Artificial Recharge in Oregon and Washington 1962

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By DON PRICE, D. H. HART, *and* B. L. FOXWORTHY

ARTIFICIAL RECHARGE OF GROUND WATER

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A summary of all known artificial-recharge operations and tests in Oregon and Washington as of 1962 and a discussion of problems related to artificial recharge

UNITED STATES DEPARTMENT OF THE INTERIOR

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ARTIFICIAL RECHARGE IN OREGON AND WASHINGTON, 1962

By DON PRICE, D. H. HART, and B. L. FOXWORTHY

ABSTRACT

Since 1950 artificial recharge has become an increasingly common practice in Oregon and Washington to augment the natural ground-water supply, to conserve desirable physical characteristics of water, and to dispose of excess water. Prior to 1950 there was little artificial recharge in the two States, and by 1956, only nine artificial-recharge installations were known to have been in operation. By 1961, when 2- and 3-well systems had been successfully used to furnish and dispose of water for heating and cooling of buildings and demand for additional municipal water supplies had increased, the number of current and former artificial-recharge operations had grown to 23, including 2 test operations and 1 standby installation.

Natural recharge to basalt, sand, and gravel aquifers in the two States was augmented by more than 17,000 acre-feet of artificially recharged water in 1961. The largest single artificial-recharge operation is a surface-spreading operation at Richland, Wash., where as much as 12,000 acre-feet of water, diverted from the Columbia and Yakima Rivers, infiltrates each year to shallow aquifers tapped by municipal-supply wells.

Artificial-recharge tests at Walla Walla, Wash., in 1957–58 and at The Dalles, Oreg., in 1960–61 have demonstrated that recharge of basalt aquifers by the injection method is technically feasible and could be used more widely to supplement natural recharge in areas of similar volcanic terranes.

The general success of most artificial-recharge operations in the two States indicates that such operations can be a profitable means of conservation and that they will be used more widely in the future. However, improper design of systems and uncontrolled or indiscriminate recharge practices, such as injecting water of inferior quality underground, can cause undesirable changes in both the ground water and the water-bearing capacity of the aquifers.

The successful design of an artificial-recharge system depends largely on collection and proper evaluation of background data on the chemical and physical character and biota of the waters involved, the subsurface geology, the natural ground-water regimen, and the existing uses of the waters involved. Successful operation of the system depends also on continued collection and proper evaluation of such data as quantities and rates of recharge and ground-water withdrawals, chemical and physical character and biota of both the recharge and ground water, sediment content of the recharge water, type and amount of

treatment of the recharge water, and effects of recharge on ground-water levels. Early recognition and evaluation of problems that arose during operation of several existing artificial-recharge systems in Oregon and Washington were hampered because those data were not available or were inadequate.

INTRODUCTION

Where the practice of artificially replenishing the ground-water supply is feasible, it offers a means of maintaining or increasing the amount of water available from an aquifer while also conserving water that otherwise might be wasted. Correlative benefits that may accrue locally include conservation of heat (in heat-exchange systems utilizing ground water) and improvement of the quality of ground waters.

PURPOSE AND SCOPE OF THE INVESTIGATION

Planned artificial recharge was rarely practiced in Oregon and Washington prior to 1950, but it has become more common since that time and doubtless will be utilized more widely in this region in the future. By 1956, there were nine known artificial-recharge installations (in operation, discontinued, or on standby) in the two States, and by 1961 there were 23, including 2 test operations and one standby installation. The purpose of this study is to compile and disseminate the information available on the current and discontinued artificial-recharge operations—the methods used, the success attained, and problems encountered—to provide guidance for future operations.

In this report, each of the artificial-recharge operations is described in a detail consistent with the amount of information available, but with greater emphasis on operations that are not otherwise described in published reports. The most detailed description included is of the water-spreading operation at Richland, Wash. (p. C5–C19). That operation, which has been described only briefly in a previously published report (Howson, 1953), provides about 70 percent of the yearly volume of water added artificially to the ground water of the two States.

Besides descriptions of the artificial-recharge operations, the present report contains tables of data that are pertinent to these operations and also a brief discussion of the probable causes and significance of the problems involved in the subsurface-injection operations.

"Artificial recharge," as used in the present report, is defined as the deliberate addition of water to the ground-water body in such a way as to make the water (or some property of it, such as heat content) available for later recovery. Under this definition, the increase in ground water incidental to irrigation or drainage of land, or to operations intended principally for fluid disposal, is not herein considered as artificial recharge. Nevertheless, the incidental recharge from

those practices has significant effects on the amount and quality of ground water at many places in Oregon and Washington.

This investigation was made as part of the Geological Survey's program for appraising the water resources of the Nation. An earlier report of this area was released to the open file (Hart, 1957). The present paper is a revision of the earlier report; it incorporates more recent data collected by the other authors through 1962.

WELL-NUMBERING SYSTEM

In this report, wells and points of water-sample collection are designated by symbols that indicate their location on the basis of the rectangular system of land division. In the symbol 1/1–3D1, for example, the part preceding the hyphen indicates respectively the township and range (T. 1 S., R. 1 E.) south and east of the Willamette base line and meridian. For those townships west of the Willamette meridian, the range number is followed by the letter "W." For wells in Oregon that are in townships north of the Willamette base line, the township number is followed by the letter "N"; however, because all the wells in Washington are north of the base line, that letter is omitted from numbers designating the wells in that State. The first number after the hyphen indicates the section (sec. 3), and the letter "D" indicates a 40-acre subdivision of the section as shown in figure 1. The final digit is the serial number of the well within that 40-acre tract. Thus, well 1/1–3D1, if in Oregon, would be in the NW¼NW¼ sec. 3, T. 1 S., R. 1 E. If in Washington, the well would be in the same position within section 3, but in T. 1 N., R. 1 E.

Section 3

Well 3D1	D ⊙	C	B	A
	E	F	G	H
	M	L	K	J
	N	P	Q	R
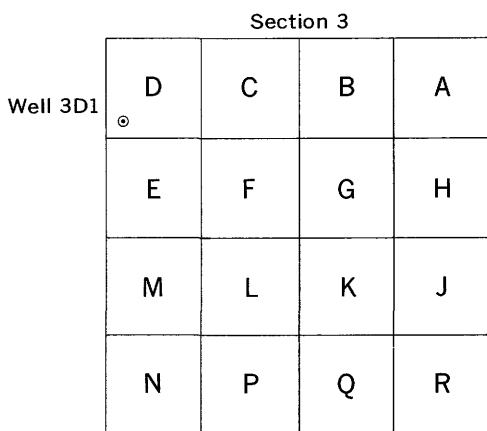
FIGURE 1.—Well-numbering system.

In table 1, numbers are not given in full for each well. Rather, the numbers are grouped by townships under appropriate subheads, and only the part of the number that indicates the section, 40-acre tract, and serial number is shown for an individual well. The data in tables 1, 2, and 3 are grouped separately by State to prevent confusion when referring to location numbers.

For consistent use of location numbers in table 3, the general locations of sampling sites on streams and of well fields from which composite samples were collected are designated by abbreviated numbers (as 9/28–15) that indicate only township, range, and section.

ACKNOWLEDGMENTS

The cooperation of those connected with the design and operation of artificial-recharge installations greatly facilitated this investigation. Mr. C. N. Zangar and the staff of the Engineering and Supplies Division of the Hanford Operations Office, Atomic Energy Commission, supplied valuable help and information. Helpful data also were furnished by Mr. R. C. Chewning, of the firm of J. Donald Kroeker & Associates, and by personnel of the following firms and agencies: Cornell, Howland, Hayes & Merryfield, consulting engineers; Robinson & Roberts, ground-water consultants; Tacoma City Light; Washington Department of Conservation, Division of Water Resources; and the office of the Oregon State Engineer. The assistance of all is gratefully acknowledged.

PREVIOUS INVESTIGATIONS

Many studies have been made of artificial-recharge operations and related subjects. Most of those studies pertain to other parts of the country, and are too numerous to list here. A few, however, contain information especially pertinent to the artificial-recharge operations in Oregon and Washington; they are cited in the text and included in the list of references in this report. A comprehensive annotated bibliography on the subject of artificial recharge through 1954 was prepared by Todd (1959a).

Except for the present study and various design studies by engineering and consulting firms, only three investigations dealing largely or entirely with artificial recharge in Oregon and Washington were completed or underway by the end of 1961. Artificial recharge of ground water in the west-side business district of Portland, Oreg., was discussed at length by Brown (1963) in a report on the utilization of ground water in that area. An experiment to determine the feasibility of recharging basalt aquifers at Walla Walla, Wash., by injecting excess surface water into a well tapping those aquifers was

described by Price (1961).　B. L. Foxworthy and C. T. Bryant, U.S. Geological Survey, described a similar experiment on artificial recharge of basalt aquifers at The Dalles, Oreg. (written comm., 1961).

METHODS OF ARTIFICIAL RECHARGE

The two principal methods by which direct artificial recharge is accomplished are surface spreading and subsurface injection. Surface spreading consists of diverting water from a stream to places where the water will flow over or stand on permeable material that will transmit it to an underlying ground-water body. Subsurface injection is the addition of water to a ground-water reservoir through tunnels, shafts, or wells.

The feasibility of these methods (or variations of them) in a particular area is governed by many factors.　(See p. C48–C49.)　In general, surface spreading is effective only for recharging ground-water bodies that are not overlain by impermeable strata, and normally is applicable only in areas where both the topography and the subsurface conditions are favorable. Subsurface injection can be used to recharge ground-water bodies that are overlain by relatively impermeable strata or that are in areas where the land is topographically unsuitable for surface spreading; however, subsurface injection usually requires very clean, good-quality recharge water.

SURFACE-SPREADING OPERATIONS

By 1962, only two surface-spreading operations were being utilized in this region.　One serves the municipal water system at Richland, Wash., and the other (Duck Lake recharge operation) stores water for irrigation supplies in the Okanogan Irrigation District, near Okanogan, Wash.　The approximate locations of these two artificial-recharge operations and of the others described in this report are shown in figure 2.

RICHLAND, WASH.

LOCATION AND DESCRIPTION OF THE AREA

Richland, Wash., is the headquarters and residential area of the Hanford Operations Office of the Atomic Energy Commission.　The city is built on glaciofluvial and alluvial terraces near the junction of the Yakima and Columbia Rivers, at the eastern edge of Benton County (fig. 2).　Most of the area is between 350 and 400 feet in altitude.　The area has an arid climate; precipitation rarely exceeds 7 inches a year and occurs mostly as snow during the winter and rain during the spring.　Air temperatures sometimes exceed 100°F in the summer and occasionally dip below 0°F in the winter.

Bellingham
Skagit River
Duck Lake
STRAIT OF JUAN DE FUCA
Everett
Port Townsend
Snohomish
Columbia River
Seattle
Spokane
Tacoma (2)
Lakewood
Naches River
Yakima River
Olympia
Yakima
Richland
Snake River
Walla Walla
Astoria
St Helens
Hazel Dell
Portland (8)
Vancouver (2)
The Dalles
Columbia River
Pendleton
La Grande
OCEAN
Salem
John Day
Baker
Willamette River
PACIFIC
Eugene
Springfield
Crooked River
Bend
Deschutes
River
Ontario
Malheur River
Snake River
Umpqua
North Bend
Coos Bay
Burns
Owyhee River
Rogue River
Medford
Klamath Falls
Lakeview
Pine Flat

50   0   50   100 MILES

FIGURE 2.—Locations of artificial-recharge operations in Oregon and Washington. (Numbers in parentheses indicate number of installations in designated area.)

The Richland area is directly underlain by permeable glaciofluvial and alluvial deposits that are, in turn, underlain by older, less permeable sedimentary deposits (Ringold Formation) at a depth of about 20 to 80 feet. (See table 2, log of well 10/28–35H4.) The water table is shallow and slopes eastward from near the Yakima River to the level of the Columbia River, which flows past the east side of the city. Much of the Richland area lies within a belt where large fluctuations of the water table formerly occurred in conformity to the rise and fall of the level of the Columbia River; since 1953 these fluctuations

have decreased greatly as a result of the impoundment of the river behind McNary Dam, about 40 miles downstream from Richland.

DESCRIPTION OF THE OPERATION

Of 23 wells used by Richland for municipal supply, 18 are within or near four basins in which water is held for artificial recharge. The recharge basins are locally called Richland, A–J, NK&K, and Duke Basins (pl. 1). Richland Basin, the oldest and largest, is in south-central Richland, and was constructed in 1944. A–J and NK&K Basins were constructed during 1948 in abandoned gravel pits; their names are the initials of firms that formerly operated the gravel pits. A–J Basin is at the south edge of the town of North Richland, and NK&K Basin is near the northern limits of Richland, on the west bank of the Columbia River. Duke Basin is about one-half mile west of NK&K Basin and a mile south of A–J Basin; it was added to the supply system about 1950.

Richland Basin, like A–J and Duke Basins farther north, lies in a narrow natural topographic depression, a segment of a former river channel (fig. 3). In contrast to the other basins, which are under-lain mainly by gravel and sand of moderate permeability, Richland Basin is directly underlain by less permeable flood-plain deposits of silt and fine sand. These deposits extend to a depth of 10 to 20 feet and are in turn underlain by unconsolidated sedimentary deposits of the Ringold Formation.

A–J Basin is the most effective of the four. As a result of its opera-tion, wells near it supplied an additional 7 mgd (million gallons per

FIGURE 3.—View southwest across the northern part of the Richland recharge basin. Well house for supply well 15A1 is in left center.

day) of water to the city, beginning on June 15, 1948 (Howson, 1953, p. 404). The basin covers an area of about 6 acres and is divided in half by an earthen dike (fig. 4). In preparation for its use as a recharge basin, the bottom of the basin was leveled and a layer of medium-grained sand was spread over it. The sand is intended to prevent sediment that is carried by the recharge water from penetrating deeply into the interstices of the underlying gravel, where it might permanently impair the infiltration capacity of that material. The sand layer is removed and replaced about once a year. The basin floor is scarified once or twice during the annual recharge period to break up a thin, less permeable layer of sediment that accumulates on its surface. Whenever the sediment load in the recharge water is heavy and appears likely to impede infiltration, the inflow is diverted around one or both halves of the basin and allowed to flow into the old river channel south of the basin, from whence a large part of it apparently reaches the ground-water body.

NK&K Basin was put in service to provide additional recharge in anticipation of an increased demand for ground water. It covers a roughly rectangular area of about 6 acres. It is about 30 feet deep—much deeper than the other basins—and has fairly steep sides. Material underlying the basin is similar to, and of about the same thickness as, the glaciofluvial and fluvial deposits at A–J Basin, but is less permeable. During gravel-removal operations prior to use of the basin for recharge, the permeability of the basin floor was drastically impaired by sediment deposited from wash water that was allowed to flow back into the pit. Therefore, recharge now occurs mainly

FIGURE 4.—View south toward the A–J recharge basin at North Richland. Water from the supply ditch enters basin at extreme right. Well houses are visible around the basin.

through the sides of the basin. Tests made during the initial recharge operation showed that if the basin were filled with water to a depth of about 20 feet, more than 3 mgd could be recharged through it.

The smallest of the recharge basins is Duke Basin, which covers less than 3 acres in the abandoned channel south of A–J Basin. Duke Basin is shallow, averaging about 5 feet in depth, and is roughly rectangular in shape. It was constructed by erecting, across the channel, a low dike of gravelly soil scraped from the basin floor. In this vicinity, the sand and gravel of the underlying glaciofluvial and fluvial deposits are about 70 feet thick. The floor of the basin is predominantly cobble-size gravel.

Most of the water for the recharge basins is brought from Horn Rapids Dam on the Yakima River (pl. 1) through 8 miles of open ditch and half a mile of wooden-stave pipe 48 inches in diameter. Northwest of Richland the ditch divides; one branch runs southward to Richland Basin and the other continues eastward to the three northern basins. Water reaches A–J Basin from the open ditch, which runs southward on the west side of the basin. Any ditch water that is surplus to requirements for A–J Basin enters a 12-inch pipeline just south of that basin and is conveyed to Duke Basin and, occasionally, to NK&K Basin (pl. 1).

The main supply for NK&K Basin is pumped from the Columbia River and is carried to the basin through a 24-inch intake pipe. The pump, which has a rated capacity of 5,000 gpm (gallons per minute), operates about every other day during the recharging period.

In 1952, a recharge well was drilled in A–J Basin in an effort to offset the periodic decrease in percolation resulting from sediment accumulation in the basin. Prior to drilling, an east-west dike was constructed to separate the basin into two sections of approximately equal size. This dike permitted use of the south half during construction of the recharge well in the north half, and it also allows separate cleaning or flooding of each half.

The recharge well was drilled approximately in the center of the northern half of the basin. The well has a steel casing 20 inches in diameter that is set to a depth of 68 feet and is perforated below the 8-foot depth. Around the casing, near its top, a collector tank 6 feet in diameter was installed in a pit excavated in the basin floor; an extension on this tank protrudes above the water surface and provides access for cleaning the well. Six horizontal tile collector pipes, each 50 feet long, radiate from the collector tank like the spokes of a wheel. The tile pipes are about 5 feet below the basin floor and are covered with sand and gravel. Construction of the recharge well undoubtedly increased the rate of recharge, but the amount of the increase is unknown.

RATE OF INFILTRATION AND VOLUME OF RECHARGE

Although the beginning and ending dates of the artificial recharging varies considerably from year to year, the infiltration basins are in operation for about 7 months each year—generally from April through October. The amount of water that reaches the water table from the four basins can only be estimated, because very few records of inflow have been kept.

Richland Basin has an average recharge rate of 3 to 4 mgd, according to Mr. Harold Petty, superintendent of Richland's water-supply system (oral commun., 1957). Water supplies to this basin in excess of the infiltration rate overflow the basin and drain to the Yakima River via a short canal.

The average inflow to A–J Basin, as estimated by Mr. Petty, is about 10 mgd; this is more than the combined inflow to the other three basins. The only records of measured inflow and ponded water in A–J Basin, and withdrawal from adjacent wells, consist of daily measurements made during the period August 20 to October 1, 1950 (fig 5).
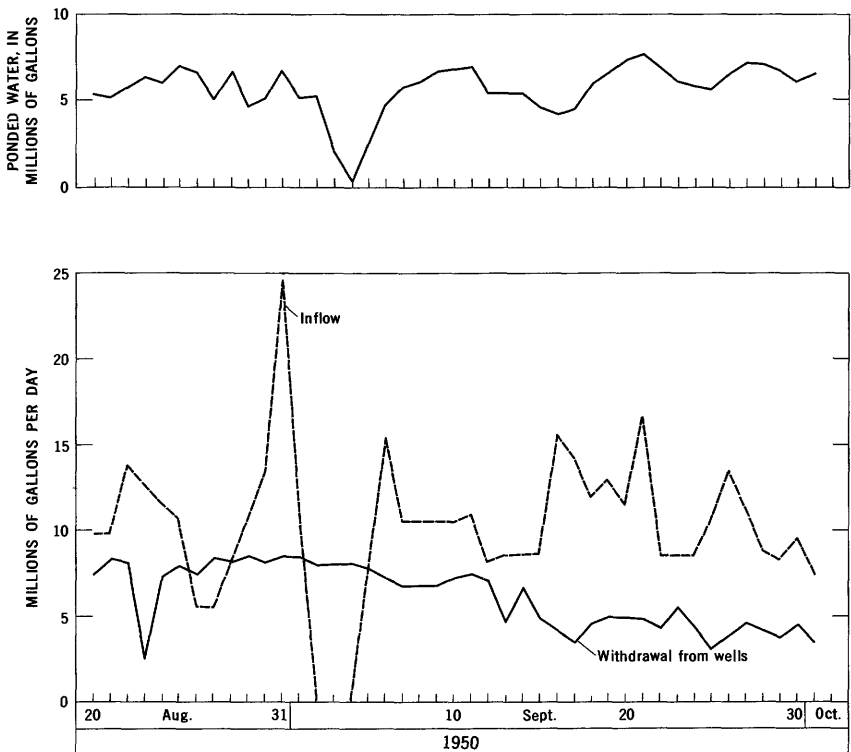

FIGURE 5.—Amounts of water flowing into and ponded in the A–J recharge basin, and the withdrawal from nearby wells, during the period August 20 to October 1, 1950.

The inflow to NK&K Basin, apart from the occasional addition of water from the Yakima River, can be estimated roughly as the amount of water pumped from the Columbia River. This amounts to about 7.2 million gallons every other day, and averages about 3.6 mgd.

The quantity of water recharged to the ground-water body through Duke Basin is estimated to be roughly 1 mgd.

Although few data are available on which to base estimates of the total amount of water recharged artificially in the area, the artificial recharge through A–J Basin can be calculated roughly by using the short-term records presented on figure 5. In the 41-day period shown on figure 5, 403 million gallons reportedly was applied to the basin. The net change in pondage during the period was an increase of about 1.2 million gallons; in this period probably about 1 million gallons was discharged by evaporation. Therefore, about 400 million gallons went to recharge—at an average rate of about 10 mgd, or 1.6 mgd per acre. During the 41-day period, the pumpage from wells in the vicinity of the basin was 251 million gallons. Thus, the net accretion to the ground-water body was about 150 million gallons, or approximately three-eighths of the water applied during the period. A large amount of the water recharged through this basin probably escapes beyond the area of influence of the wells in the vicinity of the basin; however, some of it may be intercepted by wells near Duke and NK&K Basins.

Apparently the average inflow during this short period of record did not exceed the capacity of the basin to accept recharge water, because the basin did not overflow. However, for several short periods of time, as on August 31 and September 6, 16, 17, and 21, the inflow probably was greater than the basin's capacity for infiltration.

On the basis of the estimates and the measurements given previously, the combined average infiltration from all the recharge basins at Richland is about 18 mgd. Over the 7-month recharge period, this infiltration would be nearly 4 billion gallons, or about 12,000 acre-feet. This estimate represents the maximum amount of artificially recharged water that is available for withdrawal, and is slightly greater than the average yearly pumpage from the city's wells during the period 1950–55. However, part of the artificially recharged water escaped to the Yakima and Columbia Rivers without being pumped from the wells. The increment of the artificially recharged water that was withdrawn is discussed on page C12–C14.

CONTROL OF SEDIMENT AND SLIME-PRODUCING ORGANISMS

Sediment carried by the recharge water, and algae and slime bacteria (*Sphaerotilus*) that grow in the warm river waters during the summer months (Sylvester and Seabloom, 1962, p. 75) reduce the infiltration capacities of the recharge basins. The combined effect of

accumulated sediment, algae, and slime bacteria in A–J Basin during the first summer of operation (1948) caused as much as a 90-percent reduction in the rate of infiltration. As a result, the water levels in wells near the basin declined as much as 10 feet during the following few months. Before the next recharge season, the upper 6 inches of material on the basin floor was scraped and removed. When the basin was reflooded, it accepted infiltrating water at a rate of 10 to 15 mgd, and water levels in nearby wells began to recover from the previous decline, rising at rates of about 1 foot per day.

Algal and *Sphaerotilus* growth in the Yakima River water was subsequently controlled effectively by adding 15 pounds of copper sulfate daily to the water before it entered the basins. Chlorine, as well as copper sulfate, was added to the recharge water in A–J Basin. The main supply for NK&K Basin, pumped from the Columbia River, also was treated. Copper sulfate, fed into the recharge water at the rate of 5 pounds per day from June to September 1951, effectively controlled slime growth in that basin.

To reduce the volume of suspended sediment entering A–J Basin, a settling pond was constructed adjacent to the west side of that basin. The settling pond, which covers about 4 acres, retains the recharge water for about 4 hours before the water reaches an overflow to A–J Basin. Although no flocculating agents are used in the settling pond, about 75 percent of the solids reportedly settle from the recharge water during those 4 hours.

There probably is some percolation of recharge water through the floor of the settling pond to the water table. However, the volume of additional recharge in this manner is not known.

RECOVERY OF THE ARTIFICIALLY RECHARGED WATER

Eighteen of Richland's 23 public-supply wells are clustered around the recharge basins.[1] All eighteen wells are drilled wells ranging in diameter from 12 to 36 inches, and all have perforated casings, most of which are steel. Some of the steel casings were perforated before and some after installation. Three wells have preslotted concrete casing. Depths of the wells range from 55 to 178 feet. All tap the glaciofluvial and alluvial deposits, which are the principal water-bearing formations of the area, and most extend downward into conglomerate of the Ringold Formation.

The water-yielding capacity of the wells is limited during the recharge period principally by the capacity of the pumps and, during

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[1] The Richland wells listed under the ownership of the Atomic Energy Commission, Hanford Operations Office, in table 1 include only those for which drillers' logs or hydrographs are presented in this report. Records of the other wells can be examined at the offices of the U.S. Geological Survey, Ground Water Branch, in Portland, Oreg., and Tacoma, Wash.

the nonrecharge period, by the ability of the aquifers to transmit water. The decline in water levels after the termination of recharging causes a marked decrease in the saturated thickness—and, therefore, in the transmissibility—of the aquifer materials.

More water is pumped during the 6-month period April through September than during the other 6 months. The maximum monthly pumpage usually occurs in either July or August. During the summer the eight wells near Richland Basin have a potential capacity of about 6,300 gpm, or more than 9 mgd. The greatest monthly production from this well field during the period 1949–55 was in July 1953, when 225 million gallons, or an average of more than 7 mgd, was withdrawn.

The potential summer capacity of the three wells near NK&K Basin is about 1,900 gpm and that of the two wells at Duke Basin is about 2,300 gpm. For the period 1949–55, the greatest combined monthly production from these two well fields was 170 million gallons (an average of about 5.5 mgd) during July 1952.

The potential summer capacity of the 10 production wells near A–J Basin is about 14,000 gpm, or 20 mgd. The greatest monthly production from the wells near this basin for the period 1949–55 occurred during July 1954, when 540 million gallons, or an average of 17 mgd, was withdrawn.

The combined potential summer capacity of the four well fields is more than 24,000 gpm, or about 35 mgd. The greatest monthly withdrawal for the entire system during the period 1949–55 was 860 million gallons in August 1955—an average of nearly 28 mgd.

The capacity of all the well fields is much less during the period November to April, when no artificial recharge is taking place and the water table is low. Those months also include the times of minimum demand on the Richland water system. The greatest reduction in capacity occurs at the wells near A–J Basin; capacity of those wells during the nonrecharge period declines to a little more than half of the summer capacity. The reduction in capacity during the nonrecharge period is less for wells near the other three basins than for those near A–J Basin, which suggests that a smaller percentage of the summer production of wells near the other basins comes from artificially recharged water.

Monthly production from all the wells during the periods of no artificial recharge (November–March) for the years 1949–55 ranged from a minimum of about 130 million gallons (about 4.6 mgd) in February 1952 to a maximum of 230 million gallons (about 7.4 mgd) in March 1954.

The total withdrawals, by seasons of recharge and nonrecharge, during the period 1950–55 are compared in the following table:

Withdrawals from wells, in millions of gallons

[Data reported by Engineering and Supplies Division, Hanford Operations Office, Atomic Energy Commission]

Period	Calendar years					
	1950	1951	1952	1953	1954	1955
Usual nonrecharging periods:						
January	160	150	170	130	210	180
February	130	140	130	140	190	170
March	150	170	190	210	230	220
November	130	150	150	190	180	200
December	150	150	160	180	190	200
Total (rounded)	700	800	800	800	1,000	1,000
Usual recharging periods:						
April	240	320	370	300	410	360
May	350	400	340	450	550	490
June	330	350	500	490	640	720
July	560	630	650	680	830	740
August	550	580	620	660	730	860
September	400	390	430	540	490	540
October	160	180	290	230	270	240
Total (rounded)	2,600	2,900	3,200	3,400	3,900	4,000
Difference (rounded)	1,900	2,100	2,400	2,600	2,900	3,000
Average difference per year (rounded)						2,500

As this table shows, the difference between withdrawals during the periods of recharge and nonrecharge ranged from 1,900 million gallons during 1950 to 3,000 million gallons during 1955. These differences in withdrawal are believed to indicate roughly the amount of recharge water that was recovered during the years for which data are shown. The average difference, 2,500 million gallons per year, amounts to about 60 percent of the average yearly pumpage from the wells adjacent to the recharge basins.

Of the total withdrawal during the period 1950–55 (25,000 million gallons), nearly one-half, or 11,500 million gallons, was pumped from wells near the A–J recharge basin, about 5,200 million gallons was pumped from near NK&K and Duke Basins, and about 8,300 million gallons was pumped from the vicinity of Richland Basin.

EFFECTS ON GROUND-WATER LEVELS

Plate 2 depicts, by contour lines, the position and shape of the water table in the vicinity of A–J, Duke, and NK&K Basins at selected times of artificial recharge and nonrecharge during the period 1948–52. Because the contour lines indicate the gradients on the water table, the figures also show directions of movement of the ground water. Comparison of the figures show the effects of the artificial recharge, and of the withdrawal from wells, on the position and shape of the water table and the movement of the ground water.

Plate 2A represents the configuration of the water table on December 30, 1948. Though recharge operations were begun in June 1948, the contours show that by the end of December of that year an almost uniform west-to-east gradient prevailed to within about 2,000 to 3,000 feet of the Columbia River. From there to the level of the river, the gradient increases sharply. Evidence of the previous summer's recharge appears only as a narrow band of lessened hydraulic gradient that extends north-south through A–J Basin. This narrow band coincides roughly with the old stream channel on the northwest edge of which A–J Basin is situated. The water-table contours shown on plate 2A probably approximate the natural (prerecharge) water table, which sloped generally eastward from the Yakima River toward the Columbia River.

Plate 2B shows the shape of the water table on October 17, 1951, near the end of the 7-month recharge period of that year. A comparison of plate 2A with plate 2B shows that, by October 1951, the shape of the water table in the immediate vicinity of the recharge basins had been altered from its configuration of December 1948 by broad mounds resulting from recharging and by conspicuous localized cones of depression caused by pumping of the wells. Ground-water levels near and between the basins averaged several feet higher in October 1951 than in December 1948; however, the levels west of about the 355-foot contour were 1 to 2 feet lower than they had been in 1948.

The shape of the water table on April 30, 1952, before recharging operations began during that year, is shown by plate 2C. The recharge water in ground storage, shown by the elevated water table on plate 2B had spread out and had been depleted by discharge to the Columbia River and by pumping. The cone of depression in the vicinity of A–J Basin had enlarged noticeably, the closed cone of depression at the Duke Basin well field was much deeper than it had been in October 1951 (pl. 2B), and the water table had been lowered 2 to 5 feet throughout a wide area extending through Duke and A–J Basins. Plate 2C shows that the water table in the area west of about the 355-foot water-table contour apparently is not greatly influenced by pumping.

Plate 2D depicts the water table on June 11, 1952, during the third month of the recharge operation that year. Comparison of Plate 2D with Plate 2B indicates that recharge through A–J Basin during only a few weeks had caused a general buildup of water levels around, and to the south of, the basin. Also, recharge through Duke Basin apparently was the cause of a definite ground-water mound trending south-southeast from that basin. Recharge through NK&K Basin caused changes that are less conspicuous on the water-table maps; however, it apparently caused a rise in the water table as great as 8 or 9 feet at

places near that basin. Near each of the basins, the cones of depression around the pumping wells had become smaller and steeper between April 30 and June 11, 1952.

Plates 2*B* and 2*D* show that not all of the water that was added to the aquifer artificially was withdrawn through the wells. The hydraulic gradients east of NK&K Basin and on the east sides of the aforementioned ground-water mounds south of A–J and Duke Basins indicate that much of the recharge water moved eastward and was lost as discharge to the Columbia River.

Fluctuations of water levels in wells near three of the recharge basins are shown in relation to stages of the Columbia and Yakima Rivers in figures 6 and 7. These figures show that, in general, the relative amounts of pumping and artificial recharge had a much greater influence on ground-water levels near the basins than either natural recharge or river stage. For example, during periods of no artificial recharge, when the basins are dry, the static (nonpumping) water levels generally declined in each of the wells (10/28–23P2, 35H4, and 9/28–15A1). Conversely, after artificial recharging began, the static water levels rose, and remained high throughout the periods of recharging despite the substantial increase in withdrawals that took place during those periods. Locally, near the recharge basins, however, water levels tended to decline after the latter part of July, when the water demand was at its peak and the infiltration rates from the basins usually were becoming smaller owing to accumulation of sediment.

Since the closure of McNary Dam in December 1953, the average level of the Columbia River at North Richland has been raised about 10 feet, and the annual minimum altitude of the river surface at that point is held to about 340 feet. The general effect of this increased stage on the annual fluctuations in the level of the river can be seen by comparing the hydrographs of the Columbia River at Richland for the years 1950 and 1955 (figs. 6, 7). The higher minimum stage of the Columbia River after closure of the dam undoubtedly caused substantial seasonal increases in the amount of ground water in storage near the river. Comparison of the well hydrographs in figure 6 with those in figure 7 shows that static levels during nonrecharging periods were about the same in wells 10/28–23P2 and 34H4 during 1950 and 1955; however, the levels in well 9/28–15A1 were generally several feet higher in 1955 than in 1950, which suggests that the higher minimum stages of the Columbia River since 1953 may have contributed to a rise in ground-water levels near Richland Basin. Near A–J and NK&K Basins, however, the higher river levels apparently had not caused a detectable change in ground-water levels by 1955.
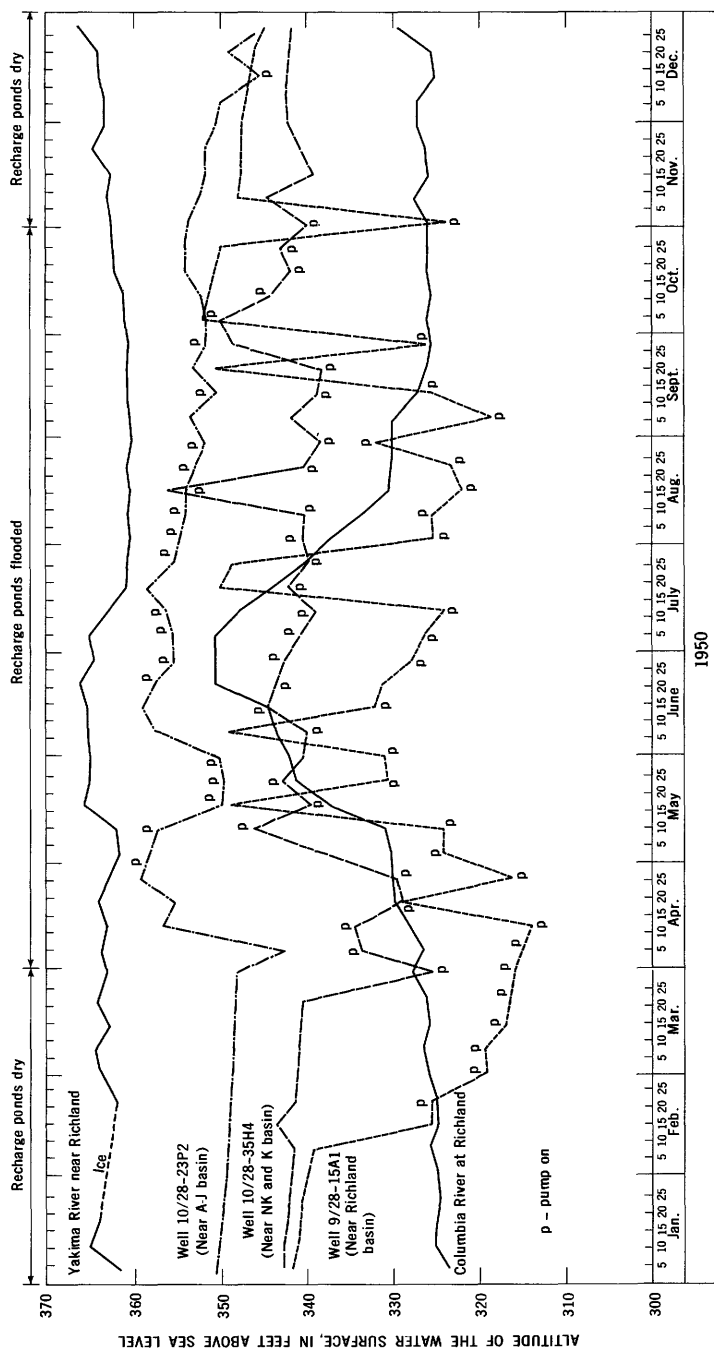
FIGURE 6.—Fluctuations of water level in three wells near recharge basins and of water stage in the Columbia and Yakima Rivers near Richland, Wash., during 1950.

FIGURE 7.—Fluctuations of water level in three wells near recharge basins and of water stage in the Columbia and Yakima Rivers near Richland, Wash., during 1955.

HARDNESS OF THE GROUND WATER

Generally, except for hardness, the chemical character of the water from all the well fields near the recharge basins is good. Two chemical analyses of composite water samples from each of the well fields, plus several partial analyses of composite water samples from wells near A–J and NK&K Basins, are given in table 3.

During each year, water from wells near each of the recharge basins varies in hardness from moderately hard to very hard, depending largely on seasonal differences in the amount and hardness of the recharge water reaching the wells. Available determinations of hardness of water from the Yakima River at Kiona during calendar year 1953 (U.S. Geol. Survey, 1958, p. 308) and from the wells at A–J Basin (Jan. 1951–Sept. 1952) show that during periods of artificial recharge the water from the wells follows the same general trends in hardness as does the river water. For example, shortly after recharge begins at A–J Basin, the normally harder well water declines rapidly in hardness to a value close to that of the water in the Yakima River. From July to October, while the hardness of the river water increases steadily, the hardness of the water from the A–J well field also increases. Following periods of artificial recharge, the hardness of the river water decreases, but the hardness of water from the wells near A–J Basin gradually increases to near the normal hardness of the native ground water.

The increase in hardness of the Yakima River water during late summer has long been an undesirable feature in respect to using its water for recharge. Plans are therefore being made to divert water from the Columbia River into the three North Richland basins and to divert Yakima River water into Richland Basin only.

OKANOGAN, WASH.

A variation of the water-spreading method of artificial recharge is practiced at Duck Lake in Okanogan County, Wash. (fig. 2), under the direction of the Okanogan Irrigation District. The principal purpose of this operation is to increase the amount of water stored in Duck Lake and in sand and gravel aquifers adjacent to, and hydraulically connected with, the lake. The water thus stored is used as an auxiliary supply during years when insufficient irrigation water is available in the district's reservoirs.

In the Duck Lake recharge operation, surplus stream water is introduced into the lake (about 20 acres in surface area); the level in the lake is thereby raised and a hydraulic gradient sufficient to cause water to move from the lake to the adjacent ground-water body is created. Because the sand and gravel aquifers that are hydraulically connected

to the lake are moderately porous and permeable, and are much more extensive than the lake itself, most of the water that is introduced into the lake goes into ground-water storage.

The water used for the artificial recharge is streamflow that temporarily exceeds the requirements for the irrigation-project lands in the vicinity of Duck Lake. The water is obtained from two streams— Johnson Creek, which passes about a mile northwest of Duck Lake, and Salmon Creek, which flows 4 to 5 miles west of Duck Lake. The Salmon Creek water passes through the district's storage reservoirs, Conconully Lake and Conconully Reservoir (which are about 12 miles northwest of Duck Lake), is diverted from Salmon Creek at a point about 5 miles west of the lake, and is conveyed to the project lands in a concrete-lined canal. The surplus water from the district's system is conveyed to Duck Lake in a small concrete-lined feeder canal at rates ranging from about 0.5 to 20 cfs (cubic feet per second), depending upon availability of the water.

According to records furnished by the Washington Department of Conservation, the natural inflow to Duck Lake was augmented by the diversion of 2,760 acre-feet of surplus water in 1958, 3,340 acre-feet in 1959, and 1,980 acre-feet in 1960. Data are not available on the amounts of water added before 1958, or on the physical and chemical character and biota of the recharge or ground water.

When the stored water is needed to meet peak irrigation demands, it is pumped from the lake or from wells along the feeder canal near the lake. When the level of the lake is lowered by pumping from it, the hydraulic gradient outward from the lake is reversed and the ground water moves inward and seeps into the lake.

A water right authorizing the Okanogan Irrigation District to divert water from Johnson Creek to Duck Lake was issued by the Department of Conservation in 1919, but the exact date when recharge was begun is not known. No data are available on the amounts of water pumped from the lake and wells.

SUBSURFACE-INJECTION OPERATIONS

To date (1962), there have been 21 projects of artificial recharge by subsurface injection in Oregon and Washington. Two of these, at Springfield and St. Helens, Oreg., were undertaken to increase supplies of ground water available for withdrawal from municipal wells; two others, at The Dalles, Oreg., and Walla Walla, Wash., were tests of artificial recharge for the same purpose. A subsurface injection operation at Pine Flat, Klamath County, Oreg., serves the dual purpose of land drainage and subsurface storage of water for irrigation use. Water used for curing newly cast concrete at a plant in

northeast Portland is injected into a well tapping a shallow gravel aquifer, and water used to cool transformers at a substation at Snohomish, Wash., is injected into a well tapping gravel aquifers. Fourteen other recharge operations, all in the western parts of the two States, are for the return of ground water following its use for heating or cooling (air-conditioning) purposes.

For most of the subsurface-injection operations, little information is available for evaluation of the operations themselves and the several problems that arose (p. C42). Few records have been kept of the amounts of water recharged and the effects on ground-water levels, and virtually no data are available on the sediment content or biota of the waters involved. The few chemical analyses that were collected during this investigation (table 3) are mostly of samples of the native ground water.

RECHARGE THROUGH WELLS AT AIR-CONDITIONING INSTALLATIONS

Two types of air-conditioning systems that utilize ground water and return the exhaust water underground have been used in Oregon and Washington. One is the reverse-cycle, or heat-pump system, that is used for both heating and cooling of buildings, and the other is the more common air-conditioning system, wherein ground water is used for cooling only during the summertime.

Heating of buildings with ground water of about normal temperature had its first large-scale application in Oregon and Washington. As practiced in this region, the operation consists of pumping water from a well and through a heat exchanger (commonly known as a heat pump), and thus extracting heat from the water. The operation of a heat pump may be reversible; that is, the pump may be used also for cooling. During the cooling phase the water absorbs heat from the air that is being cooled. Heat pumps also have operated successfully using air or surface water, but ground water is the principal medium now utilized as the source and sink for heat at most heat-pump installations in the Pacific Northwest.

Fourteen air-conditioning installations utilizing artificial recharge are described briefly in this report. Of these, 3 (in Portland) are for cooling only and 11 are used for both heating and cooling. Of the combined heating and cooling systems, 4 are in Portland, Oreg.; 2 in Vancouver, Wash.; 2 in Tacoma, Wash.; and 1 each in Hazel Dell, Lakewood, and Everett, Wash. The locations of wells used in air-conditioning installations in Portland, Oreg., and Vancouver, Wash., are shown on figure 8. The approximate locations of the other installations described below are shown in figure 2.
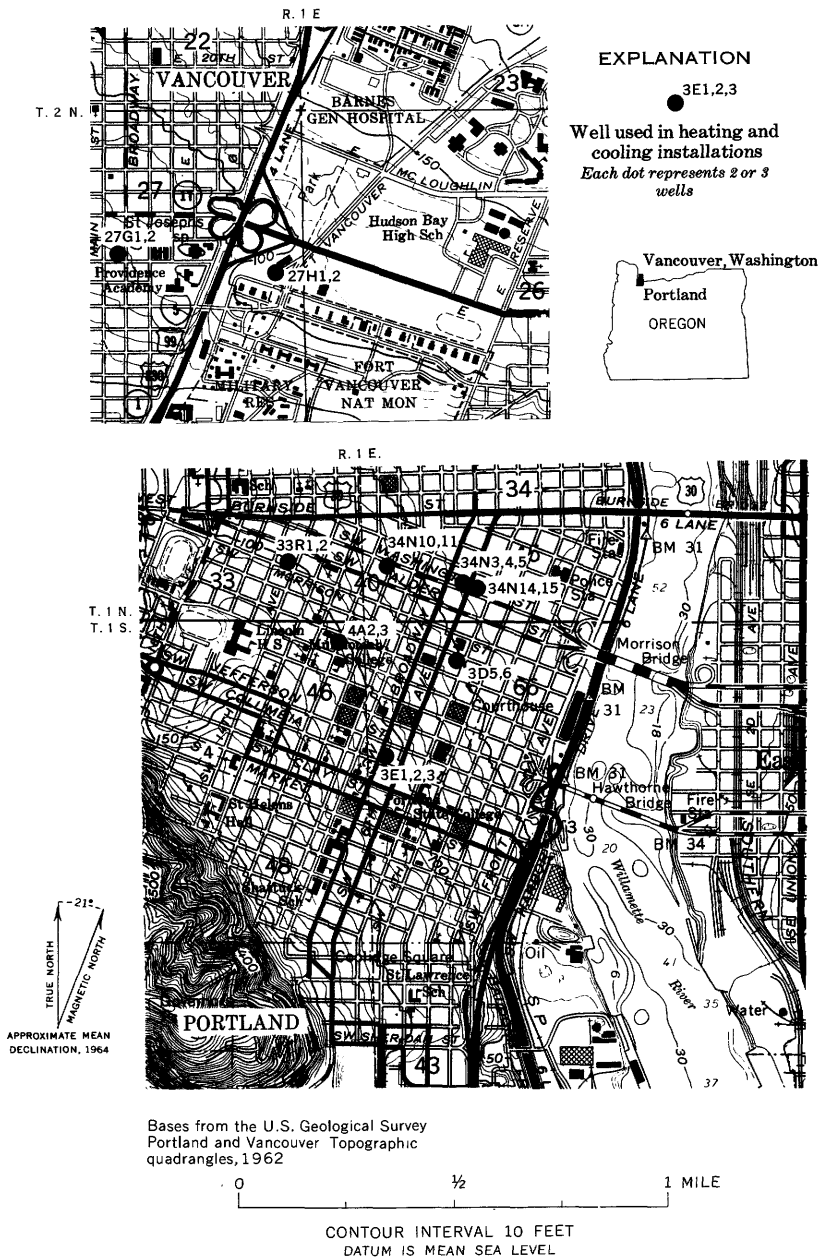
FIGURE 8.—Parts of Portland, Oreg., and Vancouver, Wash., showing locations of wells used in heating and cooling installations utilizing artificial recharge in 1962.

The use of at least two wells tapping separate aquifers is advantageous for a complete heating and cooling system. At most places the deeper well produces warmer water, which is used as the heat source during the heating phase. The cooled exhaust water from the heat exchanger during the heating phase is injected into a shallower well. During the cooling phase the water circuit is reversed; the cooler water from the shallow well is used for cooling, and after its temperature has been raised, is injected into the deeper well. In this manner, warmed water may be stored in one aquifer and cooled water in another for recovery later. As with any artificial-recharge operation, the percentage of recharge water (and, therefore, of heat) that is recovered depends on the rate of movement of the ground water away from the well, the rate of withdrawal of water from the supply well and nearby wells, and other factors.

In some installations in the two States, water is pumped from one aquifer for both the heating and cooling cycles and disposed of in another aquifer. At least for two installations, water is pumped from the bottom part and injected to the upper part of the same aquifer.

In Oregon and Washington, most air-conditioning installations returning water underground do not circulate the water in a closed system; on the contrary, the exhaust water from some is passed through a settling tank, in which it is exposed to the atmosphere before it is injected into the recharge well. In most of the recharge wells the water is allowed to cascade down inside the well casing, rather than being injected below the water level through a separate pipeline. Thus, at most of the installations there is ample opportunity for the injected water to take up air by solution and entrainment before it returns to the aquifer. (See p. C45.)

PORTLAND, OREG.

The downtown business section of Portland west of the Willamette River is well suited hydrologically, for the use of heat-pump systems utilizing ground water. Two water-bearing formations, separated by as much as 200 feet of clay (the Sandy River Mudstone) and rock, underlie most parts of this area. (See table 2, log of well 1N/1–34N14.) The shallower of these aquifers is the Troutdale Formation, which consists of mixed and interbedded gravel, sand, and clay. Wells tap permeable beds of gravel and sand in this formation at depths ranging from about 50 to 300 feet, and yield water at temperatures ranging from 55° to 69°F.

The deeper aquifer is a sequence of lava flows of the Columbia River Basalt. Near the contacts between some of the flow layers are water-bearing zones of permeable rubble 1 to as much as 30 feet thick.

In the downtown Portland area, wells tap these water-bearing zones at depths ranging from about 125 to 930 feet, and yield water at temperatures ranging from 54° to 70°F. The temperature of the water from the basalt does not vary consistently with the depth.

Reverse-cycle heating and cooling systems utilizing these two aquifers as the source and sink for heat have been installed in the Equitable, Oregonian, Pacific, and Medical-Dental Buildings. Systems for cooling only have been installed in the Portland Medical Center and two branches of the First National Bank (400 SW. 6th Avenue, and 1405 SW. Morrison Street). Water for these cooling systems is pumped from wells tapping the Columbia River Basalt and is injected into wells tapping the Troutdale Formation. Several other installations for heating and cooling, and some for heating only, utilize ground water but do not return exhaust water to the ground-water body. In these systems the exhaust water is wasted to the city sewers.

The air-conditioning systems that involve artificial recharge using part or all of the exhaust water are described briefly herein. Brown (1963) includes some of this information in his discussion of the utilization of ground water in the west-side business district of Portland, and also describes the problems that are developing or can be anticipated in this area with continued uncoordinated artificial recharge and increased pumping withdrawal. However, some of the data herein, especially concerning developments since 1958, were not available for inclusion in that earlier report.

EQUITABLE BUILDING

The Equitable Building, on the northwest corner at Sixth Avenue and SW. Washington Street, is heated and cooled entirely by a reverse-cycle system that utilizes three wells. Two wells (1N/1–34N3 and N5), 158 and 165 feet deep respectively (table 1), tap sand and gravel of the Troutdale Formation and yield about 225 and 200 gpm respectively with the present pumps. These wells supply the water for the heating phase, and receive exhaust water at a temperature of 75° to 85°F during the cooling phase. The third well (1N/1–34N4) supplies cooling water, and receives exhaust water injected at a temperature of about 48° F during the heating phase. It is 508 feet deep and yields as much as 600 gpm from permeable zones in the Columbia River Basalt. Partial chemical analyses of the native ground water from well N3 and of the water from well N4 after different periods of recharging are shown in table 3.

When the shallower "heating" wells were drilled, the temperature of the water from them was about 62° to 66°F. At the beginning of the heating phase each winter, the temperature of the water from

those wells (75° to 85°F), is close to the temperature of water injected during the previous cooling phase, but it gradually decreases to about 65°F after pumping is continued for about a week.

Water pumped from the deep well (N4) had a temperature of 56°F in 1961—2° warmer than the temperature reported in 1946.

The rate of water use for heating or cooling of the Equitable Building depends largely on the outside air temperature; however, other factors, such as the amount of sunshine, humidity, and wind velocity, also affect the rate at which the air-conditioner must be operated and, therefore, the rate at which ground water must be withdrawn. The approximate average amounts of water pumped from and recharged through the Equitable Building wells are shown in figure 9.

The outside air temperature at which the cooling requirements become greater than the heating requirements usually is about 50°F (fig. 9) for cloudy weather (average climatic conditions), but also varies with the effect of solar radiation, and has been as low as 42°F in clear weather (Kroeker and Chewning, 1948).
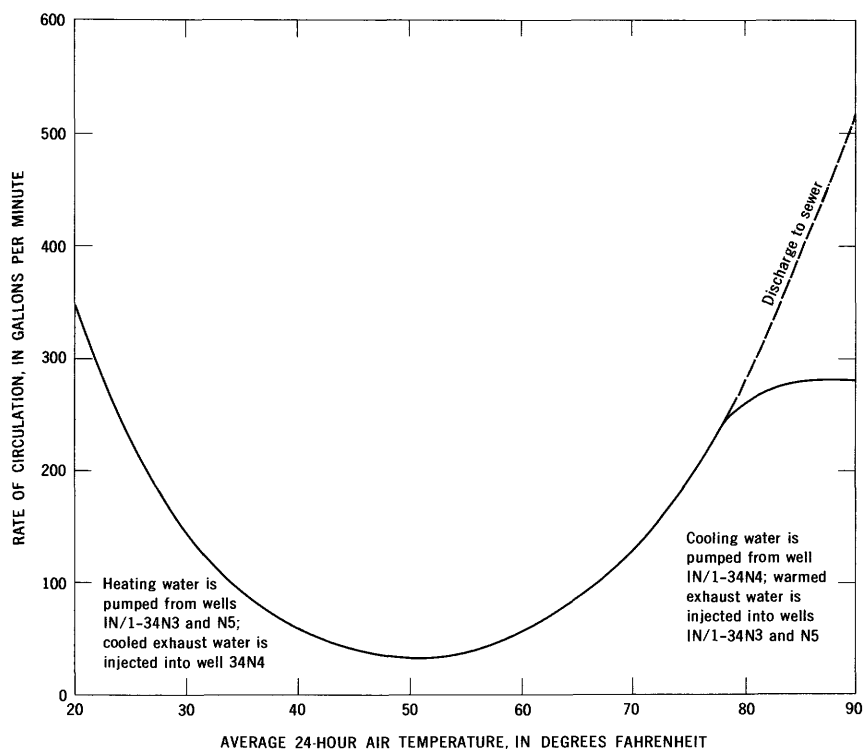
FIGURE 9.—Approximate rate of withdrawal from and recharge to the Equitable Building wells under average weather conditions. (Discharge from the cooling phase in excess of 280 gpm, shown by dashed line, is wasted to the city sewer.)

The maximum pumping rate during the heating cycle is about 350 gpm, all of which is artificially recharged through the deep well. About 280 gpm can be injected into the two shallow wells with the maximum pressure head that can be applied to the recharge water in the system. Any warm exhaust water in excess of that rate must be wasted to the sewer. Maximum discharge to the shallow wells is attained when the outside air temperature reaches about 80°F. If the average 24-hour temperature exceeds 90°F, the rate of pumping from the deep well, and discharge to the shallow wells and the sewer, may reach 550 gpm. Exact figures are not available on the total amounts of water pumped and artificially recharged.

OREGONIAN BUILDING

The Oregonian Building, which occupies the city block southeast of the intersection of Broadway and Jefferson Streets, is heated and cooled entirely by means of heat pumps using ground water. Three wells are used in this system. Two of these wells (1/1–3E1 and E2) tap sand and gravel strata of the Troutdale Formation and are 203 and 235 feet deep, respectively. The third well (1/1–3E3) is 930 feet deep and taps the Columbia River Basalt.

When the building was completed in June 1948, the two shallow wells supplied the water used for cooling and received the cooled exhaust water during the heating phase; the deep well supplied water for heating and received warmed exhaust water during the cooling phase. However, the water from the deep well was found to be undesirable because of high dissolved-solids content (table 3), and this well now is rarely used as a supply well although it regularly receives part of the exhaust water, at temperatures as high as 120°F, during the cooling phase. The two shallow wells now supply water for both the heating and cooling phases most of the time. Water pumped from the deep well is discharged to the city sewer after use; as a precaution against deterioration of the chemical quality of the shallow ground water, it is not injected into the shallow wells.

The artificial recharging has caused the local water temperature in aquifers tapped by the wells to vary widely; the overall effect may have been a slight general warming of the ground water in the vicinity of the wells. When the deep well was pumped in January 1956, for the first time in 3 years, the temperature of the water reportedly was 96°F. Formerly, however, the temperature of the water from this well was about 80°F after warmed water from the cooling phase had been injected throughout a summer season, but after the well was pumped for 6 months, the temperature reportedly dropped to about 60°F—or 2° warmer than it had been in 1947–48 (table 1). The

temperature of the water from the two shallow wells was about 55.5°F in 1961, or about 1.5° higher than in 1947.

MEDICAL-DENTAL BUILDING

The Medical-Dental Building, at 833 SW. 11th Avenue, is both heated and cooled with a heat-pump system which utilizes two wells. The system was installed in 1959 and is believed to be the newest such installation in Portland as of 1962. The supply well for both heating and cooling cycles (1/1–4A2) is 772 feet deep and taps the Columbia River Basalt. It reportedly yielded 723 gpm during test pumping, but is generally pumped at an average rate of about 150 gpm. The disposal well (1/1–4A3) is 193 feet deep and taps the Troutdale Formation. It reportedly accepts all but about 20 percent of the exhaust water from the heat pump. The rest is discharged to the city sewer.

PORTLAND MEDICAL CENTER

Ground water is pumped for cooling purposes and returned underground by means of a two-well system at the Portland Medical Center, 511 SW. 10th Avenue. The supply well (1N/1–34N10) taps the Columbia River Basalt, and the disposal well (1N/1–34N11) taps the Troutdale Formation. The system normally requires circulation of about 365 gpm to cool the building. The temperature of the water pumped by the supply well was reported to be 62°F in the spring of 1961. When it was completed, the disposal well could accept all the exhaust water injected into it; however, because sand entered and partly plugged the well, the injection rate was reduced to only about 150 gpm during the summer of 1961, and the remainder of the exhaust water was discharged to the city sewer. In 1962 the disposal well was being cleaned and an attempt was being made to locate and seal the zone in which the sand was entering the well. During this repair work, all water pumped for the airconditioning system was discharged to the sewer.

PACIFIC BUILDING

Two wells are used to supply and dispose of the water used for heating and cooling the Pacific Building, at 520 SW. Yamhill Street. The supply well (1/1–3D6) is 765 feet deep and produces water from the Columbia River Basalt for both the heating and cooling cycles of the heat pump. The well reportedly was test-pumped at a rate of 750 gpm, but the maximum rate required for the present installation is only about 300 gpm. The peak water requirements are for cooling during the summer months.

The disposal well (1/1–3D5) is 228 feet deep and taps the Troutdale Formation. Not all of the water discharged from the heat pump can

be injected into the disposal well, largely because of a low pressure head under which the water is injected; however, the well reportedly accepted all but about 100,000 cubic feet (about 1 percent) of the exhaust water from the system in 1960.

On February 21, 1961 (during the heating phase), the water pumped from the supply well had a temperature of 63°F. At the same time, the water being injected into the disposal well had a temperature of 48°F.

FIRST NATIONAL BANK BUILDINGS

The buildings of two branches of the First National Bank of Oregon are cooled, but not heated, by air-conditioning installations, each utilizing a supply well and a disposal well.

At the 1405 SW. Morrison Street Branch, the supply well (1N/1–33R1) is 460 feet deep and taps aquifers in the Columbia River Basalt and possibly the Troutdale Formation; the disposal well (1N/1–33R2) is 300 feet deep and taps the Troutdale Formation only. The average pumping requirement for the cooling system is about 300 gpm, the same rate at which the supply well reportedly was test pumped. The disposal well apparently accepts all the cooling water that is passed through the air-conditioner.

At the 400 SW. 6th Avenue Branch, the supply well (1N/1–34N14) is 544 feet deep and taps the Columbia River Basalt; the disposal well (1N/1–34N15) is 161 feet deep and taps the Troutdale Formation. The supply well reportedly was test-pumped at a rate of 1,000 gpm, but normally is pumped at an average rate of only 300 gpm during operation. The temperature of the water pumped from the supply well ranges from 58° to 64°F during operation, which is almost continuous during the summer months. The disposal well reportedly accepts all the exhaust water from the air-conditioning system.

VANCOUVER, WASH.

CLARK COUNTY PUBLIC UTILITIES DISTRICT BUILDING

A heat-pump system was installed during 1955 in the Clark County Public Utilities District Building, at 1200 Fort Vancouver Drive in Vancouver (fig. 8). The authors believe it to have been the first such installation in the Pacific Northwest using two wells that tap the same aquifer. One well is used as the supply well for both heating and cooling cycles and the other is used only as a recharge well. The supply well (2/1–27H2) is 138 feet deep and was test pumped at 670 gpm with 3.5 feet of drawdown. The recharge well (2/1–27H1), 400 feet west of the supply well, is 144 feet deep and, when drilled, was pumped at the rate of 600 gpm with 3.5 feet of drawdown (table 1).

The casings of both wells are perforated opposite a gravel-and-sand stratum in the interval 119 to 141 feet below the land surface. (See table 2, log of well 2/1–27H1.)

During the heating phase of the operation, a heat-pump transfers heat from the well water to water in a closed distribution system; during the cooling phase the cycle is reversed. Water in the closed distribution system passes from the heat-pump to 30 radiator-type air-conditioning units equipped with blowers, which circulate the air that is heated or cooled.

Well water is supplied to the heat-pump at a temperature of about 54°F. During the cooling phase, the exhaust water passes into the recharge well at a temperature of 75° to 85°F, but its temperature may be raised as high as 105°F during manual operation of the system. During the heating phase, the cooled exhaust water passes to the recharge well at 48°F. The average rate of withdrawal and recharge during operation of the heat-pump is estimated at about 100 gpm, and the amount of water used each year is about 160 acre-feet.

Even though water in the same aquifer is used as both the source and sink for heat, no temperature change was noticed in the water from the supply well during the first 6 months of operation. Temperature data for later periods are not available.

FEDERAL SAVINGS & LOAN ASSOCIATION BUILDING

Two wells, 137 and 144 feet deep, were drilled in 1961 to supply and dispose of water for a heat-pump in the Vancouver Federal Savings & Loan Association Building. The shallower well (2/1–27G1) supplies water for both the heating and cooling cycles of operation. The capacity of the installation is about 160 gpm, and the disposal well (2/1–27G2) accepts all the exhaust water from the installation. The system is closed to the atmosphere, so there is little chance for air to be dissolved or entrained in the recharge water.

The two wells tap the same aquifer, but are so spaced that the exhaust water should be near the normal ground-water temperature by the time it circulates through the acquifer to the supply well. The normal ground-water temperature is about 52°F; the temperature of the exhaust water is about 40°F during the heating cycle, and as much as 95°F during the cooling cycle.

HAZEL DELL, WASH.

The first known heat-pump for a school in this region was installed in 1961 in the Columbia River High School at Hazel Dell, about 2 miles north of Vancouver, Wash., although it was not yet in operation in 1962. The installation is designed for circulation of water at a

maximum rate of 542 gpm during the heating cycle and about 180 gpm during the cooling cycle.

The system utilizes two wells which tap the same aquifer. The disposal well (2/1–10H2) was drilled about 1,000 feet northeast of the supply well (2/1–10H1) to place it beyond the area of influence of the supply well. The supply and disposal wells are respectively 350 and 327 feet deep. The temperature of the native ground water is about 52°F; that of the exhaust water is expected to be about 40°F during the heating cycle and as much as 95°F during the cooling cycle.

Not all the water pumped from the supply well will be used for air-conditioning. Some will be required for domestic and irrigation use at the school. Also, when the school does not need water, the surplus might be used for municipal supply in Hazel Dell.

TACOMA, WASH.

PUBLIC UTILITIES BUILDING

A heat-pump system at the Tacoma Public Utilities Building, Tacoma, Wash., utilizes two wells (20/2–13A1 and 13B1), each of which is used alternately for supply and disposal. The wells, which are 84 and 260 feet deep, respectively, tap two permeable gravel strata that are separated by about 100 feet of cemented gravel and clay (tables 1 and 2). The temperature of the water from both wells was 52°F when they were drilled.

During the heating cycle, the supply water is pumped from the shallow well (13A1) and exhaust water is artificially recharged through the deeper well (13B1) at a temperature of about 40°F. The procedure is reversed during the cooling cycle; well 13B1 supplies the water and well 13A1 receives exhaust water, which is at a temperature of about 72°F when the system is operating on automatic control, or as high as 104°F when the cooling equipment is operated manually. Virtually all of the water withdrawn is returned to the ground-water body. By the end of the average cooling season, the water temperature in the shallow gravels near well 13A1 has risen considerably, and does not return to the natural level (52°F) until the well is pumped for about a month.

Reports of the operators indicate that the rates of pumping and recharging may vary from zero to more than 800 gpm and that the yearly average is about 250 gpm. This average rate is equivalent to about 380 acre-feet per year. When the outside air temperature is about 50°F, little or no water is circulated. A graphic comparison of the rates of pumping and the outside air temperatures probably would follow a curve similar to that shown in figure 9.

Partial chemical analyses of the water from the wells were made soon after each well was drilled (table 3) and again during operation of the system (the later analyses were not available during preparation of this report). Soon after the operation was started, the chloride content of the water from the shallower aquifer reportedly increased substantially. The source of the additional chloride was found at a nearby pickling plant, where brine waste was being dumped on the land surface and had percolated to the water table. The dumping of brine was stopped, and the chloride content of the ground water reportedly declined gradually almost to its natural level.

TACOMA SAVINGS & LOAN ASSOCIATION BUILDING

A reverse-cycle heating and cooling system, using one well for supply and an adjacent well for disposal of the water, was put into operation in 1957 at the Tacoma Savings & Loan Association Building. The supply well (20/3–4D2) is 147 feet deep and has a well screen opposite beds of sand and gravel in the lower 20 feet. The disposal well (20/3–4D1) is 202 feet deep and has perforated casing in the interval 165–185 feet, also opposite sand and gravel. The operating capacity of the system is less than 140 gpm and all the water pumped is recharged through the disposal well.

Despite the different intervals penetrated, the aquifers tapped by the wells apparently are hydraulically connected, for when the supply well was test-pumped at 300 gpm, the water level in the disposal well decined about 6 feet.

The only available information on chemical quality of the ground water is a partial analysis of water from well 4D2, made soon after the well was drilled (table 3). Consequently, little is known of possible changes in the chemical character of the ground water due to mixing with the exhaust water from the system. The operator did report, however, that the recharge well had become clogged with sand in the summer of 1962 and that the exhaust water from the system was temporarily being diverted to the city sewer.

LAKEWOOD, WASH.

A cooling system using separate wells to supply and dispose of water was installed at the Villa Plaza Branch of the National Bank of Washington, Lakewood, Wash., in the summer of 1961. The supply well (19/2–2D1) is 156 feet deep and is 48 feet from disposal well (19/2–2D3), which is 36 feet deep. The wells tap separate zones in a sequence of gravel, sand, and clay.

The system is one of the few in this region that is designed to inject the exhaust water below the water surface in the recharge well, and

would be closed to the atmosphere except for the presence of air vents in a settling tank through which the water circulates. About 70 gpm is required for the system at peak demand—that is, during the warmest days—and all the water circulated is returned underground. The water is not treated prior to injection.

Reports of the operators indicate that no problems had developed by the end of the first year of operation.

<div align="center">EVERETT, WASH.</div>

A reverse-cycle heat-pump in the West Coast Telephone Co. building at Everett, Wash., utilizes two wells alternately for supply and disposal of water. One of the wells, 29/5–31A1, was finished at a depth of 237 feet, and the other, 29/5–31A2, was finished at a depth of 257 feet (table 1). Because two productive aquifers could not be found in the area, both wells tap the same aquifer of sand and gravel. However, they were spaced far enough apart (about 460 ft) that, under planned rates of recharge, the water injected into the well being used for recharge apparently has its temperature changed to near that of the native ground water (about 50°F) before it reaches the pumping well. Water for cooling is pumped from well 31A1 and is returned underground through well 31A2 at temperatures as great as about 90°F; water for heating is pumped from well 31A2 and returned through well 31A1.

Normal pumping (and recharging) rates, based on the first few months of operation (1962), range from about 20 to more than 600 gpm, depending on the air temperature. The general relationship between the rate of water circulation and air temperature probably is about the same as that shown for the system at the Equitable Building, Portland, Oreg. (fig. 9).

The heat-pump system of the West Coast Telephone Co., like the air-conditioning system at Lakewood, Wash. (p. C31), provides for injection of exhaust water into the wells through pipes that extend below the water table; however, a pressure-relief valve in the system allowed some mixing of air with the circulating water.

Chemical analyses made shortly after the wells were drilled (table 3) indicate that the native ground water was soft and contained only moderate amounts of dissolved solids, although the concentration of dissolved iron (about 0.6 ppm) was greater than desirable for some purposes.

During the first two months of operation (1962), the specific capacity (pumping yield divided by drawdown) of the well used for recharging decreased from 30 to about 10 gpm per ft. Consultants of the firm of Robinson and Roberts (oral commun., 1962) attributed that decrease to a serious clogging of the aquifer in the vicinity of the well

by either air bubbles entrained in the injected water or a precipitate of iron, or both. (See p. C45.)

The capacity of the clogged well was partly restored by pumping and treatment with a wetting agent (sodium hexametaphosphate) during 1962. After the well was pumped almost continuously during the summer of that year, its specific capacity increased to about 14 gpm per ft of drawdown. The well was then treated again with the wetting agent, and its specific capacity increased further—to about 20 gpm per ft. Plans for future operation of the system call for continuous treatment of the recharge water with regulated amounts of sodium hexametaphosphate.

OTHER SUBSURFACE-INJECTION OPERATIONS

PINE FLAT, OREG.

Pine Flat, in south-central Oregon, comprises about 4 square miles of farmland approximately 12 miles east of the city of Klamath Falls. It occupies one of the many closed structural basins of that region, and has no external surface drainage.

A large body of ground water occurs in basaltic lava rocks beneath that area and is tapped by several large-yield irrigation wells. The regional water table slopes southward at about 3 feet per mile. The fact that it extends without interruption or significant change in gradient into adjacent basins on the north and south indicates that the topographic divides do not constitute effective barriers to movement of the ground water.

Beginning about 1947, waterlogging as a result of irrigation threatened the productivity of the lowest parts of Pine Flat. In 1951, to combat this problem and at the same time to increase the supply of water available for withdrawal from his irrigation wells, Mr. L. L. Porterfield began to inject drainage water from his fields into three irrigation wells (38/11½–32G1, 39/11½–5D1, and 5B1). The wells are respectively 197, 260, and 270 feet deep (table 1). They tap highly permeable zones of flow breccia in the basalt, and reportedly have a combined yield of about 5,000 gpm. The static water levels in the wells are about 70 feet below the land surface.

Drainage water from the land is collected and carried almost to wells 38/11½–32G1 and 39/11½–5B1 in ditches which are 5 to 15 feet deep and as wide as 15 feet. The water passes through a ½-inch mesh screen, and then flows the final 15 to 20 feet to the wells through 12-inch pipes that are welded into the well casings 5 to 10 feet below the ground surface. Drainage water from higher ground collects in a small surface reservoir near well 39/11½–5D1, and is diverted into the well only when the reservoir becomes filled to capacity. Recharge

through this well takes place mainly during the spring freshet; however, occasionally during the irrigation season, drainage water in excess of the amount that can be accepted by the other two wells is pumped from the drainage ditches into well 5D1. According to Mr. Porterfield (oral commun., September 1961), all three wells receive recharge water throughout the year except during freezing weather, but most of the artificial recharge takes place during the winter and spring.

Large amounts of suspended materials are carried at times by the recharge water, but no plugging of the wells had been noticed by the owner by 1961. Likewise, the owner reported no noticeable rise of water levels in the vicinity of his wells, nor any effect on the capacity of the wells, as a result of the artificial recharge. Probably only a small amount of the water injected during the fall and winter months is recovered by pumping of the wells during the subsequent irrigation season.

No data are available on the chemical character of the recharge water or the native water from the wells.

Artificial recharge to these wells began in the fall of 1951, although the collector ditches were shallower than they are now, and the amount injected reportedly was small during that first year. In 1952 the collector ditches were deepened and the inlet pipes to the wells were lowered to their present position. It is estimated that 75 to 100 acre-feet of water was recharged through the 3 wells during 1952—50 acre-feet to 38/11½–32G1, 25 to 50 acre-feet to 39/11½–5D1, and only a small amount to 5B1. The volume of water injected during each of the 3 years 1953–55 probably was about 100 acre-feet or slightly more. During the period 1959–61, however, the amount of water available for recharge decreased owing to below-normal precipitation and runoff.

The amount of sediment accepted by the Pine Flat recharge wells without evidence of clogging is a remarkable feature of this artificial-recharge operation. The authors know of few places where such a roily water has been successfully injected into wells. The apparent lack of clogging probably is due to (a) the large openings in the highly permeable breccia tapped by the wells and (b) the high rate at which the wells are pumped, which causes most of the sediment deposited by the recharge water to be flushed from the aquifer materials adjacent to the wells.

ST. HELENS, OREG.

The town of St. Helens, Oreg., is built on a terrace beside the Columbia River about 30 miles northwest of Portland. It has a population of about 5,000 (1960). In July 1955 the city installed a gallery-type water collector, which drains ground water from the alluvium adjacent to the Columbia River. Previously the town water supply was

obtained from three sources—well 4N/1W–5R1, a drilled well 12 inches in diameter and 421 feet deep that taps the Columbia River Basalt (table 1); five springs; and a small stream (Salmon Creek). The spring facilities are still maintained on a standby basis, but the well is no longer used.

The natural recharge to the basalt aquifer tapped by the well was not adequate to supply the pumping demand. The static water level in the well, which had been about 30 feet below the land surface in May 1940, was reported to be 109 feet below the surface in April 1949; it had declined to 196 feet below the land surface by May 1952. The pump intake was lowered to the 360-foot depth in May 1952, but by the following September the pumping level had declined to that depth and the pump could be operated only intermittently.

To augment the natural recharge to the ground-water body, artificial recharge by injection into the well was started in November 1952 and was repeated every winter season until early in 1955. During the latter year, the water collector was put into service and use of the well was discontinued. The water used for recharging was surplus water from Salmon Creek and the springs; it was delivered to the well through the city mains. The following table shows the amounts of water recharged through and withdrawn from the well during the period of artificial recharge.

Recharge to and withdrawal from the St. Helens well (4N/1W–5R1), in millions of gallons

[Data from city of St. Helens]

Period	Recharge	Withdrawal
Winter 1952–53	17.2	
Summer 1953		22.0
Winter 1953–54	15.8	
Summer 1954		12.5
Winter 1954–55	8.1	
Summer 1955		6.0
Total	41.1	40.5

Other than the figures shown in the table, few data are available from this artificial-recharge operation; for example, records were not kept of the water level in the well. However, Mr. Morton, St. Helens city engineer at the time, reported that the temperature of the water entering the well ranged from about 38° to 46°F. The recharge water reportedly was slightly turbid in the fall, but the amount of sediment carried is unknown. Also unknown is the effect of the recharge operation on the capacity of the well or on the quality of the water in the recharged aquifer.

A chemical analysis of recharge water sampled in February 1954 is given in table 3. That sample probably represented about 95 percent

spring water and 5 percent Salmon Creek water. The water was slightly turbid when the sample was collected; however, it was of excellent chemical character, being very soft and containing only small amounts of dissolved solids.

Although the records are inadequate to permit a thorough appraisal of this recharge operation, the apparent success of the operation for the three-year period suggests that subsurface storage of water in the Columbia River Basalt might be practical at other places underlain by that rock unit.

SPRINGFIELD, OREG.

The city of Springfield is in Lane County, Oreg., about 1 mile east of Eugene (fig. 1). The water supply for most of the 14,000 inhabitants (1960) of Springfield is furnished by a private utility company. The water is obtained from eight wells on the flood plain of the Middle Fork of the Willamette River. Those wells are on the north bank of the river about 1 mile south of the town, in the SE¼ sec. 1, T. 18 S., R. 3 W. They have a combined potential yield of 9,500 gpm. All are about 60 feet deep and obtain water from a coarse alluvial gravel that apparently extends only to no more than 60 feet below the surface and is probably underlain by impermeable shale.

River water infiltrates the alluvial materials of the river banks and channel floor and recharges naturally the ground-water body tapped by the wells. However, during the summer, when the stage of the stream is low and much silt is deposited in the channel, the rate of natural infiltration is very low.

To insure that the public-supply wells sustain a near-maximum yield during periods of peak summer requirements, the gravel aquifer is recharged artificially. For this purpose, four recharge wells have been drilled near the river and adjacent to the well field. The two drilled most recently, wells 18/3W–1J1 and J2, penetrate sand and gravel to depths of 44 and 30 feet respectively (table 1).

Water from the Willamette River is pumped into the recharge wells at unscheduled intervals. The practice is an emergency measure used only in the summer (May through September) when the normal yield of the pumped wells will not supply the demand. The maximum total rate at which water can be injected is about 3,000 gpm. Although no records have been kept of the amounts of water added to the ground-water body, reports from the operators suggest that about 200 acre-feet per year is injected. The water is chlorinated before it is injected into the wells.

NORTHEAST PORTLAND, OREG.

In northeast Portland, Oreg., ground water used to cure concrete at American Pipe & Construction Co. is returned underground through

the same well from which it is pumped. A large part of the natural precipitation that falls within the plant area is collected in drains and is also diverted into the well. The well (1N/1–11N2) is 91 feet deep and taps a gravel aquifer (table 1).

Water pumped from the well is sprayed on stacks of concrete pipe in the plant storage area. The rate at which the well is pumped ranges from about 100 to 1,100 gpm, depending on the amount of sprinkling that is needed. Of the water that is sprayed on the pipe, only a small amount is adsorbed and some is evaporated; most, however, trickles to the ground surface.

The ground surface at the plant is paved with asphalt and underlain by a drainage system to collect the excess sprinkling water and the natural precipitation. Part of the drainage system empties into the county storm sewer north of the plant, and part empties into a sump adjacent to the recharge well, near the west end of the plant. The water from the sump is diverted directly into the well. The part of the drainage system that empties into the sump drains an area of about 12 acres—about 3 acres of pipe storage area, and about 9 acres of parking, roadway, and rooftop area.

The sump occupies an area of about 770 square feet and is about 10 feet deep. It acts as a retaining basin in which suspended sediment settles out of the recharge water. Most of the larger debris is removed by screens placed in various parts of the drainage system and in the intake pipe to the well. If the sump fills so rapidly that the well cannot accept all the drainage water, two sump pumps, activated by an automatic float switch, pump the excess water to a sewer south of the plant. This diversion occasionally happens during violent rainstorms or when the screen between the sump and well becomes clogged.

The volume of water that is returned underground through well 1N/1–11N2 can be estimated only roughly, for neither the amount pumped nor that injected is measured. Water is seldom pumped to spray the pipe during the winter because the natural precipitation is generally sufficient. However, large amounts of water are pumped during the dryer months, especially July and August. It is estimated that the well is pumped during about 6 months of the year at an average rate of 300 gpm, equivalent to a total withdrawal of about 240 acre-feet per year. According to Mr. V. O. Scholz, plant engineer (oral commun., October 1962), about 10 percent of the sprayed water is adsorbed by the concrete and at least another 5 percent evaporates before the remainder of the pumped water, roughly 200 acre-feet per year, is available for recharge.

The amount of precipitation that drains to well 1N/1–11N2 is only a fraction of the total injected. The average annual precipitation in

the vicinity is about 35 inches (U.S. Weather Bur., Portland Munici-
pal Airport). In the 12-acre plant drainage area, this amounts to
about 36 acre-feet per year, of which perhaps 30 acre-feet actually
reaches the recharge well.

This artificial-recharge operation was started about 1958 and, al-
though the water is not treated in any way prior to injection into the
well, the operators reported no evidence of growth of nuisance bacteria
or clogging of the well as of 1962.

SNOHOMISH, WASH.

Ground water used for cooling electrical equipment at the Bonne-
ville Power Administration substation at Snohomish, Wash., is re-
turned underground through two disposal wells. An average of 100
gpm, or about 160 acre-feet per year, of clear, warmed water is in-
jected into the disposal wells.

Water pumped from a separate supply well (28/5–12R1) is passed
through the cooling system of a synchronous condenser and discharged
to the two disposal wells (28/5–12R2 and R3), which are respectively
214 feet southeast and 324 feet southwest of the supply well. All the
wells tap sand and gravel strata. Both the supply well and disposal
well 12R2 are 150 feet deep and have casings perforated opposite the
same zone of sand and gravel. Disposal well 12R3, which is 235 feet
deep, penetrated slightly different strata in the same general aquifer
and encountered no water-bearing materials below 164 feet (table 1).
The water table was about 73 feet below the land surface (24 feet
above sea level) at all three wells when they were drilled.

The temperature of the native ground water was 50°F when the
first two wells were drilled. Recharging with exhaust water at a
temperature of 68°F through well 28/5–12R2 was started about 1953.
After 6 months of injection, there was a noticeable increase in the
temperature of the water from the supply well. In 1956 the tem-
perature of the water from the supply well had increased to about
60°F, and that of the exhaust water, which was being returned through
both disposal wells, was 67° to 68°F.

In 1961 the temperature of the exhaust water was reported to be
about 80°F. Although the temperature of the water from the sup-
ply well probably was also higher in 1961, the system reportedly was
operating satisfactorily.

The ground water used for cooling reportedly contains objection-
able quantities of iron in solution, and soon after the start of the
recharge operation clogging began at the disposal wells because of the
growth of iron bacteria in the circulating water. Chlorination of
the water from the supply well reportedly has eliminated this
difficulty.

ARTIFICIAL-RECHARGE TESTS

The cities of Walla Walla, Wash., and The Dalles, Oreg. (fig. 2), obtain part of their respective municipal water supplies from wells tapping aquifers in the Columbia River Basalt and part from streams. The streams serving the two cities have identical names (Mill Creek), but the one serving Walla Walla rises in the Blue Mountains in eastern Oregon, whereas the one serving The Dalles rises in the Cascade Mountains.

Declining ground-water levels in the vicinities of Walla Walla and The Dalles during recent years led to artificial-recharge tests to determine the feasibility of recharging the basalt aquifers with excess surface runoff. The test at Walla Walla was conducted in the winter of 1957–58, and the test at The Dalles was conducted in the winter and spring of 1960–61. Both tests were similar in that the recharge water was diverted directly from the surface-water supplies of the respective cities into pre-existing municipal-supply wells. However, the manner in which the water was injected into the wells and the overall procedures of the tests differed to some extent. Both tests were conducted by the U.S. Geological Survey under cooperative agreements—with the State of Washington Department of Conservation for the Walla Walla test, and with Dalles City for the test at The Dalles. A report describing the procedures and results of the test at Walla Walla has been published (Price, 1961), and a similar report describing the test at The Dalles is being prepared by B. L. Foxworthy and C. T. Bryant, U.S. Geological Survey (written commun., 1961). The brief discussions below have been drawn largely from these two reports.

WALLA WALLA, WASH.

The city of Walla Walla (population about 15,000 in 1960) is in an area of southeastern Washington (fig. 2) that receives about 16 inches of precipitation a year. The city obtains its municipal water supply from four wells tapping the Columbia River Basalt, and from Mill Creek, a stream that flows through the city on its course to the Walla Walla River. Well 7/37–18F1 (table 1), the well into which the recharge water was injected during the test, is near Mill Creek about 5 miles upstream from Walla Walla, and is the deepest of the four municipal wells. The other three wells are downstream—two of them about 1 mile, and one about 4 miles from the injection well. Before artificial recharge was begun, there was very little, if any, natural hydraulic gradient between the injection well and the two nearest supply wells (Price, 1961, p. 8).

The water used for recharging was taken from a 20-inch supply line which normally conveys water from a filter plant on Mill Creek to a

city reservoir. The water was diverted into the well through a 6-inch branch line and a control valve, and was measured by means of a displacement-type flow meter. The recharge water was allowed to cascade down inside the pump column from near the surface to the water level; the rate of injection was not great enough to keep the pump column filled with water.

The chemical and bacteriological quality and sediment content of the recharge water were analyzed prior to the recharge test and were found to be suitable for injection (Price, 1961, p. 10–18). Chemical analyses of Mill Creek water and native ground water from well 7/37–18F1 (table 3) show that the waters were of the same chemical type and were of generally excellent quality. The sediment content of the recharge water had been checked over a period of several months before the test, and was found to be low enough that the water could be injected without further filtration. A sample of the Mill Creek water was tested for the presence of nuisance bacteria; none could be isolated (although a laboratory culture from the water sample produced a stringy growth), and the chances of well damage or water deterioration by nuisance bacteria were considered slight. Chlorine is added to the Mill Creek water above the point where the recharge water was diverted.

The recharging period was from December 11, 1957, to January 8, 1958, but there was about a 3-day period (December 20–23) when injection into the well had to be stopped because the Mill Creek water had become excessively turbid owing to storm runoff. One of the nearby supply wells was pumped during that nonrecharging period.

The rate of recharge during the test ranged from 630 to 670 gpm, and the total quantity of water injected into the well was 23 million gallons, or about 71 acre-feet. The water level in the injection well and in at least one of the nearby supply wells rose during the period of injection, and this increase in ground-water storage was attributed mostly to the artificial recharge. Price (1961, p. 26) estimated that about 53 percent of the recharged water was recovered during discontinuous periods of pumping between January 11 and February 26, 1958.

Comparison of data from pumping tests made before and after the recharge operation showed that the yield of the injection well had declined from 1,800 to 1,540 gpm and the specific capacity from 35 to 23 gpm per ft during the recharge operation. Because the recharge water was nearly saturated with dissolved air when it entered the injection well and probably entrained some additional air as it cascaded down into the well, this decline in capacity was attributed to a clogging of the aquifer materials near the well by bubbles of air or by a combination of suspended sediment and air bubbles (Price,

1961, p. 28). The greater viscosity of the injected water, which was significantly cooler than the native ground water, may also have contributed to the decrease in capacity.

The study at Walla Walla indicated that there probably are subsurface hydraulic barriers that limit natural recharge in the vicinity of the recharge well and the nearby supply wells to amounts less than the yearly pumpage. Hence, artificial recharge is needed and could be accomplished at relatively low cost under the present arrangement of the city water system. However, before continuing the recharge tests or beginning a long-term program of artificial recharge, steps should be taken to reduce the amount of sediment and dissolved and entrained air in the recharge water (Price, 1961, p. 29).

THE DALLES, OREG.

The city of The Dalles (population about 12,000 in 1960) is on the Columbia River about 80 miles upstream from Portland (fig. 2) in Wasco County in north-central Oregon. The city obtains its municipal water supply from Mill Creek, which flows through The Dalles on its course to the Columbia River, and from three wells tapping the Columbia River Basalt. The wells are spaced within about a 1-mile radius and tap the same artesian zone, locally called "The Dalles pool." Well 1N/13–4F1 (table 1), which is the city's "Jordan Street well," was the injection well for the artificial-recharge test.

Preliminary work for the test was done in November 1960 and included the collection of background data on well performance, the chemical and physical character of the native ground water and of the surface water to be injected into the well, and the air content and biological suitability of the recharge water.

The stream water used for recharging during the test was diverted from the city's 14th Street reservoir, which in turn was fed from the Mill Creek filter plant about 8 miles upstream from the city. The water was filtered, chlorinated, and fluoridated prior to injection.

The artificial recharging was accomplished during four periods ranging from 8 hours to more than 14 days. The water was injected into the well under high pressure through the same piping (including the pump column) and metering system through which the ground water is normally pumped. The water was injected at a rate of about 1,500 gpm. A total of 81.4 million gallons, or about 250 acre-feet, of water was injected into the well during the recharge experiment. A short-duration rise of water level in the injection well and several nearby observation wells which was attributed to the artificial recharge indicated that an increase in storage had occurred.

During the nonrecharging periods the injection well was pumped (usually for 8-hour periods) to determine the effects of recharging

on the aquifer, the well performance, and the character of the ground water. About 16 acre-feet was pumped from the injection well during the pumping phases of the test, and an unmeasured but small percent was pumped during surging phases. More than 85 percent of the water pumped from the well during these periods was recharge water.

Chemical analyses (examples in table 3) of the recharge water and native ground water from well 1N/13–4F1 showed that the major chemical constituents of both, except for silica and dissolved oxygen, were generally similar with regard to percentage composition. The normal sediment content of the recharge water was very low (0–3 ppm) and the temperature was as much as 23°F lower than that of the native ground water. Laboratory cultures of samples of the recharge water failed to reveal the presence of any nuisance bacteria.

As a result of the tests, the specific capacity of the injection well was reduced temporarily owing to: (a) increased viscosity of the ground water caused by the cooling effect of the recharge water, (b) partial plugging of the water-bearing zones by bubbles of air that came out of solution in the recharge water, and (c) clogging of the aquifer materials by an undetermined amount of chemical floc which was introduced into the recharge water as the water passed through the filter plant. Following the last two periods of recharge, of 10 and 14 days' duration respectively, it was necessary to surge the injection well by intermittent pumping to restore the capacity of the well to near its prerecharge value. However, the recharge experiment was considered successful in proving the technical feasibility of artificially recharging basalt aquifers in that area.

PROBLEMS RELATED TO THE SUBSURFACE-INJECTION OPERATIONS

Aside from those already mentioned in connection with the artificial-recharge tests, some serious difficulties had been reported from several of the subsurface-injection operations by 1962:

1. In the heat-pump system for the Oregonian Building, Portland, Oreg. (p. C26), the original supply well, which taps basalt, yielded water that was chemically undesirable for the system and had to be converted to use primarily as a disposal well.
2. Water pumped for cooling purposes from the supply well at the Snohomish, Wash., Bonneville Power Administration substation (p. C38), has been warmed substantially by heat from the water injected through the recharge well.
3. During the summer of 1961 the disposal well for the Portland Medical Center cooling system (p. C27) decreased greatly in its capacity to accept water, reportedly owing to a large amount of sand entering and partly clogging the well bore.

4. After only 2 months of recharging, the acceptance capacity of one well of the two-well system at Everett, Wash. (p. C32), decreased greatly, probably because of clogging by iron precipitate and bubbles of air.
5. Several of the wells used for injection of exhaust water from heating and cooling systems, in Portland, Oreg., and Snohomish, Wash., reportedly have become seriously clogged at times by iron bacteria.

The decrease in capacity of the Portland Medical Center recharge well probably is unrelated to the use of the well, although it shows that proper construction is as important for injection wells as for supply wells. The other problems listed above are not only troublesome at the specific installations cited, but are related, directly or indirectly, to current subsurface-injection practices in Oregon and Washington. They may be expected to remain troublesome, and even to become more widespread and serious, unless measures are taken to counteract or forestall them.

CONTAMINATION BY SALINE WATER

Throughout much of western Oregon and Washington, fresh-water aquifers are underlain by sedimentary rocks that contain saline water. At some places, as in the Tualatin Valley, Oreg. (Hart and Newcomb, 1965, p. 55), the saline water may migrate upward naturally along zones of fracture and contaminate shallower aquifers. At other places, as in districts in and near Portland (Brown, 1963, p. 23; Hogenson and Foxworthy, 1965, p. 44), the hydrostatic head in the fresh-water aquifers has been lowered by pumping, and the saline water has moved upward into those shallower aquifers.

The deterioration in the quality of water from the original supply well for the Oregonian Building air-conditioning system is a result of such saline-water contamination. The well taps aquifers in the Columbia River Basalt, which, in the Portland area, is the rock unit that directly overlies the saline-water-bearing rocks. Locally, intensive withdrawal from the basalt aquifers, to supply air-conditioning systems utilizing artificial recharge as well as for other purposes, has caused artesian pressures in those aquifers to decline. The significance of the saline-water contamination in relation to the artificial-recharge operations in the west-side business district of Portland was discussed by Brown (1963, p. 23):

If these artesian pressures decline further because of continued intensive pumping, further deterioration in quality of the water in the basalt can be expected, at least locally. The saline water might also contaminate aquifers in the Troutdale Formation [overlying the basalt], if the saline water is used to recharge those aquifers artificially, or if a well taps aquifers in both the Troutdale

Formation and the basalt, and saline water in the basalt is under sufficient pressure to cause it to move upward in the well and outward into higher aquifers. Conversely, the quality of the water in the basalt aquifers might be improved substantially by increased artificial recharge with water of better quality, either from the Troutdale Formation or from some other sources.

The existing and potential problems of saline-water contamination, as discussed above, are not unique to the Portland area. This type of contamination has been reported in several other parts of western Oregon and Washington (Newcomb, Sceva, and Stromme, 1949, p. 40; Newcomb, 1952, p. 38; Sceva, 1957, p. 36; Weigle and Foxworthy, 1962, p. 18; Hart and Newcomb, 1965, p. 55), and could develop in any area where fresh-water aquifers closely overlie such saline-water-bearing rocks and where pumpage from the fresh-water aquifers exceeds the natural and artificial recharge to aquifers. In areas where such conditions are likely to exist, the possibility of saline-water contamination should be a major consideration in the design and operation of air-conditioning and other artificial-recharge systems using wells for both supply and disposal of water.

TEMPERATURE CHANGES

Water that is at a temperature greatly different from that of the native ground water, if injected into wells, tends to change the temperature of the water in aquifers tapped by those wells. The temperature changes thus produced depend mainly on the capacity of the aquifers to carry the water away from the wells, the temperature difference between the injected water and the native ground water, and the amount of heated or cooled water that is injected. Large temperature changes produce enough difference in the viscosity of the water to cause significant changes in the apparent permeability in the aquifers (Wenzel, 1942, p. 62). Temperature changes also affect the growth of any nuisance organisms that are in the water (Am. Public Health Assoc., 1960, p. 531).

Change in temperature of ground water may radically affect the usefulness of the water for some purposes. At the power substation at Snohomish, Wash. (p. C38), for example, the warming of the ground water used for cooling, caused by artificial recharge with warmed exhaust water from the cooling system, doubtless has decreased the efficiency of the cooling system and probably has increased the cost of operation. Conversely, cooling produced by artificial recharge with cold exhaust water from a heat-pump system might impair the usefulness of the ground water for some purposes, as for heating, and improve it for others that require water of a lower temperature.

To some extent, systems involving subsurface injection of water that is radically different in temperature from the native ground water can

be designed and operated to minimize unwanted changes in temperatures of the ground water. However, where such artificial-recharge operations are concentrated in small areas, as in the west-side business district of Portland, Oreg., coordination between individual operations is needed to minimize problems resulting from incompatible uses of the ground-water bodies as sources and sinks of heat.

CHEMICAL PRECIPITATION

The chemical and physical character of the waters mixed during subsurface injection may be such as to cause unwanted chemical precipitation. Even small changes of pH, Eh (reduction-oxidation potential), temperature, pressure, concentration of some dissolved gases, or exposure to air can cause the precipitation of chemical constituents such as iron, aluminum, calcium carbonate, and silica. For example, ground water commonly contains some dissolved iron that is in the ferrous, or lower oxidation state. If such iron-bearing water is mixed with an oxygen-rich water or is exposed to the oxygen in the atmosphere, much of the iron is oxidized to the ferric state and precipitates in the form of ferric hydroxide, which is virtually insoluble at normal pH values of ground water (Hem, 1959, p. 60). Likewise, if ground water that contains abundant silica in the ionic state is cooled, as by cold recharge water, some of the silica may precipitate (Siever, 1962, p. 128–134). When such chemical precipitation is substantial, aquifer permeabilities may be greatly decreased.

The rapid decrease in the intake capacity of the well at Everett, Wash. (p. C32), apparently was caused partly by the precipitation of ferric hydroxide in the recharge water after air was allowed to enter the system. The serious problem at that installation emphasizes the necessity of evaluating the physical and chemical compatibility of the recharge water and the native ground water before embarking on a program of artificial recharge through wells.

DISSOLVED AND ENTRAINED AIR

In addition to the chemical processes that lessen the permeability of the aquifer, air, in the form of bubbles entrapped in the pore spaces of the aquifer materials during artificial recharge, may drastically impede the movement of water through the aquifer (Orlob and Radhakrishna, 1958, p. 648). Even a few air bubbles in an aquifer can greatly reduce its permeability, for the bubbles tend to be carried into and lodge in the main paths of water movement. Once in place, they are tightly held to the aquifer materials by molecular attraction; to dislodge them, water moving in the aquifer must travel at great velocities. Under normal conditions, air occurring as bubbles dissolves very slowly, even in water that has a very low dissolved-air content.

Air can enter the aquifers tapped by the injection well in two ways—dissolved in the recharge water, or entrained as bubbles in the column of recharge water as it moves to or falls into the well. Some air invariably is taken into solution by flowing water that is exposed to the atmosphere; for example, by water flowing in a stream or moving through a surface reservoir. Air dissolved in water in a state of equilibrium (saturation) tends to come out of solution if the water becomes warmer or if the pressure on the system is reduced. In rapidly moving water, especially in a closed system, air dissolved in the water is likely to come out of solution at points of sharp pressure reductions, such as on the inside of sharp bends in a pipeline, or on the downstream side of valves.

The importance of air as a clogging agent was recognized in the artificial-recharge operation at Everett, Wash. (p. C32), and in the experimental operations at Walla Walla, Wash. (Price, 1961, p. 28), and at The Dalles, Oreg., B. L. Foxworthy and C. T. Bryant, U.S. Geological Survey (written commun., 1961). In other places where recharge wells in this region or the aquifers tapped by them have become clogged, air bubbles generally have not been considered as a possible cause of the clogging, and other causes have been postulated.

NUISANCE BACTERIA

Accumulations of brown slime that have been reported in several of the recharge wells in Oregon and Washington have been generally assumed to be the result of so-called nuisance bacteria, although the writers know of no tests that have been made to identify such organisms in wells of this region. The term "nuisance bacteria" has been applied rather loosely to any of a number of organisms that are not disease producing in humans but are troublesome in water supply and distribution systems in that they produce slimes or other objectionable products and cause unpleasant color, taste, or odor of the water. They apparently are worldwide in distribution.

The nuisance bacteria that are most troublesome in well supplies and in subsurface-injection operations are types that require little or no oxygen or organic material and no light, and which can develop in water containing incompletely oxidized inorganic substances such as iron or sulfur. Of these, probably the most common, and certainly the most notorious, are the iron bacteria and sulfur bacteria (Harder, 1919; Starkey, 1945). The iron bacteria include a number of different types that either oxidize ferrous to ferric iron and cause the precipitation of ferric hydroxide, or that cause changes in the dissolved-iron content of water by altering the environmental conditions. Related types are sulfur bacteria and sulfate-reducing bacteria, which can also produce insoluble iron compounds (Starkey, 1945, p. 964). Different

species of these bacteria cause hard deposits that encrust pipes, well casing, and screens, or gelatinous or filamentous slimes that can effectively clog wells and the interstices of an aquifer. These organisms require some carbon dioxide and various trace elements for their physiologic processes (Lees, 1961, p. 92–93); temperature, light, pH, and oxygen also affect their growth in some way (Am. Public Health Assoc., 1960, p. 531). Heavy chlorination has been the usual method of controlling their growth.

In the west-side business district of Portland, iron bacteria apparently are widespread in the aquifers, and reportedly are a major cause of clogging of recharge wells and the aquifers tapped by those wells. These bacteria reportedly also caused significant clogging at the recharge wells of the power substation at Snohomish, Wash. (p. C38). According to Mr. Ray Chewning (oral commun., 1962), these bacteria were noticed during the drilling of wells for the first artificial-recharge installation in the Portland area (the Equitable Building wells drilled in 1946); the presence of those bacteria prior to the artificial recharge in this area is thus suggested. However, the subsurface-injection operations probably have hastened the spread of nuisance bacteria through the aquifers.

At some of the artificial-recharge installations described herein, chlorination of the injection water was started with the beginning of the recharge operation, and nuisance bacteria have never been a problem. At other installations, the growth of the nuisance bacteria was underway before the problem was recognized. However, even in those cases, heavy chlorination of the recharge water, either continuously or periodically, apparently has been effective in controlling the growth and plugging effects of the nuisance bacteria.

SEDIMENT

It is generally understood that water that is injected into a well should be as nearly free of sediment as possible. The clogging that occurred during one of the tests at The Dalles, Oreg. (p. C41), as a result of a chemical floc being introduced into the well with the recharge water, substantiates this requirement. Conversely, the continued trouble-free operation of the recharge wells at Pine Flat, Oreg. (p. C33), where unusually large amounts of sediment enter the wells, shows that some aquifers having large openings can accept great amounts of sediment without being clogged substantially. However, in the Pine Flat wells, and also at some of the other installations described herein, the dangers of plugging that are inherent in the subsurface-injection operations probably are considerably reduced by pumping the recharge wells during part of the year. The pumping tends to remove much of the clogging material (sediment, air bubbles,

chemical precipitate, or bacterial growth) that was introduced or that developed during previous periods of injection.

SUMMARY OF AMOUNTS RECHARGED ARTIFICIALLY

The total volume of water recharged artificially to aquifers in Oregon and Washington during any year can be estimated only roughly because the amount recharged at any one installation may vary considerably from year to year. In the water-spreading operation at Richland, Wash., the average amount of water recharged annually is estimated to be about 12,000 acre-feet. Near Okanogan, Wash., about 2,000 to 3,000 acre-feet per year is added to Duck Lake and underlying aquifers. Each year about 100 acre-feet flows from irrigated farmlands into wells tapping basalt aquifers at Pine Flat, Oreg., and about 200 acre-feet of Willamette River water is pumped into recharge wells at Springfield, Oreg. Another 160 acre-feet is returned to the ground water from the cooling installation at Snohomish, Wash. As much as 1,700 acre-feet probably is recharged annually through wells at air-conditioning installations in Portland, Oreg., and Vancouver, Tacoma, and Lakewood, Wash. Of that amount, about 800 acre-feet is recharged through wells at the air-conditioning installations in Portland alone. As much as 230 acre-feet of precipitation and excess sprinkling water may be injected underground through a well at the American Pipe & Construction Co. plant in northeast Portland. During the period 1952–55 about 40 acre-feet per year was recharged to basalt aquifers at St. Helens, Oreg. During the recharge tests at Walla Walla, Wash. (1957–58), and at The Dalles, Oreg. (1960–61), more than 320 acre-feet was recharged to basalt aquifers—71 acre-feet at Walla Walla, and 250 acre-feet at The Dalles. Available information on the rates and periods of recharge and on total amounts recharged artificially is summarized in table 4.

The total amount of water recharged artificially in the two States during 1961 probably was about 17,000 acre-feet, not including the water injected during the test at The Dalles, Oreg. The water-spreading operation at Richland, Wash., constituted about 71 percent of this total.

DATA NEEDED FOR ARTIFICIAL-RECHARGE OPERATIONS

As the need for water increases and the untapped reserves of economical water supplies become fewer, the prudent use of artificial recharge will become steadily more important. The opportunities

for artificial recharge in Oregon and Washington are numerous and diverse, and the benefits to be derived therefrom are substantial. However, the degree of success—or even the feasibility—of an individual artificial-recharge operation may depend on the acquisition and proper interpretation of a fund of background data.

Proper planning and design of an artificial-recharge operation, like any other engineering work, require the best possible knowledge of the characteristics of the materials that are to be used and all phases of the process in which they will be involved. Thus, such factors as the physical and chemical character and biota of the waters involved, the subsurface geology, the natural ground-water regimen, and existing uses of the water involved must be understood before the many possible effects of an artificial-recharge operation can be predicted or evaluated and the feasibility of the various methods can be judged. Some important considerations in the selection, design, and operation of different artificial-recharge systems are discussed by Todd (1959a) and in a task-group report of the American Water Works Association (1963, p. 697–704).

As pointed out by Price (1961, p. 10), some of the possible effects or results of an artificial-recharge operation may be impossible to predict on the basis of available information and previous experiences. Therefore, operating-control tests and records are needed to determine the effectiveness and efficiency of the system, to indicate deviations from normal operation, and to evaluate problems that may arise. The following represent the minimum operational data that are needed for most artificial-recharge operations:

1. Quantities and rates of recharge, and relation to water levels in recharge basins or injection wells.
2. Sediment content of the recharge water; temperature, chemical character, and biota of the recharge and ground water.
3. Fluctuation of water levels in observation and supply wells; ground-water withdrawals.
4. Dates of operation, shutdown, and maintenance.
5. Type, amounts, and dates of treatment of the recharge water or system.

Additional data may be needed, depending on the type of recharge operations or the ultimate use of the water (Task Group 2440-R, 1963, p. 704).

The lack of adequate background data on several of the existing artificial-recharge operations in Oregon and Washington has seriously hampered the early recognition and the evaluation of some of the problems described (p. C42–C48).

SUMMARY AND CONCLUSIONS

The principal conclusions resulting from this study are:

1. Except for the one at Everett, Wash., the 23 artificial-recharge operations described in this report have so far been considered generally satisfactory by the respective operators. The surface-spreading operations at Richland and near Okanogan, Wash., and the injection operation at Springfield, Oreg., are serving their respective purposes of augmenting municipal and irrigation water supplies, as had the installation at St. Helens served that city until 1955. The recharge operations at Pine Flat, and in northeast Portland, Oreg., are serving a two-fold purpose of disposing of unwanted water and adding to the ground water in storage in those areas; although the aquifers recharged by those operations may eventually become plugged by sediment carried in the recharge water, such plugging had not been noticed by 1962.

2. The ability to recharge local sand and gravel aquifers through wells has been demonstrated at Springfield, Oreg., and by the general success of multiple-well heating and cooling systems in both States. Likewise, the artificial-recharge operation at St. Helens, Oreg., and the tests at Walla Walla, Wash., and The Dalles, Oreg., have shown the technical feasibility of recharging basalt aquifers.

3. The amount of water recharged artificially to aquifers in Oregon and Washington during 1961 probably was more than 17,000 acre-feet. Although the total is small compared to amounts recharged artificially in some other Western States, the advent and general success of the operations since 1945 indicate the growing importance of artificial recharge in Oregon and Washington.

4. Most of the water that is recharged artificially in the two States is added to the ground-water body through the surface-spreading operation at Richland, Wash. That operation has been continued successfully since 1944, although chemical treatment has been needed to control the growth of slime-forming organisms, and periodic cleaning and scarifying of the recharge basins has been required to maintain adequate rates of infiltration.

5. Although the present multiple-well air-conditioning systems thus far have been considered generally successful, serious problems have arisen at some of the installations. These problems include undesirable changes in temperature and chemical character of the ground water, and clogging of wells and aquifers by chemical precipitation, air bubbles, and nuisance bacteria; clogging by

sediment may also be a potential problem in some subsurface-injection operations. As the practice of artificial recharge continues and spreads to other parts of the region, these problems are likely to become more serious and widespread unless suitable measures are taken to mitigate and forestall them. The results of artificial-recharge experiments and other water-resource studies during recent years provide guidance for meeting many of these problems.

6. Wise and efficient design of an artificial-recharge system requires a fund of background data on the hydrologic framework in which the system must operate. These data should include a thorough knowledge of the subsurface geology; aquifer properties and conditions of ground-water occurrence; the chemical, physical, and biological character of the native ground water and the recharge water; and existing uses of the waters involved. The degree of success of operation of the system will depend a great deal on the effects the recharging has on the ground-water regimen. Therefore, continuous or periodic records should be collected of the chemical and physical quality and biota of the waters involved, the quantity of water recharged and withdrawn, the type and amount of treatment, and the fluctuations of the ground-water levels.

REFERENCES

American Public Health Association, Inc., 1960, Standard methods for the examination of water and wastewater: New York, Am. Public Health Assoc., 626 p.

Brown, S. G., 1963, Problems of utilizing ground water in the westside business district of Portland, Oregon: U.S. Geol. Survey Water-Supply Paper 1619–O, 42 p., 2 pls., 4 figs.

Harder, E. C., 1919, Iron-depositing bacteria and their geologic relations: U.S. Geol. Survey Prof. Paper 113, 89 p., 12 pls., 14 figs.

Hart, D. H., 1957, Artificial recharge to ground water in Oregon and Washington: U.S. Geol. Survey open-file report, 54 p., 11 figs.

Hart, D. H., and Newcomb, R. C., 1965, Ground water of the Tualatin Valley, Oregon: U.S. Geol. Survey Water-Supply Paper 1697, 60 p., 3 pls., 17 figs.

Hem, J. D., 1959, Study and interpretation of chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 269 p., 2 pls., 40 figs.

Hogenson, G. M., and Foxworthy, B. L., 1965, Ground water in the east Portland area, Oregon: U.S. Geol. Survey Water-Supply Paper 1793, 78 p., 2 pls. 2 figs.

Howson, A. W., 1953, The atomic city water supply: Water Works Eng., v. 106, no. 5, p. 403–404, and 482–486, 3 figs.

Kroeker, J. D., and Chewning, R. C., 1948, A heat pump in an office building: Am. Soc. Heating and Ventilation Engineers Jour. Sec. Heating, Piping and Air Conditioning, v. 54, p. 1–8, figs. 1–13.

Lees, Howard, 1961, Bacterial nutrition, *in* The encyclopedia of the biological sciences : New York, Reinhold Publishing Co., p. 92–94.

Muckel, D. C., and Schiff, Leonard, 1955, Replenishing ground water by spreading, *in* Water : U.S. Dept. Agr. Yearbook, p. 302–303.

Newcomb, R. C., 1952, Ground-water resources of Snohomish County, Washington : U.S. Geol. Survey Water-Supply Paper 1135, 133 p., 19 figs.

Newcomb, R. C., Sceva, J. E., and Stromme, Olaf, 1949, Ground-water resources of western Whatcom County, Washington : U.S. Geol. Survey open-file report, 134 p., 11 pls.

Orlob, G. T., and Radhakrishna, G. N., 1958, The effects of entrapped gasses on the hydraulic characteristics of porous media : Am. Geophys. Union Trans., v. 39, no. 4, p. 648–659, 10 figs.

Price, C. E., 1961, Artificial recharge through a well tapping basalt aquifers, Walla Walla area, Washington : U.S. Geol. Survey Water-Supply Paper 1594–A, p. 1–33, figs. 1–4.

Sceva, J. E., 1957, Geology and ground-water resources of Kitsap County, Washington : U.S. Geol. Survey Water-Supply Paper 1413, 178 p., 26 figs.

Siever, R., 1962, Silica solubility, 0°–200°C, and the diagenesis of siliceous sediments : Jour. Geol., v. 70, no. 2, p. 127–150.

Starkey, R. L., 1945, Transformation of iron by bacteria in water : Am. Water Works Assoc. Jour., v. 37, no. 10, p. 963–984.

Sylvester, R. O., and Seabloom, R. W., 1962, A study on the character and significance of irrigation return flows in the Yakima River basin : Washington Univ. Dept. Civil Eng., 104 p., 19 figs.

Task Group 2440–R on Artificial Ground Water Recharge, 1963, Design and operation of recharge basins : Am. Water Works Assoc. Jour., v. 55, no. 6, p. 697–705.

Todd, D. K., 1959a, Annotated bibliography on artificial recharge of ground water through 1954 : U.S. Geol. Survey Water-Supply Paper 1477, 115 p.

——1959b, Ground water hydrology : New York, John Wiley & Sons, Inc., 336 p.

U.S. Geological Survey, 1958, Quality of surface waters of the United States, 1953, pts. 9–14, Colorado River basin to Pacific slope basins in Oregon and lower Columbia River basin : U.S. Geol. Survey Water-Supply Paper 1293, 372 p., 1 fig.

Weigle, J. M., and Foxworthy, B. L., 1962, Geology and ground-water resources of west-central Lewis County, Washington : Washington Dept. Conserv. Water-Supply Bull. 17, 248 p., 5 pls., 13 figs.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials : U.S. Geol. Survey Water-Supply Paper 887, 192 p., 6 pls., 17 figs.

TABLES 1–4

TABLE 1.—*Records of selected wells used in artificial-recharge operations in Oregon and Washington*

[All wells in this table are drilled]

Altitude: Altitude of land-surface datum at well, in feet above mean sea level interpolated from topographic maps or reported.
Ground-water occurrence: C, confined or partly confined; U, unconfined.
Water level: Figures expressed in feet and decimals measured by the U.S. Geological Survey; those in whole feet were reported by owner, driller, or operator.
Type of pump: T, turbine; N, none.

Use (of water or well): H, heating and (or) cooling; In, industrial; Ir, irrigation; PS, public supply; R, receives recharge; S, stock.
Remarks: Ca, chemical analyses in table 3; dd, drawdown; gpm, gallons per minute; H, hydrograph in this report; L, log in table 2; ppm, parts per million; Temp, temperature of water in degrees Fahrenheit (date of measurement given if known). Specific remarks concerning the wells were reported by owners, operators, drillers, and others.

Well	Owner or operator	Altitude (feet)	Depth of well (feet)	Diameter of well (inches)	Depth of casing (feet)	Water-bearing zone(s) Depth to top (feet)	Thickness (feet)	Character of material	Ground-water occurrence	Water level Feet below datum	Date	Type of pump and yield (gallons per minute)	Use	Remarks
Oregon														
4N/1W-5R1	City of St. Helens	150	421	12	15	---	---	Basalt	C	30	5--40	T, 300	PS, R	
1N/1-11N2	American Pipe & Construction Co.	40	91	12	91	40	51	Gravel	U	25-30	1957	T, 1,100	In, R	
33R1	First National Bank, 1405 S.W. Morrison St. Branch.	100	460	10 / 8	300 / 460			Gravel(?) and basalt.		88	11--55	T, 300	H	Pumped 300 gpm for 8 hr, dd 62 ft; 8-inch casing perforated 300-460 ft.
33R2	---do---	100	300	10	300	106	194	Gravel	U	91	1956		R	Casing perforated 150-300 ft.
34N3	Equitable Bldg ---	40	188	14	155	67	88	Gravel, slightly cemented.	U	15	10--46	T, 225	H	Pumped 225 gpm, dd 117 ft. Temp 66, 1946; Ca. Casing perforated 60-140 ft.
34N4	---do---	40	508	14 / 12	163 / 380	370	188	Basalt	C	36	12--46	T, 600	H, R	Pumped 600 gpm for 1 hr, dd 28 ft. Temp 56, 2-21-61; Ca.
34N5	---do---	40	165	12	165	55	107	Sand and gravel.	U	15	2--47	T, 200	H, R	Pumped 510 gpm, dd 92 ft. Casing perforated 55-117 and 127-165 ft. Temp 62.5, 1947.

TABLE 1.—*Records of selected wells used in artificial-recharge operations in Oregon and Washington*—Continued

Well	Owner or operator	Altitude (feet)	Depth of well (feet)	Diameter of well (inches)	Depth of casing (feet)	Depth to top (feet)	Thickness (feet)	Character of material	Ground-water occurrence	Feet below datum	Date	Type of pump and yield (gallons per minute)	Use	Remarks
								Oregon—Continued						
1N/1-34N10	Portland Medical Center.	65	591	12	380	385	206	Basalt	C	59	4-14-58	T	H	Pumped 650 gpm for 12 hr, dd 260 ft. Temp 62, 1961.
34N11	___do___	65	418	12	327	130	138	Gravel, cemented.	U				R	Casing perforated 135-320 ft.
34N14	First National Bank, 400 S.W. 6th Ave. Branch.	36	544	16	368	365	179	Basalt		45	4- 9-59		H	Pumped 1,000 gpm for 12 hr, dd 223 ft. Temp 54, 1959; L.
34N15	___do___	37	161	14	148	65	95	Gravel		18	5- 1-59		R	Pumped about 100 gpm. Temp 63. Ca.
1N/13-4F1	City of The Dalles.	190	299	18	145	242	38	Basalt	C				PS, R	Pumped 450 gpm for 20 hr, dd 53 ft; 765 gpm for 20 hr, dd 95 ft. Temp 60, 1959. Casing perforated 130-140 and 198-207 ft.
1/1-3D5	Ladd Building Co.	60	228	14	228	125	15	Sand and gravel.	U	55	5-15-59	T, 2,300	R	
						198	9	_____do_____						
3D6	Pacific Bldg	60	765	16	386	403	362	Basalt	C	53	1959	T	H	Pumped 750 gpm, dd 206 ft. Temp 63, 2-21-61. Chloride 376 ppm, hardness 333 ppm.
3E1	Oregonian Bldg	110	203	18	191	127	15	Sand and gravel.	U	95	6- -47	T, 750	H, R	Pumped 750 gpm for 24 hr, dd 49 ft; 1,100 gpm for 24 hr, dd 80 ft. Casing perforated 127-142 and 171-188 ft. Temp 55.5, 1961; Ca.
						171	18	_____do_____						

Well no.	Owner							Water-bearing material	Use		Date	Yield	Use	Remarks
3E2	...do...	110	235	14	189	128	12	...do...	U	101	6- -47	T, 500	H, R	Casing perforated 128-206 ft. Temp 5.5, 1961; Ca.
3E3	...do...	110	930	10	216	191	19	...do...	C	86	1- -48	T, 490	H, R	Temp 58, 1947-48; 78, 1960; Ca.
4A2	Medical-Dental Bldg.	110	772	16, 12, 10	198, 390, 558	226, 558	704, 214	Basalt / ...do...	C	100	1959	T	H	Pumped 723 gpm; dd 91 ft. Temp 60, 1959. Casing perforated 0-558 ft.
4A3	...do...	115	193	12	193	150	25	Gravel	U	101	...do...		R	Pumped 600 gpm, dd 32 ft. Temp 56, 1959. Casing perforated 151-175 ft.
18/3W-1J1	Pacific Power & Light Co.	460	44	16	44	11	33	Sand and gravel	U	9	7- -56	N	R	Casing perforated 19-44 ft.
1J2	...do...	460	30	12	30	13	17	...do...	U	9	7-30-56	N	R	Casing perforated 12-30 ft.
38/11½-32G1	L. L. Porterfield	4,185	197	16	64	130	67	Cinders and rock	C	72.2	4- 2-48	T, 2,000	Ir, R, S	Pumped 1,500 gpm, dd 8 ft.
39/11½-5B1	...do...	4,183	270	16				Basalt	C	72	4-23-52	T, 2,000	Ir, R	
5D1	...do...	4,205	260	16	21			...do...	C	93.67	11-19-49	T, 1,600	Ir, R	

Washington

Well no.	Owner							Water-bearing material	Use		Date	Yield	Use	Remarks
2/1-10H1	Columbia River High School	200	350	16	320	288	21	Sand and gravel		112	1961		H	Pumped 900 gpm, dd 87 ft. Casing perforated 265-277 and 288-310 ft.
10H2	...do...	200	327	16		297	26	Cemented gravel				N	R	Pumped 900 gpm, dd 114 ft.
27G1	Vancouver Federal Savings & Loan Assoc.	85	137	10	137	120	13	Sand and gravel		91	9- -55	T, 160	H	Pumped 650 gpm for 4 hr, dd 3 ft. Casing perforated 120-131 ft.
27G2	...do...	85	144	10	144	119	21	...do...	U	98	9- -55	N	R	Pumped 600 gpm for 4 hr, dd 3.5 ft. Casing perforated 125-140 ft.
27H1	Clark County Public Utilities Dist.	100	144	10	144	119	22	Gravel and sand		96	8-29-55	N	R	Pumped 600 gpm, dd 3.5 ft. Temp 54; Ca, L.
27H2	...do...	100	138	10	137	122	18	...do...	U	94	9-20-55	T, 670	H	Pumped 670 gpm, dd 3.5 ft. Temp 54.

TABLE 1.—Records of selected wells used in artificial-recharge operations in Oregon and Washington—Continued

Well	Owner or operator	Altitude (feet)	Depth of well (feet)	Diameter of well (inches)	Depth of casing (feet)	Depth to top (feet)	Thickness (feet)	Character of material	Ground-water occurrence	Feet below datum	Date	Type of pump and yield (gallons per minute)	Use	Remarks
						Water-bearing zone(s)				Water level				
									Washington—Continued					
7/37-18F1	City of Walla Walla.	1,317	1,169	20-16	176	149		Basalt	C	133 / 164	4-30-47 / 1-11-58	T, 1,800	PS, R	Latest water level represents about a 9-ft rise after 28-day recharge period; Ca.
9/28-15A1	Atomic Energy Commission, Hanford Operations Office.	352	68	36-14	51	23	28	Sand and gravel.	U	4.14	6-16-48	T, 800	PS	Casing 36-inch to 25 ft; 24-inch to 30 ft; 4-inch to 51 ft; perforated from 28-51 ft. Gravel pack from 25-51 ft; H.
10/28-23P2	do.	395	88	20	90	40	42	do.	U	37	7-16-48	T, 1,000	PS	Casing perforated from 47-81 ft; H.
35H4 / 19/2-2D1	do. / National Bank of Washington.	377 / 255	77 / 156	20 / 10	77 / 156	25 / 66	48 / 5 / 11	Sand, gravel and clay. Sand and gravel.	U / •U	24 / 16.4	7-10-48 / 8-14-61	T, 1,100	PS / H	H, L. Pumped 66 gpm, dd 106 ft. Perforated interval unknown.
2D2 / 20/2-18A1	do. / City of Tacoma.	255 / 258	36 / 84	16 / 24	36 / 63.5	20 / 63	16 / 23	Gravel. do.	U			N / T, 2,500	R / H, R	Well screen 63.5-85.2 ft. Pumped 2,500 gpm, dd 32 ft. Temp 52; Ca.
13B1	do.	258	260	18	185	185	27	Sand and gravel.	U	38.6	6-18-53	T, 650	H, R	Pumped 690 gpm, dd 31 ft; Ca, L.
20/3-4D1	Tacoma Savings & Loan Assoc.	120	202			95	107	do.		95	1956	N	R	After water was injected at 300 gpm for 8 hr, level in well rose 25 ft. Casing perforated 165-185 ft.

													Remarks
4D2	------do------	120	147	------	------	96	52	------do------	------	95	1956	------	H	Reportedly pumped 300 gpm. Temp 55, May 19, 1956; Ca. Well screen 127–147 ft.
28/5–12R1	Bonneville Power Administration.	97	150	10	150	104	41	------do------	U	72.5	1- –50	T	H	Temp 50.
12R2	------do------	97	150	10	150	98	42	------do------	U	73	1953	N	R	Do.
12R3	------do------	97	235	10	165	150	14	------do------	U	72.5	1955	N	R	
29/5–31A1	West Coast Telephone Co.	237	237	18	206	31	60	------do------		120	7–19–60		H, R	Reportedly pumped 870 gpm for 11 hr, dd 45 ft; Ca. 10-inch well screen 206–237 ft.
31A2	------do------	259	257	------	206	51	------	------do------	------	140.8	7–19–60	------	H, R	Pumped 990 gpm for 25 hr, dd 32 ft; Ca. Well screen 206–257 ft.

TABLE 2.—*Drillers' logs of selected wells in Oregon and Washington*

Material	Thick-ness (feet)	Depth (feet)	Material	Thick-ness (feet)	Depth (feet)

1N/1–34N14

[Portland, Oreg., First National Bank, 400 SW. 6th Avenue Branch. Altitude 36 ft. Drilled by Barron and Strayer, 1959. Casing: 16 in. to 368 ft]

Material	Thick-ness (feet)	Depth (feet)	Material	Thick-ness (feet)	Depth (feet)
Alluvium, fluviolacustrine deposits, and Troutdale(?) Formation:			Sand River Mudstone—Con.		
			Clay, layered brown, black, blue, and yellow	73	325
Gravel	85	85	Columbia River Basalt:		
Gravel and sand	35	120	Rock (basalt), brown and		
Troutdale Formation:			black	115	440
Gravel, coarse	45	165	Rock, porous, some water	53	493
Gravel, cobbles, and boulders	20	185	Rock, hard, black; water		
Clay, blue and green	5	190	level dropped 20 ft	15	508
Gravel, hard	30	220	Rock, black, "coarse		
Sandy River Mudstone:			cuttings"	20	528
Sand, hard	25	245	Rock, porous, black	15	543
Sand and clay, blue	5	250	Rock, hard	1	544
"Hard shell" (sandy bed, cemented?)	2	252			

2/1–27H1

[Clark County, Washington, Public Utilities District. Altitude 100 ft. Drilled by R. J. Strasser & Sons Drilling Co. Casing: 10 in. to 144 ft, perforated from 125 to 140 ft]

Material	Thick-ness (feet)	Depth (feet)	Material	Thick-ness (feet)	Depth (feet)
Fluviatile deposits of Pleistocene Age and Troutdale(?) Formation:			Fluviatile deposits of Pleistocene Age and Troutdale(?) Formation—Con.		
Gravel and clay	42	42	Gravel, coarse, some sand; water-bearing	22	141
Gravel, cemented	10	52	Gravel, cemented	3	144
Sand, gravel, and clay	54	106			
Gravel, cemented	13	119			

10/28–35H4

[Atomic Energy Commission, Hanford Operations Office, Washington. Altitude about 377 ft. Drilled by R. J. Strasser & Sons, 1948. Casing: 20 in. to 77 ft perforated from 36 to 73 ft]

Material	Thick-ness (feet)	Depth (feet)	Material	Thick-ness (feet)	Depth (feet)
Recent alluvium:			Glaciofluvial and alluvial deposits—Con.		
Glaciofluvial and alluvial deposits:			Gravel	2	30
Sand	2	2	Gravel and sand (20 percent sand)	26	56
Gravel and clay	2	4	Gravel and sand (30 percent sand)	10	66
Sand	1	5	Gravel, sandy	7	73
Sand and gravel	3	8	Ringold Formation:		
Gravel, sandy	9	17	Clay, conglomerate	4	77
Gravel	6	23			
Gravel and sand	5	28			

TABLE 2.—*Drillers' logs of selected wells in Oregon and Washington*—Continued

20/2–13B1

[City of Tacoma, Washington. Altitude 258 ft. Drilled by L. R. Gaudio, 1953. Casing: 18 in. to 185 ft; well screen (100-mesh) from 185–212 ft]

Materials	Thick-ness (feet)	Depth (feet)	Materials	Thick-ness (feet)	Depth (feet)
Glacial outwash:			Till of the Vashon glaciation—Con.		
Gravel and sand, dirty	5	5	Sand, gravel and clay	18	158
Sand, coarse, dirty, some			Sand and gravel, cemented		
gravel	45	50	with brown clay	4	162
Sand and gravel	15	65	Sand and gravel below the till of		
Gravel, coarse, some sand	24	89	the Vashon glaciation:		
Till of the Vashon glaciation:			Clay, brown, sandy	5	167
Sand and gravel, cemented			Sand, brown, little clay	8	175
with blue clay	31	120	Clay and sand	3	178
Sand and gravel, cemented			Sand, gravel and clay	9	187
with brown clay	5	125	Sand and gravel	15	202
Sand and gravel, cemented			Sand, gravel and clay	6	208
with blue clay	7	132	Sand and gravel	5	213
Sand and gravel, cemented			Sand, gravel and clay	9	222
with green clay	4	136	Gravel and sand, some clay	4	226
Sand and gravel, coarse, little			Sand, gravel and clay	29	255
blue clay	4	140	Clay	5	260

TABLE 3.—*Chemical analyses of water from wells and streams*

[Type of water; Gn, native ground water, before recharge; Gm, mixed ground water, after recharge. GE, General Electric Co., 100-area laboratory; HOOL, Hanford Operations Office analytical

Well or sampling location	Name of stream or type of water-bearing material	Type of water [1]	Date of collection	Temperature (°F)	Parts per million				
					Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)
Oregon									
4N/1W–5N [1]	Salmon Creek and springs.	R	2–18–54	------	16	0.10	------	3.2	1.1
1N/1–34N3	Gravel	Gn(?)	10–25–46	66	52	14	------	31	10
34N4	Basalt	Gm	1– 9–47	------	35	.2	------	45	1.8
			3– 9–55	------	------	------	------	------	------
1N/13–4 [1]	Mill Creek	Gn	10–27–60	52	38	.10	------	8.0	3.5
4F1	Basalt	R	----do----	62	62	.07	------	37	14
1/1–3E1	Sand and gravel	Gn	6–11–47	------	53	.01	0.06	36	16
3E2	----do----	Gn	7– 1–47	------	49	.03	.27	39	17
			7–14–50	------	44	.2	.6	41	8
3E3	Basalt	Gn(?)	1– 7–48	------	58	.4	------	115	6
		Gm	3– 1–55	78	------	------	------	------	------
Washington									
2/1–27H1	Gravel and sand	Gn	10–10–55	------	6.0	0.02	------	26	7.2
7/37–18F1	Basalt	Gn	1–28–57	59	56	.0	------	17	6.5
18 [1]	Mill Creek	R	3–26–57	------	33	.04	.0	4.8	2.1
9/28–15 [4]	Glaciofluvial and fluvial deposits.	Gm	4–24–51	------	55	.02	0	50	16
			6– 3–55	------	17	.00	.01	63	4.4
10/28–23 [5]	----do----	Gm	4–24–51	------	38	.02	<.01	27	5.8
			6– 3–55	------	13	.02	.01	45	.0
35 [6]	----do----	Gm	4–24–51	------	52	.01	<.01	34	7.5
			6– 3–55	------	17	.03	.02	92	0
20/2–13A1	Gravel	Gn	8–18–53	------	27	.18	.08	24	18
13B1	----do----	Gn	----do----	------	21	.2	.06	14	8.4
20/3–4D2	Sand and gravel	Gn	5– –56	55	------	.01	------	------	0
29/5–31A1	----do----	Gn	7–15–60	------	33	.55	.13	------	------
31A2	----do----	Gn	6– 2–60	------	28	.58	.10	13	5.3

[1] Samples collected from supply mains of cities served by respective streams (probably chlorinated and/or fluoridated).
[2] Residue on evaporation at 180°C.
[3] Includes .04 ppm boron.

used in artificial recharge operations in Oregon and Washington

Laboratory making analysis; BT, Bennetts, Tacoma, Wash.; CLP, Charlton Laboratories, Portland, Oreg. laboratory; NWLS, Northwest Laboratories, Seattle, Wash.; USGS, U.S. Geological Survey]

Parts per million—Continued												Specific conductance (micromhos at 25° C)	pH	Laboratory
Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$	Dissolved oxygen	Free carbon dioxide (CO_2 calculated?)			
Oregon—Continued														
2.9	1.2	18		1.6	2.8	0.1	1.3	[2]39	12				43	6.9	USGS
				18	29			312	117		60			6.5	CLP
174				13	308				119		3			7.8	CLP
		116	0		400				290			1,510	7.1	USGS
5.9	1.2	52	0	.6	3.8	.8	.2	[2]88	34	11			7.5	USGS
39	9.3	249	0	28	10	.7	.5	[2]328	152	1.2		470	7.7	USGS
4.7				9.1	18	.3	1.6	156			55			6.7	CLP
8.3				14	22	0	2.3	168			66			6.7	CLP
42		169	0	15	52	.7		287	138		21			7.2	CLP
154		149	0	7.1	356			[2]918	312		0			8.2	CLP
		154	0		233				300			1,070	7.2	USGS
Washington—Continued														
		105	0	4.1	3.6	0.2	0.4	[2]150	94				7.3	FP
9.3	2.6	106	0	2.5	1.0	.2	.2	[2]132	69			169	8.0	USGS
1.8	1.5	30	0	.7	1.0	.1	.0	[3]60	21			54	7.3	USGS
21	4	206	0	44	8.5	.2	.9	307	202			424	7.7	GE
45				18	5.2	0		175					8.6	GE
8.5	1.3	100	0	12	4.0	.2	.8	148	90			202	7.8	GE
16				20	6.8	.0		164	113				8.2	HOOL
17	2.7	141	0	18	5.5	.2	.3	186	114			283	7.8	GE
56				48	7.6	0		230					8.5	HOOL
24				14	67	.2	3.5	234	132	5.3			7.4	BT
9.6				3.7	15	.4	.5		69	1.5			7.6	BT
				12	20				82	3.0			7.8	NWLS
		67	0		2.7			92	49				6.9	BT
6.4		79	0	0	2.7	.1	.1	[7]112	53				7.4	BT

[4] Common discharge from Richland Basin wells.
[5] Common discharge from A-J Basin wells.
[6] Common discharge from Duke Basin wells.
[7] Includes 0.74 ppm aluminum.

TABLE 4.—*Summary of artificial-recharge*

Benefits or purpose: D, underground disposal of excess water; HC, conservation of heat content of water, water supply for irrigation; L, sustaining ground-water levels; M, augmenting
Sediment removal: B, settling basin or tank; Fi, filtration; Sc, screening.
Chemical treatment: Cl, chlorination; CuSO₄, addition of copper sulfate; F, fluoridation.
Temperature of recharge water: (H), temperature(s) during heating phase of reverse-cycle air-conditioning

Location	Owner or operator	Benefits or purpose	Period of operation	Estimated rates of recharge (gallons per minute)			Average annual amount of recharge (acre-feet)
				Minimum	Average	Maximum	
Richland, Wash.	Atomic Energy Commission, Hanford Operations Office.	L, M	Apr.–Oct. since 1944.	----------	12,500	17,350	12,000
Okanogan, Wash.	Okanogan Irrigation Dist.	L, Ir	Seasonal since 1958.	----------	----------	----------	2,700
Portland, Oreg__	Equitable Bldg___	L, HC	Continually since 1947.	30	100	350	160
Do_____	Oregonian Bldg__	L, HC	Continually since 1948.	0	95	500	150
Do_____	Medical-Dental Bldg.	L, HC	Continually since 1959.	0	65	120	110
Do_____	Portland Medical Center.	L, D	Summers since 1958.	0	150	365	90
Do_____	Pacific Bldg_____	L, D	Continually since 1959.	0	60	270	100
Do_____	First National Bank of Oregon (1405 S.W. Morrison St. Branch).	L, D	Summers since 1956.	0	300	----------	100
Do_____	First National Bank of Oregon (400 S.W. 6th Ave. Branch).	L, D	Summers since 1959.	0	300	----------	100
Vancouver, Wash.	Clark County Public Utility Dist.	L, HC	Continually since 1955.	30	100	280	160
Do_____	Federal Savings & Loan Assoc.	L, HC	Continually since 1961.	30	75	160	120
Hazell Dell, Wash.	Columbia River High School.	L, HC	-------------	55	----------	542	----------
Tacoma, Wash__	City of Tacoma___	L, HC	Continually since 1953.	0	250	800	380
Do_____	Tacoma Savings & Loan Assoc.	L, HC	Continually since 1957.	0	----------	135	230
Lakewood, Wash.	National Bank of Washington.	L, HC	Continually since 1961.	----------	50	70	80
Everett, Wash__	West Coast Telephone Co.	L, HC	Continually since 1962.	20	160	600	----------
Pine Flat, Oreg_	L. L. Porterfield__	L, D, Ir	Continually since 1951.	----------	----------	----------	100
St. Helens, Oreg_	City of St. Helens_	L, M	Winters (1952–55).	----------	----------	----------	43
Springfield, Oreg.	Pacific Power & Light Co.	L, M	May–Sept. since 1958.	1,000	2,000	3,000	200
Portland, Oreg__	American Pipe & Construction Co.	L, D	Continually since 1956.	0	----------	----------	230
Snohomish, Wash.	Bonneville Power Administration.	L, D	Continuously since 1953.	----------	100	----------	160
Walla Walla, Wash.	City of Walla Walla.	T	Dec. 1957 to Jan. 1958.	630	----------	670	----------
The Dalles, Oreg_	City of The Dalles.	T	Nov. 1960 to Apr. 1961.	1,370	1,500	1,770	----------

operations in Oregon and Washington, 1962

either at high or low temperatures, for reverse-cycle air-conditioning systems; Ir, augmenting ground-ground-water supply for municipal use; T, artificial-recharge test.

system; (C) temperature(s) during cooling phase of reverse-cycle air-conditioning system.

Recharge medium	Source of recharge water	Sediment removal	Chemical treatment	Temperature of recharge water (°F)	Remarks
Spreading basins___	Columbia and Yakima Rivers.	B_____	Cl, CuSO₄__	_____	Floor of A–J Basin scraped periodically to remove accumulated silt.
Duck Lake_____	Johnson and Salmon Creeks.	_____	None_____	_____	No records kept prior to 1958.
Wells 1N/1–34N3, N4, and N5.	Wells 1N/1–34N3, N4, and N5.	B_____	___do_____	(C) 75–85___ (H) About 48.	The wells are used alternately for supply and recharge.
Well 1/1–3E3_____	Wells 1/1–3E1 and 3E2.	_____	Cl_____	(C) As high as 120.	Well 1/1–3E3 yields water of inferior quality; it is used almost exclusively for recharge.
Well 1/1–4A3_____	Well 1/1–4A2_____	_____	None_____	_____	
Well 1N/1–34N11__	Well 1N/1–34N10_	None_____	___do_____	_____	Recharge well clogged with sand and not used in 1962.
Well 1/1–3D5_____	Well 1/1–3D6_____	___do_____	___do_____	(C) 48_____	
Well 1N/1–33R2___	Well 1N/1–33R1___	___do_____	___do_____	_____	
Well 1N/1–34N15__	Well 1N/1–34N14_	None_____	None_____	_____	
Well 2/1–27H1_____	Well 2/1–27H2_____	___do_____	___do_____	(C) 75–105___ (H) 48	
Well 2/1–27G2_____	Well 2/1–27G1_____	___do_____	___do_____	(C) 95 (H) 40	
Well 2/1–10H2_____	Well 2/1–10H1_____	___do_____	___do_____	(C) As high as 95. (H) 40	Not yet in use in 1962.
Wells 20/2–13A1 and 13B1.	Wells 20/2–13A1 and 13B1.	___do_____	___do_____	(C) 72–104___ (H) 40	The wells are used alternately for supply and disposal.
Well 20/3–4D1_____	Well 20/3–4D2_____	___do_____	___do_____	_____	Recharge well clogged with sand in summer of 1962; exhaust water temporarily diverted to sewer.
Well 19/2–2D2_____	Well 19/2–2D1_____	B_____	_____	_____	
Wells 29/5–31A1 and 31A2.	Wells 29/5–31A1 and 31A2.	___do_____	None_____	_____	After 2 months of operation one well was seriously clogged, probably by air bubbles and precipitated iron.
Wells 38/11½–32G1, 39/11½–5B1 and 5D1.	Irrigation water and natural runoff.	B, Sc_____	___do_____	_____	Most of the recharge occurs during spring runoff.
Well 4N/1W–5R1__	Salmon Creek and 5 unnamed springs.	None_____	___do_____	_____	Recharging discontinued in 1955.
Four shallow wells_	Willamette River_	_____	Cl	_____	
Well 1N/1–11N2____	Well 1N/1–11N2 and natural runoff.	B, Sc	None_____	_____	
Well 28/5–12R2_____	Well 28/5–12R1____	None_____	Cl_____	67–80_____	Water from supply well shows progressive increase in temperature owing to mixing with heated recharge water.
Well 7/37–18F1_____	Mill Creek, Wash_	B, Sc_____	Cl_____	39–44_____	71 acre-feet injected during the test period.
Well 1N/13–4F1___	Mill Creek, Oreg_	Fi_____	Cl, F_____	37–43_____	250 acre-feet injected during the test period.