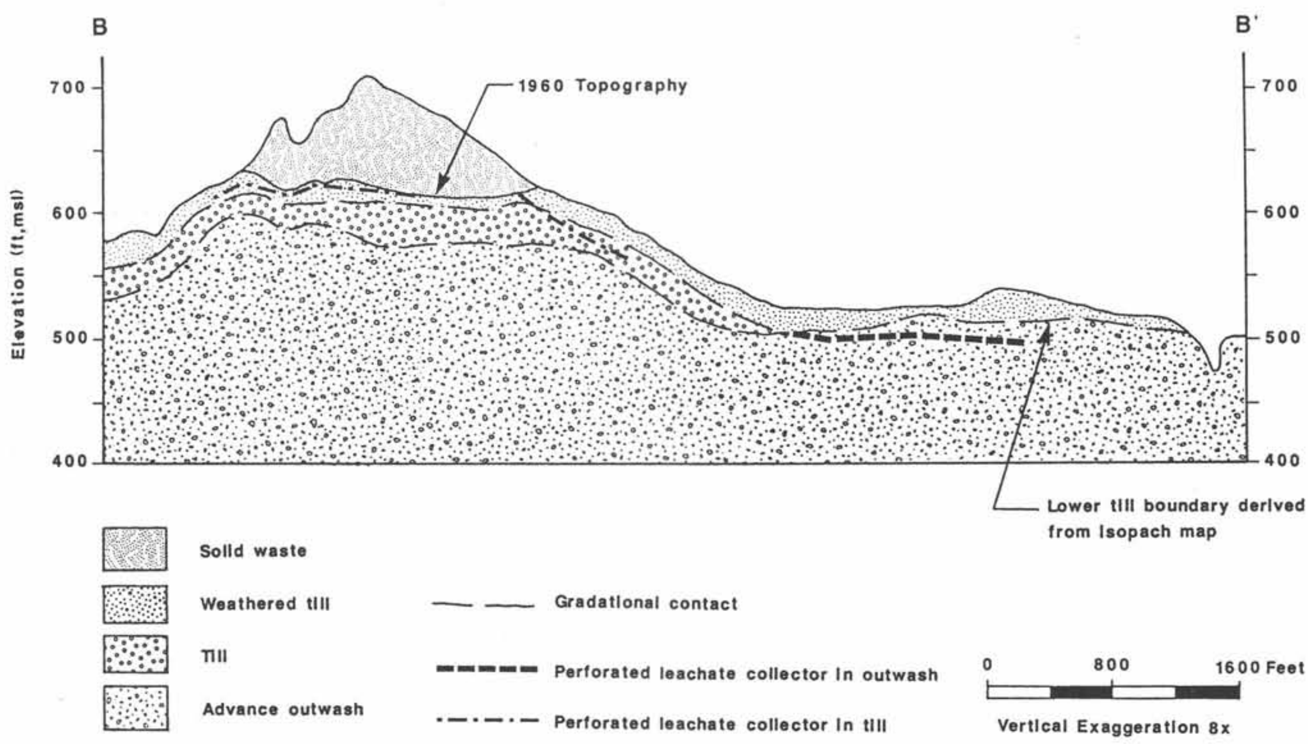


Figure 7. Cross-section B-B′ showing the position of the leachate collector relative to the geologic units at the landfill. See Figure 4 for cross-section location.

on two wells completed in the saturated refuse. Leachate levels near the pumping wells were monitored in several observation wells. The average hydraulic conductivity calculated was 2.4×10^{-3} cm/sec. The storage coefficient was 7×10^{-4}, suggesting that the leachate reservoir is acting as a confined or, more likely, a partially confined "aquifer".

For the feasibility study, it was assumed that the hydraulic properties of leachate are similar to those of ground water. In reality, however, the hydraulic properties of leachate and water are dissimilar. Consistency, specific gravity, viscosity, temperature, gas saturation, and composition all influence the hydraulic properties of leachate. The wide variation in leachate characteristics prevents direct comparison with water.

On the basis of theoretical analysis, leachate extraction is feasible, and a system of vertical extraction wells appears to be the most flexible and efficient means of removing leachate from the refuse. As part of the site development plan, the county is planning to implement a leachate head reduction program by the end of 1989.

REFERENCES

CH2M Hill Northwest, Inc., 1985, *Cedar Hills Regional Landfill, Phase 2–Site Development Plan, Task 13.0; Subtask 13.1, Preliminary Geotechnical Site Evaluation*: Report to King County Solid Waste Division, Seattle, WA, 19 p.

Converse, Ward, Davis, and Dixon, 1980, *Geotechnical and Groundwater Evaluation, Proposed Queen City Farms Landfill Site*: Report to Parametrix, Inc., Bellevue, WA, 18 p.

Hart-Crowser and Associates, Inc., 1983, *Assessment of Hydrogeology and Ground Water Quality Surficial Aquifer, Queen City Farms, King County, Washington*: Report for Queen City Farms, Inc., Seattle, WA, 12 p.

Livingston, V. E., Jr., 1971, *Geology and Mineral Resources of King County, Washington*: Washington Division of Mines and Geology Bulletin 63, Olympia, WA, 200 p.

Luzier, J. E., 1969, *Geology and Groundwater Resources of Southwestern King County, Washington*: Washington Division of Water Resources Water Supply Bulletin 28, Olympia, WA, 260 p., 13 plates.

Mills, D. E. and Cordell, D. A., 1988, *Evaluation of In-Waste Leachate Head Reduction*. In Proceedings, Second International Conference on Case Histories in Geotechnical Engineering, June 1-5, 1988, St. Louis, MO, Vol. I, Paper No. 10: University of Missouri, Rolla, MO, pp. 35-41.

Robinson and Noble, Inc., 1974, *Geological Investigation Report for Cedar Hills Disposal Site*: Report to King County Solid Waste Division, Seattle, WA, 14 p.

Robinson and Noble, Inc., 1978, *Results of Test Drilling Program at the King County Cedar Hills Landfill*: Report to King County Solid Waste Division, Seattle, WA, 12 p.

Rosengreen, T. E., 1965, *Surficial Geology of the Maple Valley and Hobart Quadrangles, Washington* [M.S. thesis]: University of Washington, Seattle, WA, 71 p., 1 plate.

Sweet, Edwards & Associates, Inc., 1984, *South Cedar Hills Draft Geotechnical Report*: Report to King County Solid Waste Division, Seattle, WA, 34 p.

Sweet, Edwards & Associates, Inc., 1985a, *Cedar Hills Regional Landfill, Phase 2–Site Development Plan, Task 13.0; Subtasks 13.4 and 13.5, Leachate Collection Trench and Subsurface Water Quality Investigations*: Report to CH2M Hill Northwest, Inc., Bellevue, WA, 16 p.

Sweet, Edwards & Associates, Inc., 1985b, *Cedar Hills Regional Landfill, Phase 2–Site Development Plan, Task 13.0; Subtask 13.3, Investigations of Leachate in Solid Waste*: Report to CH2M Hill Northwest, Inc., Bellevue, WA, 14 p.

Sweet, Edwards & Associates, Inc., 1986, *Cedar Hills Regional Landfill, Phase 2–Site Development Plan, Existing Area Report*: Report to CH2M Hill Northwest, Inc., Bellevue, WA, 40 p.

Sweet, Edwards & Associates, Inc., 1987, *Cedar Hills Regional Landfill, Site Development Plan, Task 45.0, Investigation of the Feasibility of In-Waste Leachate Head Reduction*: Report to CH2M Hill Northwest, Inc., Bellevue, WA, 99 p.

Vine, J. D., 1962, *Preliminary Geologic Map of the Hobart and Maple Valley Quadrangles, King County, Washington*: Washington Division of Mines and Geology Geologic Map GM-1, Olympia, WA, 1 sheet, scale 1:24,000.