Hydrologic Conditions and Artificial Recharge Through a Well in the Salem Heights Area of Salem, Oregon

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1594-F

Prepared in cooperation with the Salem Heights Water District

Foxworthy—HYDROLOGIC CONDITIONS AND ARTIFICIAL RECHARGE, SALEM HEIGHTS AREA, OREGON—Geological Survey Water-Supply Paper 1594-F

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By BRUCE L. FOXWORTHY

ARTIFICIAL RECHARGE OF GROUND WATER

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CONTENTS

ILLUSTRATIONS

TABLES

ARTIFICIAL RECHARGE OF GROUND WATER

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By Bruce L. Foxworthy

ABSTRACT

In the Salem Heights area of Salem, Oreg., pumping from wells that tap a permeable zone of limited extent in basalt of the Columbia River Group caused serious year-to-year declines of ground-water levels. To determine the feasibility of reducing these declines by artificially augmenting the natural recharge and to develop techniques applicable to a municipal program of artificial recharge, a series of tests was made jointly by the Salem Heights Water District and the U.S. Geological Survey. A total of 24.5 million gallons of surplus water was purchased from the public-supply system of the city of Salem and injected under pressure into one of the municipal wells through the existing pump column during three periods, ranging in duration from 1 to 15 days, at an average injection rate of about 830 gallons per minute. The recharge water contained abundant dissolved air and, at times, excessive sediment; in other respects it was of excellent quality and was compatible with the native ground water. Before the experiments, water in the main aquifer contained unusually large amounts of dissolved oxygen, which apparently was introduced by water cascading from higher zones within unlined intervals of the wells.

As a result of the injection, the specific capacity of the well (ratio of pumping yield to drawdown) was reduced temporarily because of clogging of the water-bearing material near the well by sediment and, probably, by bubbles of air which came out of solution in the recharge water. Following each of the last two periods of injection it was necessary to surge the well by intermittent pumping to restore the specific capacity.

The artificial recharge had no apparent deleterious effects on the quality of the ground water. Sediment that was injected was virtually all removed from the recharge well during pumping and surging, and the chemical quality and bacteriological purity of the ground water did not deteriorate.

Pressure rise from the injected water spread rapidly through the permeable aquifer, but the residual buildup of ground-water levels was soon masked by a seasonal rising trend of levels. The geologic and hydrologic conditions, however, preclude the escape of substantial volumes of the recharge water from the Salem Heights area. The conditions appear to be favorable for further artificial recharge of the main aquifer. Changes in the specific capacity of the recharge well provide valuable guidance for subsurface injection operations.

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

In 1960, the Salem Heights Water District and the residents then served by it faced a severe shortage of water. The water district, which supplied most of the water for a 3¼-square-mile suburban area adjacent to Salem, Oreg., owned 12 wells and pumped as much as 260 million gallons of ground water per year. Most of the water, however, was obtained from three wells that tap the same highly productive aquifer. Increasing pumpage associated with rapid suburban development of the area had resulted in progressive declines of water levels in the most productive wells to an extent that dewatering of the principal aquifer was inevitable unless withdrawal from it were decreased or recharge increased.

After three deep wells drilled during 1958–60 failed to increase appreciably the capacity of the water district well system, the district arranged to purchase water from the city of Salem. Upon completion of a booster-pump station and pipeline in August 1961, additional water became available to help meet the large summertime demands within the district; consequently, pumping from the public-supply wells was decreased. The interconnection of the two water systems raised the possibility of artificially recharging the Salem Heights ground-water reservoir by using surplus water from the Salem system to build up the supplies of ground water for future long-term and emergency needs.

The Salem Heights Water District, with the concurrence of the Oregon State Engineer, requested the U.S. Geological Survey to make a study of the technical feasibility of artificially recharging the principal aquifer and to develop practical techniques that could be used by personnel of a small water-supply agency in a continuing program of artificial recharge. The investigation consisted of a preliminary evaluation of the suitability of conditions for artificial-recharge tests, a study of the geologic and hydrologic conditions in the area, and the conduct and interpretation of artificial-recharge experiments in which water from the Salem water system was injected through one of the water district's wells.

The investigation was financed cooperatively by the U.S. Geological Survey and the Salem Heights Water District, and personnel of both agencies participated in the collection of the field data.

LOCATION AND EXTENT OF THE AREA

Salem Heights is the name given to a rolling upland area of indefinite extent near the southern limit of the city of Salem. It is included in the northeastern part of the more extensive Salem Hills area (fig. 1).

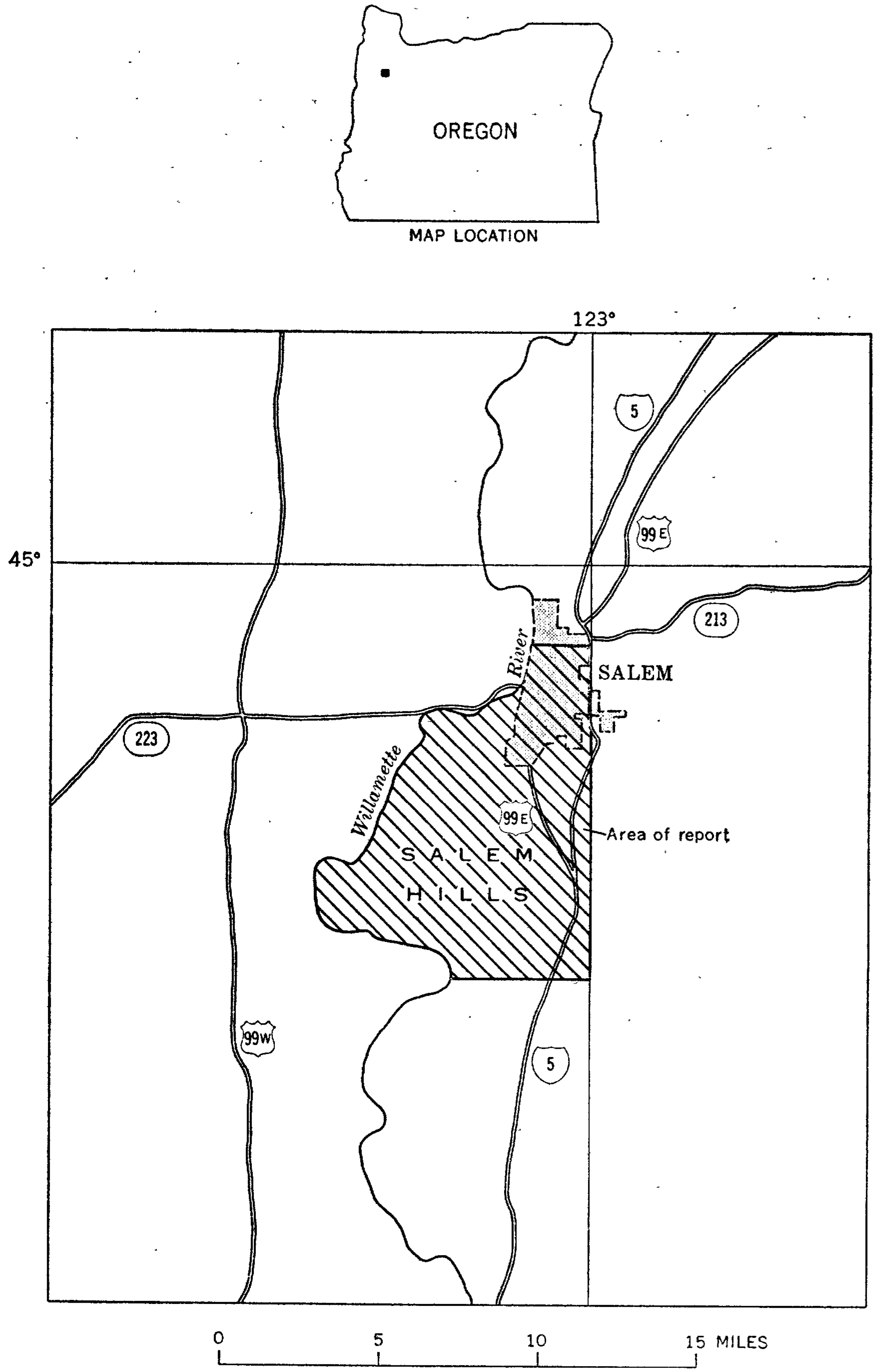

FIGURE 1.—Location of report area.

The Salem Hills area includes about 60 square miles and rises southward from the city of Salem at an altitude of about 200 feet above mean sea level to an altitude of slightly more than 1,100 feet at Prospect Hill. The southern and western boundaries of the Salem Hills area are steep bluffs that descend to the flood plain of the Willamette River. The eastern boundary is formed by small valleys that separate the Salem Hills from similar upland areas farther east.

Except for the geologic reconnaissance, which covered most of the Salem Hills area, the fieldwork for this study was mostly confined to sections 3, 9, and 10, T. 8 S., R. 3 W., which include all the productive wells of the Salem Heights Water District.

RELATED INVESTIGATIONS

Although artificial recharge through wells has been accomplished in several other parts of the country, only two controlled studies of such recharge in wells that tap water-bearing zones in basalt had been made before the beginning of this investigation. The previous studies were at Walla Walla, Wash. (Price, 1961), and The Dalles, Oreg. (Foxworthy and Bryant, 1967). During the first study, about 23 million gallons of surface water was injected into the basalt through a municipal-supply well of the city of Walla Walla at rates ranging from 630 to 670 gpm (gallons per minute). The experiment was considered to be successful because the injected water caused a rise of the water level and, therefore, increased the volume of ground water in storage in the vicinity of the well. However, the injection caused a decrease in the yield and specific capacity (pumping yield divided by drawdown of water level) of the recharge well, most of which was probably due to partial clogging of the water-bearing materials in the vicinity of the wells by bubbles of air.

During the second study, 81.4 million gallons of surplus treated stream water from The Dalles municipal supply was injected at moderately high pressures through one of the city's supply wells. Injection was at an average rate of about 1,500 gpm, the water being cooler than the native ground water by about 6°–13°C (11°–23°F). A temporary reduction in the specific capacity of the recharge well was due to (a) increased viscosity of the ground water caused by the cooling effect of the recharge water; (b) clogging of the aquifer materials near the well by bubbles of air; and (c) in at least one experiment, by a chemical floc that was introduced into the well with the recharge water. However, the specific capacity of the recharge well was restored by surging, and the experiments were considered to be proof of the technical feasibility of recharging the basalt aquifers, although the recharge water spread rapidly away from the well. Experience and data gained during the experiments at Walla Walla and The Dalles have proved to be valuable in the planning and conduct of the present study.

Among artificial-recharge experiments that provided helpful guidance to the present investigation was an exhaustive and well-documented series of subsurface-injection studies in the Grand Prairie region, Arkansas. Various aspects of those studies are described in a series of reports by Sniegocki and coworkers (U.S. Geol. Survey Water-Supply Paper 1615, chapters A–G).

Prior to the present study, the general geology of the Salem Hills and adjacent areas to the east had been mapped and described by T. P. Thayer (1939). Also, geologic and ground-water data from the Salem Heights area were being gathered concurrently with this study by Messrs. J. E. Sceva and W. S. Bartholomew, of the office of the Oregon State Engineer, for an evaluation of relations between ground-water withdrawals and water-level declines in the area.

ACKNOWLEDGMENTS

The investigation was facilitated by the assistance of many persons. The excellent cooperation of the water district officials and personnel made possible the collection of many important data that otherwise would not have been available. Valuable assistance and information concerning the district's water-supply facilities were furnished by the firm of Clark & Groff Engineers, Inc., and data pertaining to the district's wells and pumping equipment were supplied by the Stettler Supply Co.

The United Growers, Inc., permitted the use of a deep well for observation purposes. Data from concurrent studies were provided by Messrs. J. E. Sceva and W. S. Bartholomew. Water samples were analyzed for bacteriological quality by the Public Health Laboratory of the Oregon State Board of Health. Preliminary barometric data were furnished by the U.S. Department of Commerce office at Salem Airport. The friendly cooperation of all is gratefully acknowledged.

WELL-NUMBERING SYSTEM

Wells discussed in this report are designated by symbols that indicate their location according to the rectangular system of land division. In the symbol 8/3W–3M1, for example, the part preceding the hyphen indicates respectively the township and range (T. 8 S., R. 3 W.) south and west of the Willamette base line and meridian. Because most of the State lies south of the Willamette base line and east of the Willamette meridian, the letters indicating the directions south and east are omitted, but the letters "W" and "N" are included for wells lying

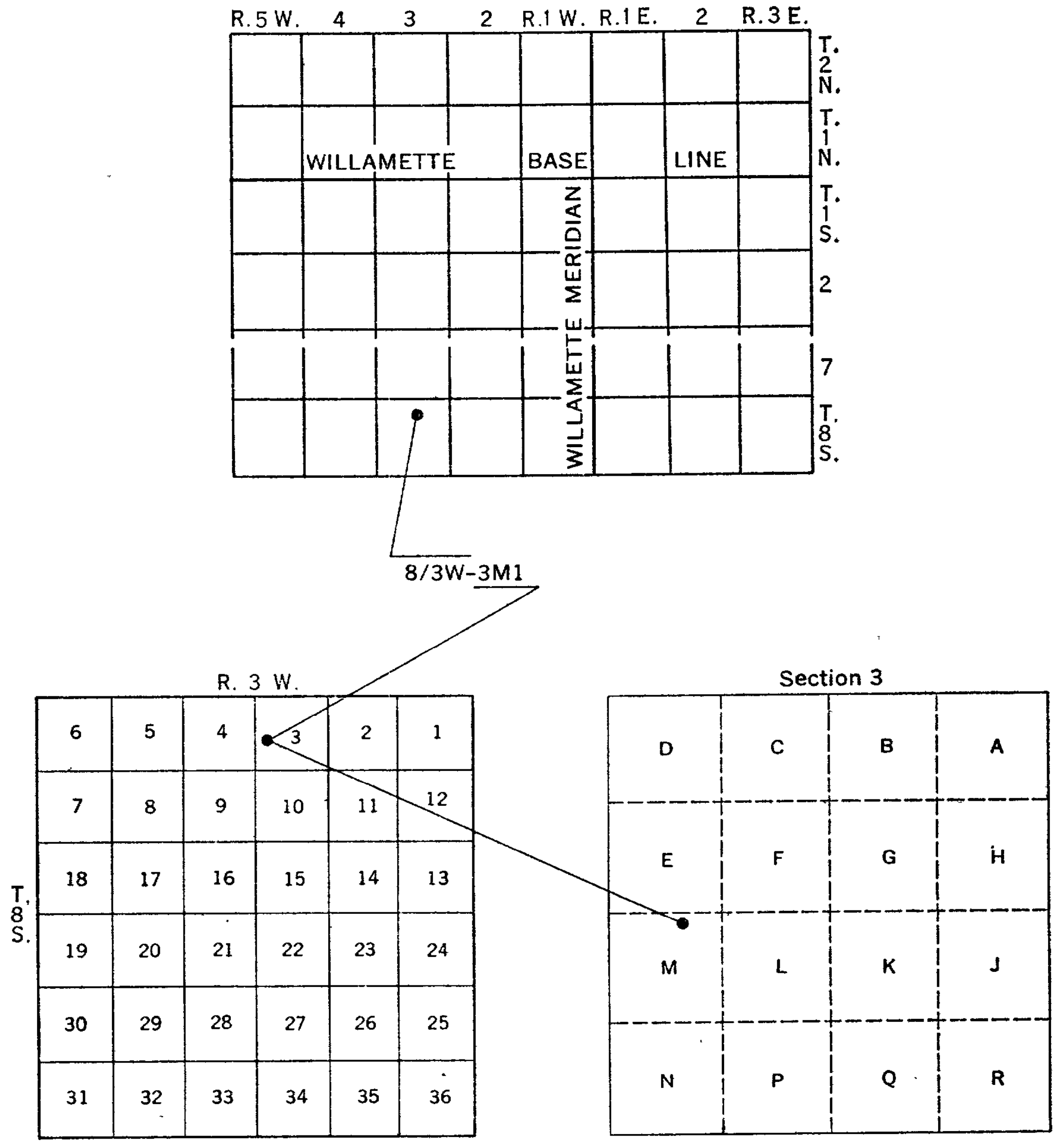

FIGURE 2.—Well-numbering system.

west of the meridian and north of the base line. The first number after the hyphen indicates the section (sec. 3), and the letter (M) indicates a 40-acre subdivision of the section as shown in figure 2. The final digit is the serial number of the well within that 40-acre tract. Thus, well 8/3W–3M1 is in the NW¼SW¼ sec. 3, T. 8 S., R. 3 W., and is the first well in the tract to be listed.

To relate the well numbers to the local designations for the wells, both the well number and the local designation (as Park well 2) are given in the first few references to each well.

THE HYDROLOGIC SYSTEM AND GEOLOGIC CONTROLS

Any successful artificial-recharge operation, especially one involving injection through wells, must function compatibly with the local hydrologic system, which in turn is controlled largely by the geologic conditions. Therefore, an understanding of the hydrologic system and its geologic framework is essential for adequate design, operation, and evaluation of subsurface-injection operations. In the Salem Heights area, the preexisting information on local conditions was not sufficiently detailed and thus was augmented by considerable field mapping and interpretation of well records during this study.

The part of the hydrologic system that is most pertinent to this study is the ground water in the basalt rock that caps the Salem Hills. Therefore, that rock unit and its function as a ground-water reservoir were major subjects of the present study.

CHARACTER AND EXTENT OF THE BASALT

The basalt that supplies water to the wells in the Salem Heights area is part of the Columbia River Group (Stayton Lavas of Thayer, 1939, p. 7). This basalt forms the Salem Hills as well as other similar uplands to the northeast, east, and southeast; it also extends northward beneath the alluvial plain on which the city of Salem is built. The basalt of this area consists of remnants of a huge series of lava outpourings that extended through much of the Pacific Northwest during Miocene time. Most of the basalt rock that resulted from this volcanic activity is east of the Cascade Range, and Thayer (1939, p. 8) considered the remnants in this area to be near the western margin of that vast lava sequence.

The basalt of the Salem Hills consists of several individual flow layers, each probably thicker than 10 feet and some probably thicker than 100 feet locally. The total thickness of basalt in the Salem Hills varies considerably—the basalt is probably more than 500 feet thick in the vicinity of Prospect Hill (pl. 1) and less than 100 feet thick where it is penetrated in some wells in Salem.

The basalt is underlain by marine sedimentary rocks of Oligocene age. These rocks consist mostly of tuffaceous siltstone and sandstone, which are readily recognized by their characteristic tan, gray, and buff colors. The marine sedimentary rocks in this area are mostly saturated, but they are poorly permeable.

Prior to the outpouring of the basalt, the upper surface of the marine sedimentary rocks had been eroded into a rolling landscape which had a local relief of more than 400 feet. The earliest lava flows occupied the lowest parts of the prebasalt surface. Each later extrusion of lava inundated the previous flow layer as well as a higher and more extensive part of the prebasalt landscape. The differences in the thickness and the number of flow layers of the basalt in the area are due mostly to the irregularities in the prebasalt land surface.

The basalt flow layers, which were virtually flat before cooling, have been tilted along with underlying rocks by regional earth movements, and locally have been involved in landslides and slumping. The basalt now has a general northeast dip of 10° or less. Section *A–A′* (pl. 1) shows the relationship of the basalt and the underlying marine sedimentary rocks along a line approximating the general direction of dip.

The in-place basalt that forms the Salem Hills terminates on the west and south at steep slopes and bluffs overlooking an extensive band of landslide debris made up of the basalt and the underlying marine sedimentary rocks. On the northwest side of the Salem Hills, an area of about 2½ square miles that includes Croisan Ridge and Plank Hill apparently has slumped and perhaps tilted to the northwest along a curved fault of relatively small displacement (pl. 1). The structural conditions in the Salem Hills—the cuestalike abrupt western and southern sides and gentle northeast dip to the lower plain—are duplicated in the Eola Hills across the Willamette River to the northwest.

The basalt in individual flows is generally dense and impermeable. Near the upper and lower surfaces of flows, however, the basalt commonly is rubbly, scoriaceous, and vesicular. These rubbly zones associated with the contacts between individual flow layers are termed "interflow zones" (Price, 1967b, p. 18; Hampton, 1970). Columnar jointing, characteristic of the basalt in many other areas, is not common nor well developed in the Salem Heights area. In the bluffs along the west side of the area, where the best exposures of the basalt occur, joints are not abundant, and those observed tend to delineate irregularly shaped massive blocks rather than prismatic columns.

The upper part of the basalt has been deeply weathered and moderately eroded since its extrusion. It has weathered to a reddish-brown saprolitic soil, commonly as thick as several tens of feet. In many places the soil contains isloated less-weathered remnants of cobble and boulder size which can still be identified as basalt rock. The deep residual soil has contributed to the rounded, rolling configuration into which the upland has been eroded.

OCCURRENCE OF WATER IN THE BASALT

Water occurs in the basalt chiefly in cooling-contraction joints within the flow layers and in the porous interflow zones. Although the few exposures of relatively unweathered basalt in the area exhibit some jointing, these and other water-bearing features of the local basalt sequence must be assessed largely from the data on local wells (including those listed in tables 2 and 3) and from hydrologic studies in other areas underlain by basalt of the Columbia River Group (Foxworthy, 1962, p. 14, 15, 38; Hart and Newcomb, 1965, p. 17, 33–35; Price, 1967b, p. 18).

Because most of the observed joints appear to be tightly closed, they probably can transmit water vertically across flow layers only at a very slow rate even where hydraulic gradients are steep. Near the margins of the in-place basalt, where incipient slumping is common, joints may be more abundant and open. Such joint systems, if they occur, probably constitute the main conduits through which water moves from the soil zone into the deeper aquifers; however, no direct evidence of such open joints was found during this study.

Appreciable flow of ground water to wells and springs is principally through permeable zones at and near the contacts between certain flow layers. In the basalt of this region, such permeable interflow zones are characteristically discontinuous and of small extent, and their occurrence in any location or at any horizon generally is unpredictable. Therefore, the chances that a well will tap a productive water-bearing zone improve as more flow layers are penetrated.

Water-bearing interflow zones in the basalt are permeable because of one or a combination of several geologic processes. The upper part of most flows commonly contains abundant gas bubbles, or vesicles, which give the rock a spongy appearance and relatively great porosity. Even in flows where the vesicles are poorly connected, the vesicular zones may contribute to the permeability of the rock, especially if they were subjected to fracturing by earth movements or to weathering before inundation by a subsequent flow. Permeability also may result from the incomplete closure of one flow over surface irregularities in the flow below it. In some flow layers the permeability may be principally in the lower part of the flow, above the contact. For example, highly permeable zones may exist as a result of lava flowing into a pond or marsh. The steam that resulted from such occurrences altered and tended to inflate the lava and thus contributed to the permeability of the resultant rock materials.

Ground water exists in the basalt under three conditions of occurrence—unconfined, confined, and perched. Although the present study is concerned mainly with the artificial recharge of a deep confined aquifer, the movement to and character of water in that confined aquifer is inseparably related to the shallow unconfined and the perched ground water.

The upper surface of the unconfined ground water (the water table) in the area is indicated by the static (nonpumping) water levels in the shallowest wells. Below the shallowest saturated zone, however, ground water at most places in the basalt is confined to some degree by less permeable rock layers. All the wells of moderate to large yield in the area are believed to tap one or more confined zones in the basalt—that is, permeable interflow zones that are confined by the dense central parts of the enclosing flow layers, or basal zones in the basalt sequence that are confined between the underlying marine sedimentary rocks and overlying denser basalt. The imaginary surface that coincides with levels to which confined water rises in these wells is called the potentiometric surface. (See fig. 4.)

Ground water that was truly perched—underlain by an unsaturated zone—probably did not exist in the Salem Heights area under natural (predevelopment) conditions. However, perching probably has developed locally where some permeable interflow zones, in the upper part of the basalt sequence but below the water table, have become unsaturated by continuous drainage to deeper zones through the unlined parts of the deeper wells. (See fig. 3.)

THE MAIN CONFINED AQUIFER

The large-yield wells in the area, including the recharge well and most of the observation wells used in this study, are believed to tap the same highly permeable confined zone, of irregular thickness and limited extent, in the lower part of the basalt sequence. This zone yields as much as 1,000 gpm of water to wells that have specific capacities as great as 11 gpm per foot or greater. (See table 2.) In contrast, most of the wells in this area that tap basalt zones that are not part of the main confined aquifer produce less than 200 gpm and have specific capacities of about 2 gpm per foot or less.

This main confined aquifer lies mostly below the 100-foot altitude, and it has been found only in coincidence with the basinlike depression in the marine sedimentary rocks in secs. 9 and 10, T. 8 S., R. 3 W. Drillers' logs of wells indicate that the main aquifer may range in thickness from less than 10 feet to more than 100 feet. At most of those wells, the most productive zone in the main aquifer reportedly is not at the base of the basalt sequence but is about 20 to more than 50 feet above it.

Terms such as "carbonated," "eroded," "calcified," and "cinders" were used by the drillers to describe materials in the main aquifer. (See table 3.) Fragments of what probably are some of the materials so described were pumped from the recharge well during this study and were examined by the writer. The material was a tan to orange mixture of mostly sand-size particles (medium to coarse) composed of obsidian (volcanic glass), various secondary siliceous minerals, and palagonite (hydrated volcanic glass). Such an assemblage of minerals commonly results where molten lava of the Columbia River Group poured out into water or onto a surface that was marshy or very wet. The fact that it contains these palagonitic materials and that its known occurrence coincides with the central part of a preexisting land-surface depression—within and near the 100-foot contour on that depression (pl. 1)—strongly suggests that the main aquifer was formed by lava flowing into a marsh or pond that occupied that ancient basin. If so, there probably are not sizable extensions of the main aquifer beyond the area already defined by the wells that tap it.

GROUND-WATER RECHARGE AND MOVEMENT

Natural recharge to the basalt aquifers of the Salem Hills is derived entirely from local precipitation. A major part of the precipitation infiltrates the soil and weathered rock, but only a small fraction of this water percolates downward to the zone of saturation. Under natural (predevelopment) conditions, however, this small fraction was enough to maintain the water table at shallow depths beneath much of the Salem Hills.

From the upper part of the zone of saturation the ground water moves slowly downward to zones of progressively lower hydraulic head and toward wells or points of natural discharge. The water in the basalt follows a tortuous path, in some places flowing along the interflow zones and in others migrating across the flow layers. The water discharges naturally from the basalt, mainly through seeps and minor springs along the bluffs and canyons where the rock is exposed and by seepage into the other rock materials, notably the adjacent alluvial and lacustrine deposits and the landslide debris.

Under natural conditions, ground water did not discharge directly from the main aquifer. Water entered the unusually permeable aquifer by seepage from adjacent and overlying parts of the basalt sequence and left it, without much change in hydraulic head, by slow percolation northward, mostly through the basalt that dips beneath the city of Salem. The main route of the northward-moving ground water probably was through basalt that occupies an apparent northeast-trending trough or channel in the prebasalt land surface. (See pl. 1.) This channel-filling basalt doubtless is more permeable to laterally moving ground water than are the underlying marine sedimentary rocks; however it is less permeable than the main confined aquifer and therefore may be incapable of yielding large quantities of water to wells. This fact is suggested by the low yield of well 8/3W–3M1 (Madrona well), which completely penetrates the basalt in or near the middle part of the prebasalt channel (tables 2, 3). In other words, no evidence is available to indicate that a highly permeable extension of the main confined aquifer exists along this channel in the underlying rock.

Even though the main aquifer and the basalt that extends northward from it reach depths below the Willamette River and locally below sea level, the hydraulic heads of the confined water in the basalt are sufficient to raise the water to the level of the Willamette, which is the hydraulic "base level" for the region. Under natural (predevelopment) conditions, most of the ground-water discharge from the lower parts of the basalt in the area was by seepage to the alluvial and lacustrine deposits and landslide debris. In turn, water was discharged from those deposits by seepage to the Willamette River and the smaller streams, by evapotranspiration, and by spring flow.

During this study and for at least a few years preceding it, discharge of water from the main aquifer was principally by withdrawal from wells. The artesian heads have been lowered as much as several tens of feet by pumping (table 2), and as a result, subsurface migration of ground water from the main aquifer has greatly diminished.

Under present conditions, the main aquifer doubtless receives some inflowing ground water from higher parts of the basalt beyond the limited area of the main aquifer. The full extent of the recharge area for the main aquifer is not known, but the area probably includes some of the higher hills to the south and west. It is hydraulically impossible, however, that any natural recharge for the main aquifer is originating beyond the Salem Hills, and the actual recharge area probably constitutes only a fraction of that upland region.

In general, the hydraulic heads in the basalt sequence decrease progressively from the upper to the lower zones. This vertical difference in heads was large even under predevolpment conditions; it reportedly was about 235 feet between the water table and the main confined aquifer at well 8/3W–9K1 (United Growers, Inc.) in 1947. This head difference provides the energy of position to move the ground water downward across the poorly permeable layers in the basalt sequence. The natural vertical head difference has been increased by the lowering of heads in the main aquifer by pumping. Consequently, the downward percolation of shallower ground water into the main aquifer has been substantially increased during recent years.

The development of ground-water supplies from the main confined aquifer has also increased the recharge to that aquifer in another way. The slow natural percolation of ground water from higher to lower parts of the basalt sequence has been short circuited locally by unlined wells. Most of the drilled wells that tap the basalt have casings that extend only through the upper part of the hole—commonly into the first solid layer of rock. As shown by figure 3, the higher water-bearing zones in the unlined interval can drain, more or

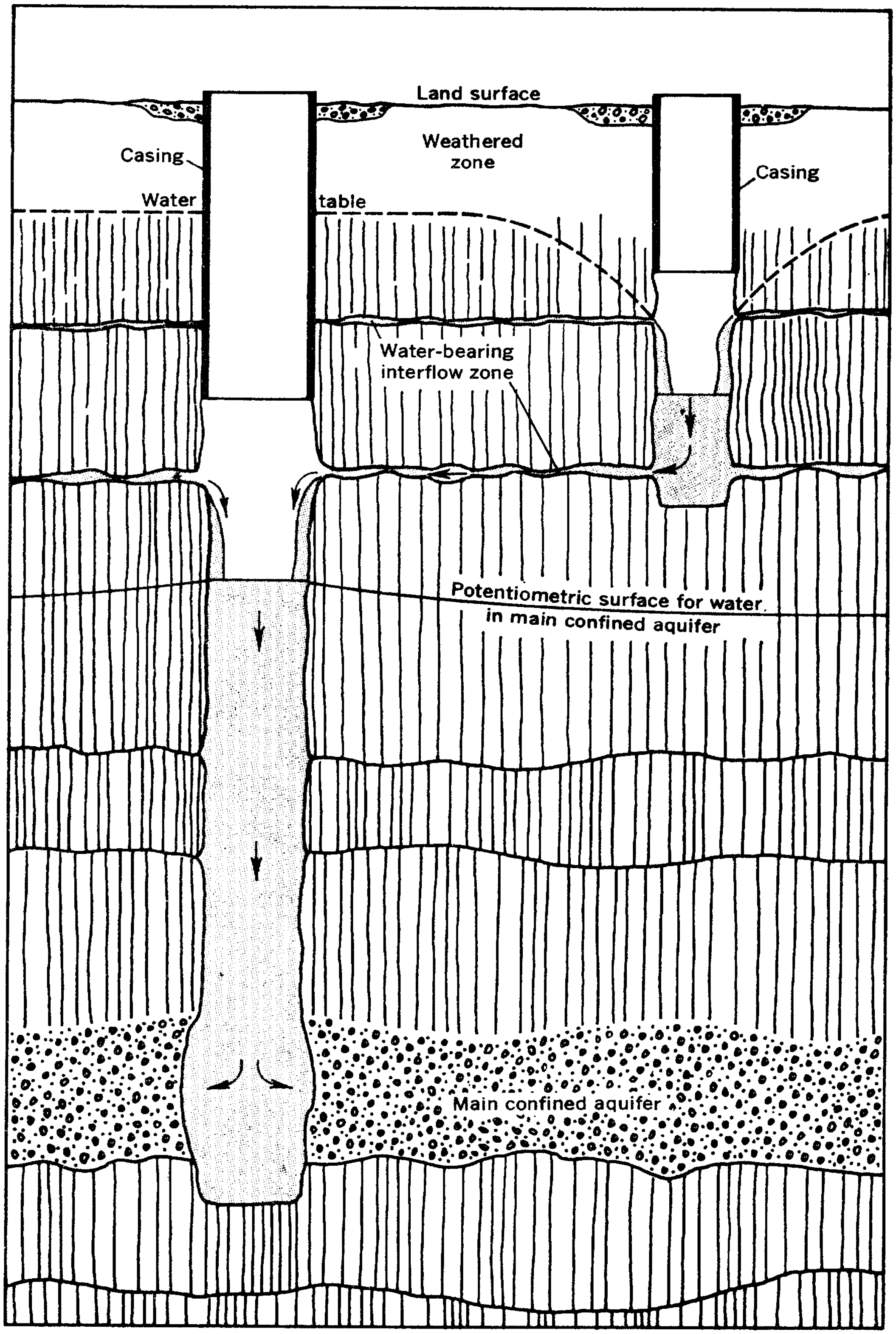

FIGURE 3.—Diagrammatic section showing downward migration of ground water through unlined parts of wells that tap the basalt.

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less continuously, through the well bore to the zone having the lowest hydraulic head. In the wells that tap the main aquifer, wherin heads are generally lower than those in any other parts of the local basalt sequence, the main aquifer can receive recharge for any of the higher water-bearing zones that are not blocked off by the casing. Not only does this drainage through the unlined wells augment the recharge to the main aquifer, it also has important water-quality implications. It constitutes a route to the main aquifer for oxygen-rich water, discussed subsequently, and for any contamination that may be present in the higher water-bearing zones.

WATER-LEVEL FLUCTUATIONS

Despite the aforementioned increased recharge to the main aquifer and the decrease in natural discharge related to the increased pumping, the water levels in wells that tap the main confined aquifer have been declining progressively from year to year during at least the last few years prior to this study. Water-level data furnished by the Oregon State Engineer indicate that the level in well 8/3W–3M1 (Madrona well) declined about 17 feet from May 1958 to May 1961. Actually, the progressive decline of artesian heads in the main aquifer probably began at least as early as 1954, when well 8/3W–10K2 (Part well 1) began operation. In well 8/3W–9K1 (cannery well), which was the first well in the area to tap the main aquifer, the level declined about 38 feet, from about 275 feet to 313.4 feet below land surface, in the period February 1947 to February 1962 (table 2). Virtually all that decline was caused by the increased pumping from the main aquifer during that period.

Fluctuations of hydraulic head in the main confined aquifer, which probably amounted to only a few feet per year under natural conditions, have been increased substantially by pumping. Water levels in wells that tap the main confined aquifer usually are highest in spring, when the greatest recharge from precipitation and snowmelt can be expected. The levels usually are lowest in late summer or early autumn, when there is little precipitation and withdrawals from wells are greatest. However, water-level measurements made during February–November 1962 indicated that, during that year, the highest water levels in several of the wells occurred during the last half of July or the first part of August (pl. 2). Measurements for this study had not yet begun during the period of lowest ground-water levels in 1961, which occurred in August of that year.

Short-term fluctuations, resulting from different causes, are superimposed on the seasonal fluctuations of the potentiometric surface. Included are fluctuations in response to changes in atmospheric pressure, water-level declines caused by intermittent pumping of wells tapping the main aquifer, and rises in water level resulting from the artificial-recharge tests. Water levels in each of the more productive wells tapping the main aquifer generally respond fairly rapidly to pumping by other wells, even those a considerable distance away. Such rapid and widespread response to changing pressure is characteristic of confined aquifers.

SOURCE AND TREATMENT OF THE RECHARGE WATER

The water that was experimentally injected during this study was chlorinated and fluoridated water from the Salem municipal-supply system. The water is from infiltration galleries (lateral wells) on Stayton Island in the North Santiam River about 17 miles southeast of Salem and just upstream from the town of Stayton (not shown on pl. 1). Upon withdrawal from the galleries, the water is treated with chlorine gas and then flows about 10 miles through a pipeline to Franzen Reservoir in the village of Turner (not shown), where it is again chlorinated to maintain a chlorine residual of about 0.2 mg/l (milligrams per liter). From Turner a pipeline carries the water the remaining distance to Salem.

The water from the Stayton Island galleries constitutes the entire normal supply for the city of Salem. The capacity of the system is 75 mgd (million gallons per day), and the city's water right on the North Santiam River allows an average withdrawal of 85.3 mgd. The average output of the Salem system in 1962, including the water supplied to the Salem Heights Water District, was about 8 mgd.

The recharge water was taken from the city's main pipeline where it passes near a booster-pump station that was built by the Salem Heights Water District near the center of sec. 2, T. 8 S., R. 3 W. (pl. 1). At the pumping station, fluoride was added to produce a fluoride-ion concentration of about 1–2 mg/l in the water, and the water was then pumped toward a storage reservoir for the Salem Heights distribution system.

The recharge water was diverted from the pipeline between the booster-pump station and the local storage reservoir where the pipeline passed near the wellhouse of the recharge well (fig. 5). The water withdrawn from the recharge well was also pumped through the same pipeline to the reservoir. None of the recharge water passed through the local reservoir before it was injected.

METHODS OF STUDY AND EQUIPMENT

In general, the methods and procedures used in this study were patterned closely after those used in the previous artificial-recharge study at The Dalles (Foxworthy and Bryant, 1967, p. 13). Because the depleted aquifer is a deep confined zone whose recharge area is not known precisely, the only method of artificial recharge that was considered was direct injection of water through wells that tap the aquifer. The injection was accomplished during three separate test periods, each longer than the preceding, with the recharge water being injected through the existing turbine pump in one of the water district's supply wells. Each period of recharge was followed by at least one pumping test to determine the effect of the recharge on the capacity of the well and on the character of the water in the vicinity of the well. Water levels in observation wells in the area were measured during the recharge and pumping tests and periodically throughout the period of investigation. As in The Dalles study, the actual recharge experiments were preceded by preliminary tests and evaluation (a) to determine prerecharge conditions, (b) to foresee possible problems, and (c) to guide the injection experiments.

PRELIMINARY EVALUATION

The preliminary evaluation included consideration of several physical and engineering factors that have constituted actual or potential problems in previous subsurface-injection operations:

1. Adequacy of the supply of recharge water.
2. Permeability and storage capacity of the aquifer.
3. Clogging of the well and the aquifer materials.
4. Temperature changes of the water in the recharged aquifer.
5. Recovery of the injected water from subsurface storage.
6. Suitability of the recovered water for the intended use.

Some of these factors can be evaluated by methods now available; others are more difficult to determine. Even under the most favorable conditions, and where the chemical and physical characteristics of both the native ground water and the recharge water are known reasonably well, it is often impossible to predict reliably how a subsurface-injection operation will function on a sustained basis. The risk to expensive wells and equipment is lessened if long-term subsurface injection is approached through a series of progressive, carefully evaluated injection experiments.

The preliminary evaluation necessitated the collection and interpretation of additional data as well as review of data then existing. Selected preliminary data are presented with the experimental data in the tables of this report.

The chemical and sanitary quality of the water from the Salem municipal system were evaluated in consultation with Mr. L. B. Laird, former district chemist of the Geological Survey for thePacific Northwest, and Mr. E. J. Weathersbee, district sanitary engineer for the Oregon State Board of Health. (See section on "Clogging.")

ADEQUACY OF SUPPLY OF RECHARGE WATER

Water in excess of demands within the city of Salem is available from the city system except during periods of maintenance and brief periods of peak demand which usually occur during July or August. Both the capacity of the system and the water right to withdraw the water from the Stayton Island galleries greatly exceed the average needs of the city (p. F15). Therefore, supplies of high-quality water were ample in quantity for the planned recharge experiments and also, apparently, are ample for a long-term program of artificial recharge through wells, if such a program is judged to be feasible.

STORAGE CAPACITY AND PERMEABILITY OF THE AQUIFER

The thickness and extent of the aquifer materials, as determined from the records of wells (tables 2 and 33), and the major fluctuations of water levels (p. F14) indicate that the aquifer is capable of storing and releasing large volumes of ground water—certainly more water than would be involved in any foreseeable program of subsurface injection.

One of the most fundamental requirements for successful subsurface injection is that the aquifer be at least moderately permeable and preferably highly permeable. Not only does the aquifer permeability largely govern the energy required to inject water at a given rate, but it also controls the resultant buildup of hydraulic head and the spread of the recharge water outward from the injection well. The large yields of the wells that tap the main aquifer of the Salem Heights area indicate that the aquifer is at least moderately permeable. During the preliminary phases of this investigation, additional information was collected on the water-yielding character of the main aquifer in the vicinity of the recharge well.

On February 28, 1962, a prerecharge pumping and recovery test was made at the recharge well. The main purposes of this test were to check the response of the observation wells (p. F25) and to obtain prerecharge data on the yield characteristics of the recharge well and the adjacent aquifer for later comparison with similar data from tests following each of the recharge experiments (table 1). In addition, water samples obtained during the prerecharge test were used to determine the chemical, physical, and bacteriological character of the native ground water.

During the prerecharge pumping test, an average of 669 gpm was pumped from the well for 5 hours; the resultant drawdown of water level in the well was 46.8 feet (table 1). The specific capacity was 14.3 gpm per foot of drawdown. If it is assumed that specific capacity during injection through a well (injection rate divided by water-level buildup) is approximately equivalent to the specific capacity during pumping, the above value suggests that a water-level buildup of 1 foot in the well would move water into the aquifer at a rate of about 14 gpm. Thus, about 7 feet of water-level buildup in the well might be expected for an injection rate of 100 gpm, 14 feet of buildup for 200 gpm, and so on. Because the static (nondischarging) water level in the recharge well was about 236 feet below land surface at the time of the prerecharge tests, the well obviously could readily accommodate the planned injection of several hundred gallons per minute unless severe clogging occurred.

WATER TEMPERATURES

Subsurface injection of recharge water having a temperature markedly different from that of the native ground water can cause enough temperature change to limit the usefulness of the receiving ground water for some purposes (Brashears, 1941, p. 817; Brown, 1963, p. 19). Also, the temperature of the water in the aquifer determines the viscosity of the water, which in turn affects the apparent permeability (Sniegocki, 1960, p. 1490). At The Dalles, the specific capacity of the recharge well was temporarily reduced substantially following injection with water as much as 13°C (23°F) colder than the native ground water (p. F4). Therefore, in the Salem Heights study, the possible effects of any difference in the temperatures of the recharge water and the native ground water were evaluated on October 30, 1961, beginning with a comparison of the temperatures of the Salem public-supply water and the recharge-well water (table 4). The temperature difference was only 1°C (2°F) at that time. Because of that small difference and because any large temperature fluctuations in the city water at the Franzen Reservoir were expected to be moderated by the subsequent long transmission underground, the possible effects of temperature differences during the recharge experiments were expected to be small.

CLOGGING

Clogging of the recharge well or the adjacent aquifer materials is almost universally experienced to some degree in recharge through wells. In various subsurface-injection operations, including previous operations in Oregon and Washington (Price and others, 1965), clogging has been attributed to (a) sediment in the recharge water, (b) chemical reactions in the aquifer, (c) growth of organisms in the well or aquifer, and (d) air in the recharge water.

SEDIMENT

Preliminary samples of the Salem public-supply water, collected after the water passed through the booster-pump station and the pipeline adjacent to the recharge well, contained sediment in concentrations of 0.3 mg/l (table 5, samples for March 2). This low concentration was reported to be typical of the sediment content of the Salem public-supply water. Therefore, the sediment in the recharge water was not expected to be a significant clogging agent, even during extended periods of injection, unless the sediment content were to increase markedly.

CHEMICAL REACTIONS

Chemical reactions of a recharge water with a native ground water or with aquifer materials can cause clogging by ion exchange or the formation of chemical precipitates.

Undesirable chemical precipitation may be caused by the different chemical and physical characteristics of the waters mixed during subsurface injection. Even small changes in pH, Eh (reduction-oxidation potential), temperature, pressure, and concentration of some dissolved gases (such as 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 water containing ferrous iron is mixed with oxygen-rich water or is exposed to 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 this chemical precipitation is substantial, aquifer permeabilities may be greatly reduced.

The preliminary analyses of the Salem city water and the native ground water showed that concentrations of the chemical constituents that might enter into precipitating reactions were very low and that the two waters were very similar in their chemical and physical characteristics. Therefore, the danger of incurring unwanted precipitation was considered to be slight. Also, the continued high performance of the recharge well, in spite of long-term inflow of oxygen-rich water during nonpumping periods (p. F14), was considered to be proof that oxidizing reactions within the aquifer would not be troublesome.

Of many chemical reactions that might occur when an outside water is added to an aquifer environment, one that has been considered to be a potential cause of clogging is an ion-exchange reaction involving certain clay minerals (Sniegocki, 1963a, p. 12). Some clays, when exposed to a water with a high sodium-ion content, tend to release calcium or other ions and adsorb the sodium ions. As a result, the clays swell in volume or are dispersed in a semicolloidal suspension. Either result may decrease the permeability of an aquifer and, therefore, must be evaluated as a potential problem in subsurface injection. Calcium clays of the montmorillonite group are most likely to react in this way.

Neither the swelling nor the dispersal of clay, however, was considered to be a potential problem in the Salem Heights tests. The palagonite zones in the principal aquifer may contain some calcium clays (from alteration of plagioclase in the original volcanic glass) which might tend to swell or to disperse upon reaction with sodium ions. Neither the sodium in the recharge water nor the clay, however, was thought to be abundant enough to cause a noticeable effect on the aquifer permeability.

ORGANISMS

Certain organisms can be troublesome if they are injected underground. Pathogenic bacteria, of course, can render a ground-water body unfit as a source of drinking water. However, other organisms, the so-called nuisance bacteria, although not disease producing in humans, are also undesirable because they may color the water, cause unpleasant taste and odor, or produce slimes or other products that clog recharge wells and aquifers.

The Salem city water supply is chlorinated at both the withdrawal works and the Franzen Reservoir and so is considered to be effectively free of pathogenic organisms when it reaches the booster-pump station. Before the injection tests, the existence of nuisance bacteria was tested in a series of samples of (a) chlorinated water from the booster-pump station and (b) water pumped from the injection well. The samples were tested by the public health laboratory of the Oregon State Board of Health. Laboratory cultures of the samples failed to reveal any nuisance bacteria in the waters. Therefore, no problem of water deterioration nor of clogging of the aquifer or recharge well was anticipated as a result of nuisance bacteria.

AIR

Air that is introduced into a well during artificial recharge not only can cause clogging by producing the chemical reactions mentioned previously, but also can reduce the permeability of the aquifer by physically blocking the pore spaces with bubbles. Even a relatively small volume of air in an aquifer may markedly reduce its permeability by blocking the main routes of water movement through the aquifer (Orlob and Radhakrishna, 1958, p. 648). Such bubbles normally are tightly held to the aquifer materials by molecular attraction, and high velocities are required to displace them. Furthermore, air occurring as bubbles in an aquifer can dissolve only very slowly, even in water that has a very low dissolved-air content.

Air bubbles have been cited as a cause of significant clogging during previous experimental injection into basalt aquifers and, therefore, were considered to be a potential problem in the present study. During the tests at Walla Walla, Wash., air bubbles probably were formed by air coming out of solution and also by entrainment of air as the recharge water was allowed to cascade down inside the pump column (Price, 1961, p. 17). In the tests at The Dalles, Oreg., the water was injected under pressures sufficient to prevent air entrainment, but troublesome bubbles apparently formed from air coming out of solution at points of sharp pressure drop within the piping system that carried the recharge water to the well (Foxworthy and Bryant, 1967, p. 19, 36).

Air dissolved in water in a state of equilibrium is released from solution if the water becomes warmer or if the pressure on the water decreases. Conversely, if the water becomes cooler or if the pressure increases, the air will remain in solution, and even more air can be dissolved. Pressure changes affect the solubility of air more than do changes in temperature. The Salem Heights tests were designed to have the water coming to the well under pressure considerably greater than atmospheric pressure to prevent air entrainment and to help keep any dissolved air or other gases in solution in the recharge water. Because of this design and because no large difference was expected between the temperatures of the recharge water and of the native ground water, it was assumed that any dissolved gas would tend to remain in solution once it reached the aquifer and came under the relatively great hydrostatic pressures there. Piping to the well was designed to minimize the expected problem of air coming out of solution in the pipeline carrying the recharge water. (See section on "Recharge well and accessory equipment.") Also, to facilitate the the removal of the air bubbles that were anticipated, or of any other clogging agents, periodic pumping and redevelopment of the recharge well were planned.

RECOVERY OF INJECTED WATER

One of the most important questions in assessing the feasibility of any subsurface-storage operation is, "Will enough of the injected water be economically recoverable?" Obviously, an adequate quantitative answer to this question could only be obtained by experiment. A preliminary qualitative evaluation, however, was needed to guide the experiments.

As a mound of pressure builds up around a recharge well during injection, water moves outward from the well through the aquifer. The water continues to move away from the well not only during

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injection but also after injection has stopped—at least until an equilibrium is reestablished with the regional hydraulic gradient. The volume of injected water that is recoverable, therefore, depends not only on the volume injected and rate of injection but also on the preinjection conditions in the aquifer and the elapsed time between injection and withdrawal. The aquifer boundaries, as well as the relative locations of the points of injection and withdrawal, also are important considerations. Commonly, some of the injected water moves away from the recharge well far enough that it cannot be pumped back through that well and can only be recovered from wells located downgradient.

Preliminary water-level data for the deep wells, as well as water-level measurements made at the time of the prerecharge pumping test (February 28–29, 1962), were furnished by the office of the Oregon State Engineer. Those data showed that the potentiometric surface of the main confined aquifer contained a major closed cone of depression extending mostly west of the recharge well and centered around well 9J1 (fig. 4). The water-level data, plus the evidence of the limited extent of the main aquifer, strongly indicated that the water injected during the experiments would not escape rapidly from the aquifer. Furthermore, the data indicated that although the recharge water might pass beyond the area of influence of the recharge well, it would

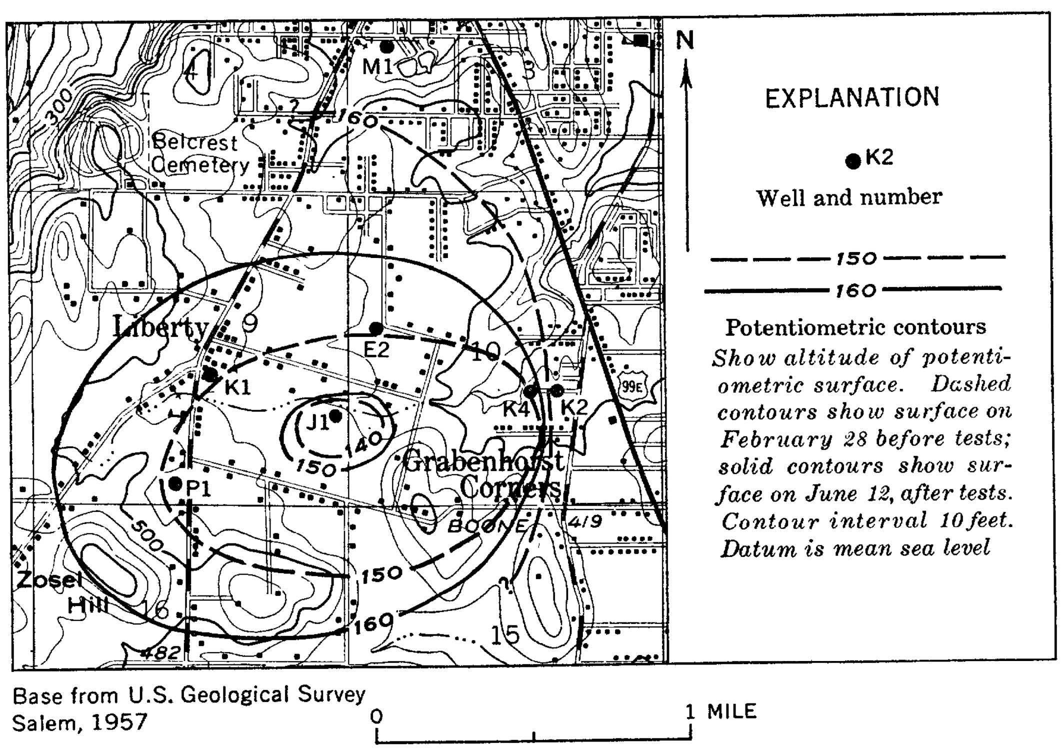

FIGURE 4.—Contours on the potentiometric surface of the main confined aquifer before and after artificial-recharge tests, 1962.

likely move in the general direction of the water district's well 9J1, which would be capable of intercepting most of the water.

Information furnished to the Salem Heights Water District by Clark & Groff Engineers, Inc., indicated that the surplus water could be obtained from the city of Salem at a very favorable price during the 8-month period October–May. The price was such that, barring major difficulties with the injection operation, the surplus water could be injected through the water district's wells and subsequently pumped back from the ground-water reservoir at about half the cost for direct use of Salem water during June–September. Therefore, a subsurface-storage operaiton appeared to be economically beneficial if more than about 50 percent of the injected water could be recovered later.

SUITABILITY OF RECOVERED WATER

As both the recharge water and the native ground water were suitable for public-water supplies, they were expected to be suitable for that purpose after mixing. The preliminary analyses of samples collected on October 30, 1961 (table 4), indicated that both waters surpassed the chemical-quality standards for drinking water recommended by the U.S. Public Health Service (1962). Furthermore, no major temperature change and no deterioration of taste, color, odor, or bacteriological quality of the waters were foreseen as a result of the subsurface injection and later withdrawal.

RECHARGE WELL AND ACCESSORY EQUIPMENT

Well 8/3W–10K4 (Park well 2) was the recharge well and the pumped well in tests made during this investigation. It is at the end of Woodmansee Court (not marked on map), near the center of sec. 10, T. 8 S., R. 3 W. It discharges into an 8-inch supply line which carries the water to a surface reservoir at a level about 208 feet higher than the pump. Prior to the connection with the Salem system, well 10K4 was one of the main sources of supply for the Salem Heights district.

As shown in table 2, well 10K4 is 345 feet deep and is cased to a depth of 107 feet with 12-inch-diameter steel casing. The principal water-bearing zone is broken basalt and basaltic cinders in a zone 256–295 feet below land surface. The well is equipped with an 8-stage turbine pump driven by a 100-horsepower electric motor. Both the turbine bowls and pump column have nominal diameters of 8 inches. The intake to the pump is through a cone-shaped wire strainer and an 8-inch-diameter tailpipe, the opening of which was at a depth of 318 feet below land surface during this study. Discharge from the pump is through a 6-inch pipe which, 23 feet north of the well, joins the main

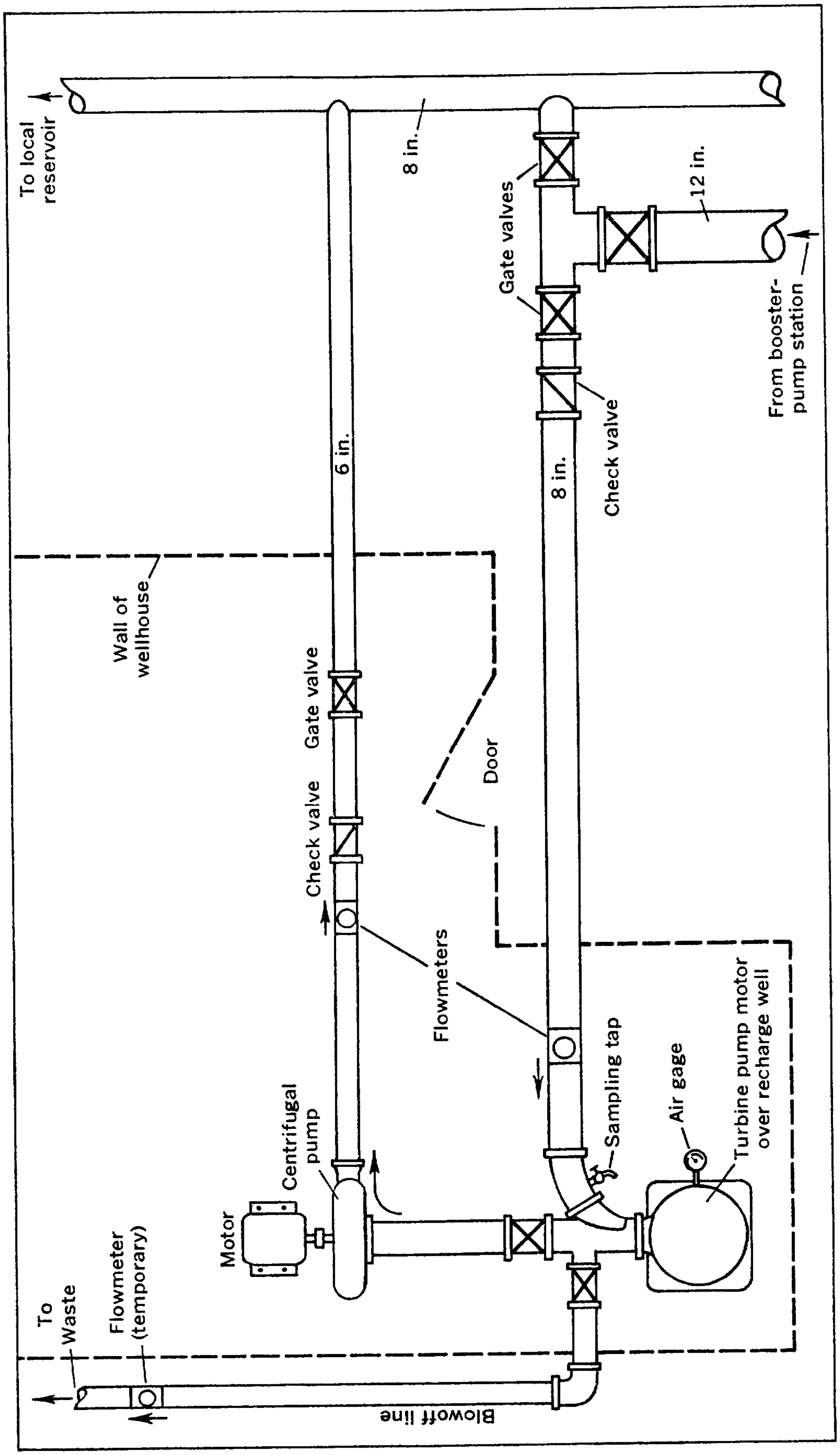

FIGURE 5.—Schematic diagram of piping and equipment at the recharge well, 8/3W-10K4 (top view).

8-inch pipeline to the aforementioned surface reservoir. The discharge line is equipped with a totalizing watermeter, located in a pit within the wellhouse. Figure 5 is a schematic diagram of the equipment and water system in the vicinity of well 10K4.

A 12-inch pipeline, bringing Salem water from the booster-pump station, was extended to the well site and connected with the existing 8-inch line to the surface reservoir. The existing piping to the wellhouse was then modified to add a separate system of piping, valves, and a flowmeter to carry the recharge water to the well (fig. 5).

Although points of sharp increase in flow velocity and resultant pressure reduction could not be avoided throughout, large-radius bends were used in the short line from the 12-inch pipeline to the well whereever possible. This minimized the pressure drops and, therefore, the opportunity for dissolved air in the recharge water to come out of solution.

Modification of the piping at the well included the extension of an existing blowoff line from the pump to a nearby depression in the land surface. The blowoff line was used to discharge turbid water at the beginning of pumping tests and during redevolpment of the injection well. At such times, a portable flowmeter was attached at the end of the blowoff line to measure the discharge through that line.

OBSERVATION WELLS

During the tests, water levels were measured not only in the recharge well (10K4) but also in six other water-district wells (3H1, 3M1, 9J1, 9P1, 10E2, and 10K2) and in a well owned by United Growers (9K1). The descriptive records and drillers' logs of these wells are presented in tables 2 and 3, respectively. Water-level measurements from the wells are shown graphically on plate 2.

Levels in wells 10E2 and 3H1 were measured with a steel tape; wells 3M1 and 9P1 had semiautomatic water-level recorders installed. Measurements from those four wells are considered to be generally accurate to plus or minus 0.02 foot. Levels in wells 9J1, 9K1, and 10K4 were measured by existing air lines and pressure gages because equipment or conditions at those wells did not allow direct measurement. The air gages at those wells probably have a sensitivity no greater than about 0.1 foot of water. Well 10K2 was measured with an electrical sounding line, under very difficult conditions, and measurements in that well probably are accurate to within 0.5 foot. Wells 9J1, 10E2, and 10K2 were the most useful in assessing the effects of the artificial recharge.

Well 9J1 (Arlene well) is about 3,200 feet west-southwest of the recharge well and was about at the center of the cone of depression in the potentiometric surface of the main confined aquifer (fig. 4). It is 475 feet deep, is unlined by casing below the 82-foot depth, and penetrates the thickest part of the main confined aquifer (at least 93 ft thick). It reportedly has yielded as much as 600 gpm, and was one of the water district's most productive wells. It showed a clear response to the injection and pumping at well 10K4 and also responded to the pumping at well 9K1 (pl. 2).

Well 10E2 (Fir Dell well) is about 2,700 feet west-northwest of the injection well and 2,000 feet north of well 9J1. It was drilled deeper than any other water district well (617 ft) and has the deepest casing (448 ft). Because its casing extended below its range of water levels (table 2), well 10E2 did not have the usual cascading water inside the well bore (fig. 3); therefore, its water levels could be measured by the wetted-tape method and probably are more accurate than those obtained from the other deep observation wells. The fluctuations of water level in the well responded quickly and smoothly to recharge and pumping at well 10K4.

The other observation wells responded little or not at all to the recharge and pumping tests at well 10K4, but provided useful background and control data. Well 3H1 (Butler well) does not tap the main confined aquifer and is north of the area of influence of the recharge and pumping tests. It was measured during the latter part of recharge test 2, during subsequent tests, and periodically for several months thereafter, to obtain data on the regional water-level fluctuations in the basalt aquifers not affected by the concentrated pumping.

Well 3M1 (Madrona well) apparently is in hydraulic connection with the northernmost part of the main confined aquifer. It reflects the general trends of fluctuations in that aquifer and has been used as a long-term observation well by the Oregon State Engineer. However, it showed very little response to the recharge or pumping tests made during this study. This well probably taps less permeable basalt which filled the prebasalt channel previously described (p. 11).

Well 9P1 (Steinke well), which may be near the western edge of the main confined aquifer, also was useful for an indication of general seasonal trends of heads in the main confined aquifer. This well responded only slightly to the first two recharge tests and associated pumping tests; any possible response to later tests was completely masked by pumping at well 9K1.

Well 10K2 (Park well 1) is 483 feet east of the injection well. It apparently penetrates only about 7 feet of permeable basalt in the main aquifer zone, which may have thinned in the interval between the two wells. Even though the wells are closely spaced, the hydraulic connection between them is not so good as was expected. The static water levels in well 10K2 consistently stood 15–25 feet higher in altitude than the levels in well 10K4, and had a net rise much greater than that in any of the other wells measured during this study (pl. 2). Furthermore, while the level in well 10K4 rose as much as 126 feet during recharge test 3, the maximum rise in well 10K2 was only about 5 feet—about twice as much as the rise in well 10E2, which is about 2,200 feet farther from the recharge well. The comparatively poor correlation of water levels in these wells may be due partly to incomplete penetration of the basalt by well 10K2. (See table 3.) Also, this observation well probably is near the edge of the main confined aquifer, where the aquifer is likely to be thinner and less permeable than it is elsewhere.

However, these discrepancies between nearby wells probably are mainly results of very erratic texture, hydraulic interconnection, and permeability of the aquifer materials. (See p. F10.)

Well 9K1, owned by United Growers, Inc., is about 5,300 feet west of the recharge well. It was the only observation well that was pumped during the period of this study—for testing and rehabilitation during April and May 1962 and for industrial use during July–October of that year (pl. 2). Pumping of well 9K1 during recharge test 3 caused measurable drawdown in well 9J1 (Arlene well) and 9P1 (Steinke well). Like well 10E2 (Fir Dell well), 9K1 has casing that extends to a considerable depth (431 ft) although the casing is perforated below the 290-foot depth.

EXPERIMENTAL PROCEDURES AND INSTRUMENTS

From March 20, to May 15, 1962, water from the Salem municipal water system was injected into well 10K4 (Park well 2) during three tests of about 1-, 5-, and 15-day durations. The first two recharge tests were made by personnel of the Geological Survey, and the last test was made largely by personnel of Salem Heights Water District. Each recharge test was followed by at least one pumping test, and the last two recharge tests were also followed by periods of surging to clean the injection well.

During the pumping tests and the first and second recharge tests, water samples were collected to determine chemical quality, dissolved oxygen, sediment content, and bacteriological quality. During the third period of recharge, samples were collected for partial chemical analysis and determination of sediment content only. During the pumping tests and the first recharge test, part of the test water was continuously passed through a conductivity cell that was connected to a conductivity bridge; this arrangement allowed instantaneous measurement of the temperature and specific conductance[1] of the water flowing into or out of the well.

[1] A measure of the capacity of the water to conduct electrical current, specific conductane varies with the concentration and degree of ionization of dissolved constitutents and also with water temperature. It is expressed herein as micromhos per centimeter at 25°C.

The flow of water was measured during pumping by a totalizing flowmeter on the discharge line and during recharge by a combination totalizing flowmeter and rate meter on the injection line. The flow rates were determined periodically by comparison of the readings of the totalizing meters during timed intervals. The flow of recharge water to the well was adjusted slightly by means of the gate valves (fig. 5). Line-pressure readings at a gage on the injection line were made periodically as a rough check against variations in flow rate.

During all the tests a recording microbarograph was operated in the wellhouse to provide data for possible use in the determination of and adjustment for any significant water-level fluctuations caused by changes in barometric pressure.

Laboratory analyses of water samples, except those for bacteriological determinations, were made in the Geological Survey Laboratory at Portland, Oreg. The analyses were made by standard methods (Rainwater and Thatcher, 1960). The results of most of the complete and partial chemical analyses are presented in table 4, and sediment determinations are shown in table 5.

To accomplish the surging that was required to clean the well after the second and third recharge tests, the pump on the well was started and allowed to run for 45 seconds and then was shut off for 45 seconds. This procedure allowed a column of water to be lifted and about 800 gallons or more of water, carrying sediment and rock particles, to be discharged through the blowoff line (fig. 5); when the pump stopped, several hundred gallons of water surged down the pump column into the well and adjacent aquifer materials.

RECHARGE AND PUMPING TESTS

In the following discussion of the individual experiments, the recharge tests are designated by the numbers 1, 2, and 3. The pumping tests that followed each period of recharge are assigned corresponding numbers, with letter designations added for tests involving more than one pumping period. Significant data from the tests, as well as from the prerecharge pumping tests, are summarized in table 1.

During the first recharge test (March 20–21, 1962), about 24 hours in duration, 1.05 million gallons of water was injected at an average rate of 725 gpm. The maximum buildup of water level in the well was 70.6 feet above the prerecharge static level. Thus, the specific capacity (rate of injection divided by water-level buildup) was about 10.3 gpm per foot. Within about 2 hours after injection was stopped, the level in the well declined to a position 1 foot above the prerecharge static level, and pumping test 1 was begun.

Although the recharge water contained much more sediment than was expected (table 5), virtually all the sediment injected during recharge test 1 probably was removed from the well during the early part of the subsequent pumping test 1. During the pumping test, the sediment content 1½ minutes after pumping began was about 1,300 mg/l; but after 1½ hours the average sediment content was only 2 mg/l (table 5), and the concentration remained at a few milligrams per liter for the duration of the test. The specific capacity near the end of pumping tests 1 was about 14.7 gpm per foot, or about 0.4 gpm per foot greater than the specific capacity of the well during the prerecharge pumping test.

During recharge test 2, the injection was continued for 5 days (April 16–21); a total of 5.82 million gallons was injected into the well at an average rate of 821 gpm. The maximum buildup of water level in the well during this recharge test was about 107 feet, at which time the specific (recharge) capacity was about 7.7 gpm per foot, or roughly half the specific capacity during pumping test 1. After recharge test 2, the water level in the recharge well did not decline to its pretest static level but remained 2 feet above the pretest level 3 days after injection was stopped.

As in recharge test 1, the water injected during recharge test 2 carried significant amounts of sediment into the well, especially during the first 8 hours, and periodically thereafter. However, most of the sediment was removed during pumping test 2. Relatively large amounts of sediment were contained in the water pumped during most of that test (table 5).

Pumping test 2 was begun 3 days after recharge test 2 ended. Pumping was continued for 5 hours, during which a total of 185,000 gallons of water was withdrawn at an average rate of 617 gpm. The maximum drawdown was 47.9 feet, at which time the specific capacity was 12.9 gpm per foot, or about 88 percent of the specific capacity measured during pumping test 1. However, the specific capacity was improved, even beyond the prerecharge value of 14.3 gpm per foot, by surging the well for about 40 minutes. Data derived from pumping test 2A, which followed that surging, indicate a specific capacity of 17.8 gpm per foot near the end of this 2-hour test.

Recharge test 3 lasted nearly 15 days (May 1–15). During that period about 17.6 million gallons of water was injected at an average rate of 834 gpm. The maximum buildup of water level in the well, measured near the end of the recharge period, was about 126 feet, and the specific capacity then was about 6.6 gpm per foot. Except for the first part of this recharge test, the sediment content of the injection water was much less than that during recharge tests 1 and 2 (table 5). Furthermore, virtually all the injected sediment was removed from the well during about the first 1½ hours of pumping test 3. Recharge test 3 was stopped because of a sharply declining trend in the specific capacity of the recharge well (fig. 6) that was suspected of indicating serious

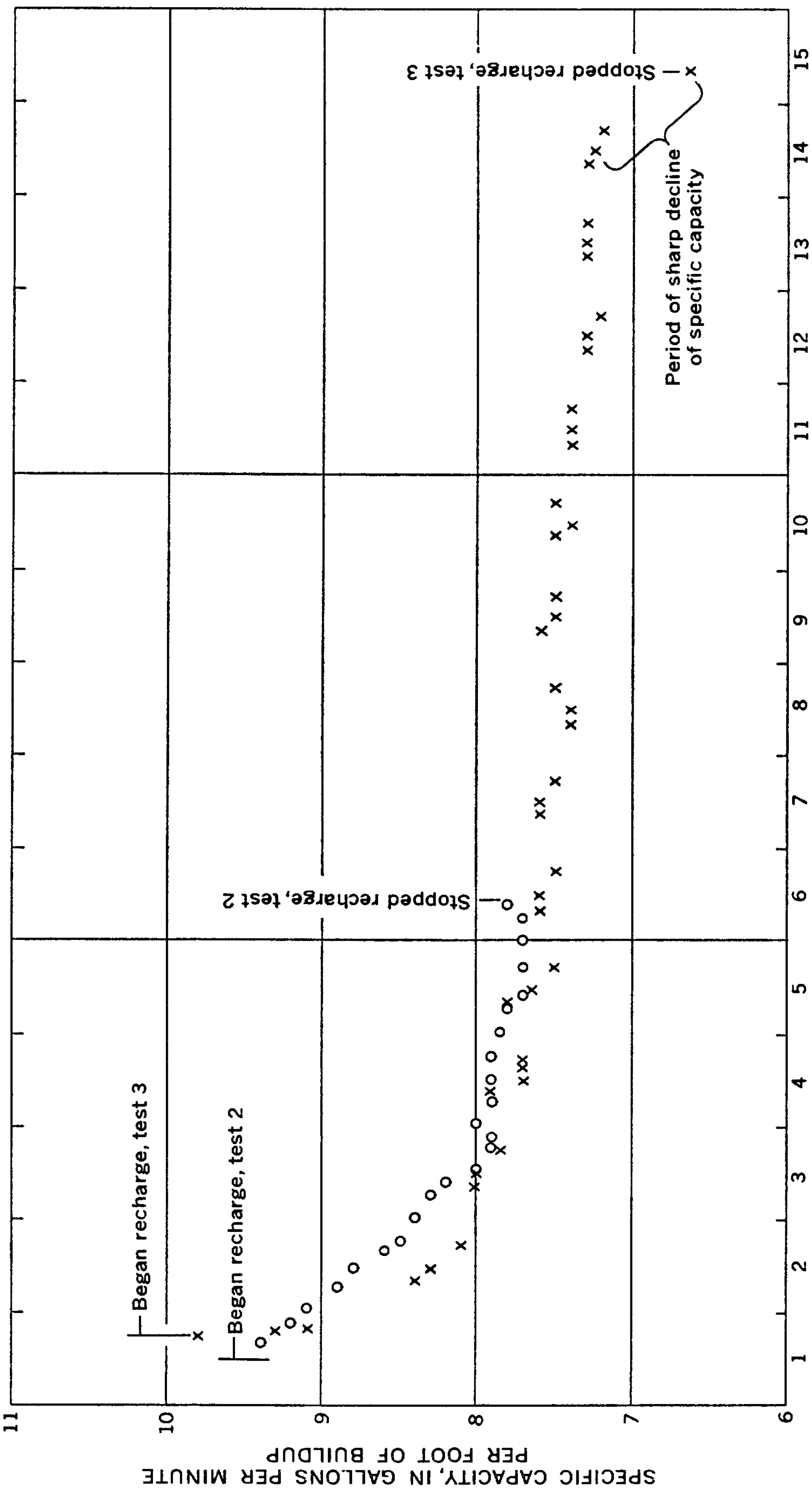

FIGURE 6.—Changes in specific capacity of the injection well during recharge tests 2 and 3.

clogging of the aquifer materials in the vicinity of the well. Fortunately, however, the specific capacity of the well was restored to above the prerecharge value during pumping test 3 and the surging that preceded pumping test 3A (table 1).

SIGNIFICANCE OF THE TESTS

Results of the tests indicate that conditions are generally favorable for additional injection of Salem municipal-supply water through recharge well 10K4. However, some possible effects of long-term injection, such as changes in chemical conditions within the aquifer, may not be determined from information available from the tests. The ultimate success of long-term artificial recharge in this area might rest largely upon cumulative effects that may not become apparent until recharge has continued for long periods, or upon economic or other considerations that are beyond the scope of this study.

CHANGES IN THE PHYSICAL AND CHEMICAL CHARACTER OF THE GROUND WATER

The injection tests caused only minor changes in the character of the water in the main confined aquifer near the well, largely because of the close similarities of the recharge water and the native ground water. Temperature and sediment content of water pumped from the recharge well before and after the tests were virtually the same; even the dissolved-oxygen content was similar, owing to the unusually high concentration of oxygen in the ground water near the well before recharging was begun. (See p. F14.)

The small magnitude of overall changes in chemical character of the ground water is readily seen from a comparison of the analyses in table 4, especially the analyses for samples collected during the prerecharge pumping test (February 28, 1962) and pumping test 3 (May 21, 1962). Comparison of those analyses shows that, although the total dissolved solids and the specific conductance of the ground water were reduced somewhat as a result of mixing with the less mineralized recharge water, no large changes occurred in the concentrations of most of the individual constituents tested. Concentrations of silica and sodium, however, were reduced to about one-half and bicarbonate to about two-thirds of their respective prerecharge values. These reductions probably were due to dilution rather than to precipitation or any other chemical reactions. Therefore, the reductions may be considered as temporary changes that diminished and disappeared entirely as the recharge water was gradually assimlated into the native ground water.

Perhaps the most interesting chemical change was the progressive increase in sulfate concentration, which coincided exactly with decreasing bicarbonate concentration that occurred during pumping test 3. No reason could be determined for this apparent shift in anion concentrations, and the test data are too few to indicate how much further the shift would have progressed if the pumping test had continued.

The anomalously high iron concentration (2.0 mg/l) in the first sample collected during pumping test 1 (table 4) probably does not reflect the normal dissolved-iron content of the water. Instead, it probably represents iron that was dissolved from basalt particles in the turbid sample by acid that was added to the sample before the analysis.

EFFECTS ON THE AQUIFER AND THE RECHARGE WELL

BUILDUP OF WATER LEVELS

The injection of water into recharge well 10K4 caused a measurable rise in level in most of the observation wells, especially during the longer periods of recharge (pl. 2). Exceptions were at well 3H1 (Butler well), which taps a zone not connected with the main confined aquifer, and at wells 3M1 (Madrona well) and 9P1 (Steinke well), both of which tap marginal parts of the main aquifer at points distant from the recharge well. At the latter two wells, any rises in response to the recharge tests apparently were masked by barometric fluctuations. The injection of water during recharge test 3 caused a maximum buildup of 126 feet in the level in the recharge well. This caused a rise of as much as 4.5 feet in well 10K2 (Park well 1) and more than 2 feet each in wells 9J1 (Arlene well) and 10E2 (Fir Dell well). The recharge tests apparently also caused some rise, probably only about 1 foot, in well 9K1 (United Growers well); however, the response in the latter well during recharge tests 2 and 3 was largely masked by drawdown because of testing and pumping of the well itself.

The water-level changes resulting from the tests were superimposed on a general seasonal rising trend in levels, largely reflecting natural recharge and recovery from record low pumping levels in the previous year (1961). Therefore, the persistence of water-level rises that resulted from the artificial recharge could not be clearly defined. However, at least in the wells nearest and most responsive to the recharge well, and especially in well 10K2, there was a marked steepening of the rising trend, or a series of steplike rises, that clearly coincided with the period of artificial-recharge tests (pl. 2).

The highest 1962 levels in wells that tap the main confined aquifer occurred in July of that year (pl. 2). It is not known how much lower, if any, the high levels would have been without the artificial recharge.

The combined effects of the regional water-level rise and the buildup of levels from the artificial-recharge tests resulted in a significant decrease in the depth of the preexisting cone of depression in the potentiometric surface of the main aquifer (fig. 4).

SPECIFIC CAPACITY

Changes in specific capacity of the recharge well were used during all the tests to detect clogging and to judge the degree of clogging and the effectiveness of redevelopment of the well. The changes from test to test are summarized in table 1, and the specific-capacity values during recharge tests 2 and 3 are plotted in figure 6.

The rapid decline of specific capacity for the early parts of the recharge tests is a normal result of the buildup of a potentiometric mound in the vicinity of the recharge well (fig. 6). The most significant elements of figure 6 relate to the values plotted for recharge test 3 after the rapid decline in the first 2 days of the test. Even though differences between consecutive values (caused by variations in recharge rate, barometric pressure, and pumping of well 9K1) sometimes exceeded 0.1 gpm per foot, the trend of changes in specific capacity became more gentle and predictable after that early rapid decline. The greatest change, a decline of 0.6 gpm per foot, occurred during a 15½-hour interval from the 14th to the 15th days. This decline together with lesser declines shown by two preceding values, clearly constituted a deviation from the previous trend of the specific-capacity values. This sharp decline of specific capacity is reflected in the hydrograph of the recharge well (pl. 2), which shows a sharp buildup of the level in the well during the last day of recharge test 3.

A sudden decreasing trend in specific capacity of a recharge well (shown by a sudden increasing rate of buildup of water level) may result from progressive clogging of the well or aquifer, or from other causes such as (1) a regional rise of water levels; (2) a reflection of the recharge mound reaching a hydraulic boundary, such as a termination of the aquifer or a decrease in its transmissibility; or (3) a decreased effective aquifer permeability owing to a decrease in temperature, and resultant greater viscosity, of the water being injected. Of these possible causes, a regional rise in water levels was discounted inasmuch as levels in none of the observation wells were rising nearly so rapidly. Also, because the temperature of the recharge water injected during this test was virtually the same as that of native ground water, a significant increase in viscosity was not possible.[2] Therefore, the conclusion reached was that, although the rapid buildup of level and decrease in specific capacity might be partly due to a hydraulic-boundary effect, a termination of the test was warranted by the possibility that serious clogging was occurring.

The specific-capacity data in table 1 include unadjusted values based on the average rate of pumping or recharge during each test period and the maximum drawdown or buildup of levels measured near the end of that period. These specific-capacity values have not been corrected for possible short-term barometric effects nor for differences in duration of some of the pumping tests; however, any inaccuracies that may result from those influences or from the minor changes in water temperature are believed to be too small to affect the general relationships shown by the table.

As the table shows, recharge tests 2 and 3 caused some reduction in specific capacity; that is, the pumping specific capacity following each of these periods of recharge was somewhat less than it was before the corresponding recharge period. The reductions are believed to have been caused by partial clogging of the aquifer in the vicinity of the recharge well. The differences in specific capacities before and after recharge indicate the relative degree of clogging. For example, recharge test 2, which caused an apparent reduction in specific capacity of only about 1.8 gpm per foot (about 13 percent of the prerecharge value), produced relatively little clogging. Recharge test 3, however, caused a decrease of 4.8 gpm per foot (34 percent of the prerecharge value) below the specific-capacity value for pumping test 2A, a decrease which suggests that a significant degree of clogging had occurred.

Clogging probably was caused chiefly by sediment carried in the recharge water, and to a lesser extent by bubbles of air coming out of solution. Other possible clogging agents, such as chemical precipitates, probably were not significant in these tests. Appreciable amounts of sediment, consisting mostly of sand- and silt-size particles, were carried into the well during each of the tests. The sediment content of the recharge water was greatest during recharge test 2 (table 5), when as much as 2,000 pounds of sediment may have been deposited in the well and adjacent aquifer materials. Several hundred pounds of sediment may also have been deposited during the longer recharge test 3, even though only a few of the daily samples of recharge water contained measurable amounts of sediment (table 5). Unfortunately,

[2] In the range of temperatures of the water pumped from the recharge well during this study (9°–12°C, or 49°–53°F), a temperature change of 1°C causes a corresponding change in specific capacity of about 3 percent.

the recharge well could not be sounded without removing the pump; so the accumulation and removal of sediment in the bottom of the well could not be measured directly.

The dissolved-oxygen analyses (table 4) show that the recharge water contained abundant dissolved air; however, bubbles of air doubtless were much less important as clogging agents in these tests than they had been in the earlier artificial-recharge tests at The Dalles, Oreg. Relatively little of the air that was dissolved in the Salem Heights recharge water came out of solution during the injection process, as shown by the dissolved-oxygen concentrations in table 4. In that table, comparisons of the concentrations for the injected water with those for the water subsequently pumped from the recharge well show a reduction of dissolved oxygen of generally less than 20 percent during these injection tests. In contrast, most of the dissolved oxygen in The Dalles recharge water came out of solution before the water was pumped back to land surface (Foxworthy and Bryant, 1967, p. 50–53).

The sediment and other clogging agents were adequately removed by combined pumping and surging of the recharge well, but not by pumping alone. As shown by table 1, the surging operations after recharge tests 2 and 3 increased the specific capacity of the well to values greater than those of the prerecharge specific capacity. This result apparently occurred because the well had not been systematically cleaned and redeveloped since being placed in service by the water district.

RECOVERY OF THE INJECTED WATER

During the pumping tests and surging operations that followed the three periods of recharge, about 770,000 gallons of water was removed from the recharge well. This figure is partly estimated, because the operation of the flowmeter on the blowoff line was erratic during surging. This volume was only about 3 percent of the total injected; therefore, the net volume of water added to the ground-water reservoir was 97 percent of that injected.

The water pumped from the well following the three periods of recharge consisted of mixtures of recharge water and native ground water in varying proportions. The specific-conductance determinations (table 4) indicate that roughly two-thirds of the water withdrawn during the pumping tests was recharge water.

METHODS AND TECHNIQUES FOR FURTHER ARTIFICIAL RECHARGE

The results of the completed study emphasize the importance of certain considerations in the design of a system for additional subsurface injection into the main confined aquifer and suggest techniques that would enhance the chances of success in any subsequent artificial-recharge operations of this type.

No serious problems are foreseen in connection with additional artificial recharge through well 10K4. The recharge operations in this study caused no apparent permanent decrease in the water-yielding capacity of the well or aquifer materials and no apparent damage to pumping equipment. However, the use of another well designed especially for injection probably would allow the greatest flexibility of artificial-recharge operations and the establishment of conditions even more favorable for long-term injection with the least risk to the water district's pumping capacity.

In any system for subsurface injection, every effort should be made to prevent the entrainment of air in the recharge water; also, unless the recharge water is degassed before injection, any dissolved air should be largely kept in solution. To this end, the recharge water should be injected into the well in a full pipe under pressure, rather than being allowed to enter by free fall. During the recharge tests previously described, the desired condition was achieved by injecting water through the impellers of the pump; the restriction of flow through the impellers was sufficient to create a large pressure drop there. If future injection is undertaken through a separate pipe or pipes, adequate back pressure can be produced by means of a fixed nozzle (reducer) or a controllable valve at the lower end of the injection pipe. Where possible, sharp pressure reductions should be prevented at other points in the system conveying the recharge water.

A recharge well should be considered as a piece of equipment that will require periodic maintenance and repair, as by cleaning or redevelopment; it eventually may need to be replaced. The information obtained from the relatively short recharge experiments that were conducted during this study is insufficient for a realistic prediction of the useful life of a recharge well that taps the main confined aquifer in the Salem Heights area. Even under the best conditions, however, flushing by pumping or surging might be needed sufficiently often that a permanently installed pump would be desirable in such a recharge well. Also, the large quantities of sediment that entered the well during the injection tests indicate the need for a sediment trap in the piping.

The value of adequate background information for planning and designing artificial recharge through wells and for interpreting and alleviating problems that may arise cannot be overemphasized. An adequate foundation should include an understanding of the ground-water system to be recharged and how the system functions; knowledge of the chemical, physical, and biotic character of the recharge water and the native ground water; and recognition of the possible problems and risks associated with the artificial recharge.

Similarly, various operational data are needed for evaluating results of artificial recharge through wells. Minimum data include records of the volumes and rates of water injection and withdrawal; the types, degree, and times of water treatment; fluctuations of ground-water levels; and periodic determinations of the physical and chemical character of the recharge and ground waters.

Hydraulic-boundary effects can be a significant factor in the rate of water-level buildup during subsurface injection, especially where the aquifer is limited in extent. In the present study, for example, an impermeable boundary reflecting the lateral termination of the main confined aquifer might have contributed to a rapid buildup of levels such as were measured at the recharge well near the end of recharge test 3. Although the data obtained during this study were not adequate for a full evaluation of boundary effects, such evaluation might be possible using the best obtainable data from a longer pumping test (Ferris and others, 1962, p. 144–166). A permeable-boundary effect, which would tend to diminish the rate of buildup of water levels, also is possible where a permeable zone, normally unsaturated, becomes inundated during injection operations. Boundary effects should be suspected when anomolous patterns of water-level buildup occur after about the same elapsed time during different periods of injection in a well.

For most subsurface-injection operations wherein the rate of injection cannot be closely regulated, a record of the specific capacity of the recharge well probably is the simplest and most useful single tool for detecting and evaluating clogging and for determining the effectiveness of redevelopment of the well. However, if water levels in the injection well fluctuate widely in response to extraneous influences, such as barometric-pressure changes or pumping from nearby wells, the specific-capacity data may not provide adequate warning of incipient clogging. In such cases, a separate observation well adjacent to the injection well and tapping the injection zone may be needed to provide reference water levels. Levels in the two wells would respond almost identically to boundary affects and extraneous causes and, for a specific injection rate, the hydraulic gradient between the two wells would be virtually constant. However, any clogging of the injection well or of the aquifer material between it and the nearby observation well would result in a steepening of the hydraulic gradient and an increase in the difference between water levels in the two walls.

CONCLUSIONS

The major conclusions resulting from this study are:

1. A total of 24.5 million gallons of water from the Salem municpal water system was injected into the Salem Heights Water District's Park well 2 during a total recharge time of 20.5 days, at an average rate of 830 gpm (1.2 million gpd). If water could be injected into the well at that rate for a total of 200 days during October to May, when excess water is normally available in the Salem system, the total recharge would amount to 240 million gallons, or about 740 acre-feet per year. This would be equivalent to the volume stored by a 160-acre surface reservoir (half a mile on a side) 4.6 feet in depth.
2. The character of the main confined aquifer and the availability and quality of the Salem city water are unusually favorable for artificial recharge of the aquifer by injection through wells. Because the aquifer materials are highly permeable, they allow a rapid spread of pressure effects from the recharge well and are less subject to clogging than materials having smaller pore spaces. The city water mixed with the native ground water without apparent undesirable chemical effects or deterioration of the bacteriological purity of the ground water.
3. The buildup of head in the main confined aquifer during periods of artificial recharge dissipated rapidly, and any residual buildup was masked by a seasonal rising trend in ground-water levels within a few days after the recharge had stopped. The rapid dissipation of the recharge mound indicates that the benefit from subsurface injection would be spread through the area of the main aquifer rather than being restricted to the vicinity of the recharge well. Moreover, the benefit would persist because the geologic and hydrologic conditions in the Salem Heights area preclude the escape of the injected water from the area by subsurface migration. The recharge tests contributed to the reduction of a preexisting cone of depression in the potentiometric surface of the main aquifer. None of the tests, however, was long enough to indicate the amount of buildup of regional levels that might be achieved during long-term injection.

4. The artificial-recharge tests caused some decrease in the specific capacity of the recharge well. The principal cause of the decrease was a partial clogging of the aquifer materials in the vicinity of the well by (a) sediment carried in the recharge water and (b) probably by bubbles of air that came out of solution from the recharge water. Virtually all the injected sediment was removed by surging (intermittent pumping) with the existing pump, and the specific capacity was thereby restored to values greater than prerecharge specific capacity.
5. No serious problem can be foreseen in connection with additional subsurface injection using the Salem city water, either through the pump and piping into Park well 2 or through a different well and injection system of adequate design. To minimize plugging, the quantity of sediment entering the injection well should be greatly reduced. The data and experience gained during this study, however, do not completely eliminate the possibility that some unforeseen problem may arise during longer periods of recharge.
6. Adequate background information and operational data are essential for effective planning, operation, and evaluation of artificial recharge through wells. The necessary foundation includes (a) an understanding of the ground-water system to be recharged and know it functions; (b) a knowledge of the chemical, physical, and biotic character of the recharge water and the native ground water; and (c) a recognition of possible problems and risks associated with the artificial recharge. The minimum operational data include records of the volumes and rates of water injected and withdrawn; the type, degree, and time of water treatment; fluctuations of ground-water levels; and periodic determination of the character of the recharge and ground waters. Changes in specific capacity of the injection well provide a generally effective warning of incipient clogging and an adequate basis for evaluating redevelopment of the well.

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TABLES 1–5

TABLE 1.—*Summary of recharge and pumping tests, well 8/3W-10K4*

Test designation	Began		Ended		Approximate duration	Quantity of water injected (i) or pumped (p) (thousands of gallons)	Average rate (gpm)	Maximum buildup (+) or drawdown (−) of water level (ft)	Specific capacity, measured (gpm per ft)	Water temperature	
	Date 1962	Time	Date 1962	Time						°C	°F
Precharge pumping test	Feb. 28	3:30 p.m.	Feb. 28	8:30 p.m.	5 hr	201 (p)	669	46.8(−)	14.3	11–11.6	52 –53
Recharge test 1	Mar. 20	8:20 a.m.	Mar. 21	8:30 a.m.	24 hr	1,051 (i)	725	70.6(+)	10.3	8.6– 8.8	47.5–48
Pumping test 1	Mar. 21	11:59 a.m.	Mar. 21	4:59 p.m.	5 hr	175 (p)	583	39.7(−)	14.7	9.3–10	48.8–50
Recharge test 2	Apr. 16	11:40 a.m.	Apr. 21	9:40 a.m.	5 days	5,816 (i)	821	106.9(+)	7.7	9.3–10	48.8–50
Pumping test 2	Apr. 24	9:10 a.m.	Apr. 24	2:10 p.m.	5 hr	185 (p)	617	47.9(−)	12.9	10–10.5	50 –51
Pumping test 2A (after surging) [1]	May 1	2:25 p.m.	May 1	4:32 p.m.	2 hr	90 (p)	704	39.6(−)	17.8	----------	----------
Recharge test 3	May 1	5:00 p.m.	May 15	9:02 a.m.	15 days	17,608 (i)	834	126.0(+)	6.6	10.6–11.6	51.2–53
Pumping test 3	May 21	9:12 a.m.	May 21	2:14 p.m.	5 hr	205 (p)	679	52.3(−)	13.0	11.6	53
Pumping test 3A (after surging) [2]	May 21	4:13 p.m.	May 21	6:13 p.m.	2 hr	89 (p)	739	43.2(−)	17.1	----------	----------

Total amount injected .... million gallons .. 24.5
Total injection time .... days .. 20.5
Average injection rate .... million gallons per day .. 1.2
Total pumped from well during tests .... gallons .. 970,000

[1] About 9,000 gallons removed during 40± minutes of surging.

[2] About 20,000 gallons removed during 90± minutes of surging.

TABLE 2.—*Records of selected drilled*

Well No.: See text for description of well-numbering system.
Finish: Casing continuous, unperforated, and open at lower end, except as noted. Perforated in depth interval shown, in feet below land-surface datum.
Altitude: Altitude of land-surface datum at well, in feet above mean sea level, determined by spirit leveling.
Water level: Depth to water below land-surface datum, measured by air line and pressure gage, electric sounder, or steel tape.

Well	Owner's designation	Year completed	Depth of well (ft)	Diameter of well (in.)	Depth of casing (ft)	Finish	Water-bearing zone(s)	
							Depth to top (ft)	Thickness (ft)
8/3W- 3H1	Butler well 4	1954	296	8	81	Lower part uncased.	>178	
3M1	Madrona well 8	1958	350	12	97	do	248	60
9J1	Arlene well 7	1957	475	12	82	do	382	93
9K1	Cannery well (United Growers, Inc.).	1947	630	10	431	Perforated 290–426 ft, lower part uncased.	398	33
9P1	Steinke well 11	1959	450	12	100	Lower part uncased.	346	
10E2	Fir Dell well 9	1959	617	12–10	448	Perforated 350–380 ft, lower part uncased.		
10K2	Park well 1	1954	292	8	104	Lower part uncased.	285 187	7 2
10K4	Park well 2	1959	345	12	107	do	256	39
11N1	Hall well 12	1960	270	12	105	do	226	26

wells in the Salem Heights area

Type of pump: T, turbine; N, none.
Use: Ind, industrial, N, unused; Obs, observation of water-level fluctuations; PS, public supply.
Remarks: Temp, temperature of water in degrees Celsius (followed by temperature in degrees Fahrenheit within parentheses). Remarks on adequacy of supply were reported by owner or driller.

Water-bearing zone(s)—Continued: Character of material	Altitude (ft)	Water level: Feet below datum	Water level: Date	Type of pump and horsepower	Well performance: Yield (gpm)	Well performance: Drawdown (ft)	Use	Remarks
Basalt	316.2	29 148.8	6- -54 4-19-62	T, 25	225		PS	
do	352.7	177 199.0	2-20-58 2-28-62	N	50	97	Obs	Temp 11 (52). Drilled for public supply. Yield inadequate.
Basalt, shattered, vesicular.	429.3	243 281.1	3-30-57 2-27-62	T, 100	600	101	PS	Temp 13 (56).
Basalt, broken	465	275 313.4	2- -47 2-28-62	T, 100	400	59	Ind	
Basalt, vesicular	471.1	316 321	10-20-59 3-13-62	N	330	48	Obs	Future public-supply use.
Basalt	420.9	256 269.9	11-15-59 2-27-62	T, 40	230	59	PS	
Basalt, vesicular	385.6	192 221.7	8- -54 2-26-62	T, 50	1,000	5(?)	PS	
Basalt, broken, vesicular.	386	212 236.3	4- 9-59 2-23-62	T, 100	920	78	PS	Temp 12 (53). Injection well during recharge tests.
Basalt, vesicular	425	19.2 21.9	2- 4-60 4-19-62	N	91	136	N	Drilled for public supply; yield inadequate.

TABLE 3.—*Drillers' logs of wells*

[Drillers' designations are edited for consistency of presentation, but otherwise unchanged. Stratigraphic and parenthetical designations are by the writer. Depths are in feet below land surface at well]

Materials	*Thickness (ft)*	*Depth (ft)*
8/3W-3H1		
[Salem Heights Water Dist. (Butler well 4). Altitude 316.2 ft. Drilled by Duffield Bros., 1954]		
Soil and weathered Columbia River Group:		
Shale and boulders (weathered basalt)	29	29
Columbia River Group:		
Basalt, fractured	9	38
Basalt	73	111
Andesite	13	124
Basalt	7	131
Basalt, vesicular	12	143
Basalt; 7–8 gpm yield at 178-ft depth	35	178
Basalt	51	229
Andesite	14	243
Basalt, vesicular	50	293
Basalt	3	296
8/3W-3M1		
[Salem Heights Water Dist. (Madrona well 8). Altitude 352.7 ft. Drilled by Duffield Bros. 1958]		
Soil and weathered Columbia River Group:		
Soil, red	2	2
Bouldery formation	10	12
Columbia River Group:		
Basalt, gray and black	71	83
Basalt, with shale lenses	8	91
Basalt, hard, brown	15	106
Basalt, decomposed	6	112
Basalt, black and gray	117	229
Basalt, fractured	16	245
Basalt, gray, fractured from 248 to 264 ft	47	292
Basalt, black, vesicular	16	308
Marine sedimentary rocks:		
Clay, yellow to red	32	340
Shale and marine deposits, gray, hard	10	350

TABLE 3.—*Drillers' logs of wells*—Continued

Materials	*Thickness (ft)*	*Depth (ft)*
8/3W-9J1		
[Selem Heights Water Dist. (Arlene well 7). Altitude 429.3 ft. Drilled by Duffield Bros., 1957]		
Soil and weathered Columbia River Group:		
Clay and decomposed rock	46	46
Columbia River Group:		
Basalt, black	70	116
Basalt, black, shattered, water-bearing; static water level of 46 ft at 128-ft depth	12	128
Basalt, black, very hard	153	281
Basalt, shattered, carbonated	7	288
Basalt, gray, very hard	21	309
Basalt, vesicular; static water level 136 ft; 35-gpm yield	4	313
Basalt, gray, very hard	58	371
Basalt, broken and vesicular, highly carbonated; static water level 242 ft	11	382
Basalt, shattered, vesicular, caving, water-bearing	93	475
8/3W-9K1		
[United Growers, Inc. Altitude about 465 ft. Drilled by Studebaker Bros., 1947]		
Soil and weathered Columbia River Group:		
Soil and clay	68	68
Columbia River Group:		
Basalt, broken	15	83
Basalt, broken, with occasional seams, water-bearing at 84-ft depth, open crevice at 273-ft depth; bailed 70 gpm	190	273
Basalt; static water level declined from 40 to 273 ft in depth range of 273–279 ft	92	365
Basalt, broken, with many seams; main water-bearing zone in depth range of 398–431 ft	68	433
Basalt, with occasional seams	71	504
Marine sedimentary rocks:		
"Rock" and shale, alternate layers	126	630

TABLE 3.—*Drillers' logs of wells*—Continued

Materials	*Thickness (ft)*	*Depth (ft)*
8/3W-9P1		
[Salem Heights Water Dist. (Steinkie well 11). Altitude 471.1 ft. Drilled by Duffield Bros., 1959]		
Soil and weathered Columbia River Group:		
Clay	4	4
Clay, red	24	28
Clay, yellow	18	46
Columbia River Group:		
Basalt, black, hard	216	262
Basalt, vesicular, very open; pieces of very light shale, tree limbs, and twigs	60	322
Basalt, black, hard	24	346
Basalt, vesicular, water-bearing	6	352
Basalt, shattered, "eroded," black with gray streaks	60	412
Basalt, black, hard	16	428
Basalt, black, soft	5	433
Marine sedimentary rocks:		
Shale, soft, squeezes	17	450
8/3W-10E2		
[Salem Heights Water Dist. (Fir Dell well 9). Altitude 420.9 ft. Drilled by Duffield Bros., 1959]		
Soil and weathered Columbia River Group:		
Clay, surface	4	4
Clay, yellow to red	41	45
Columbia River Group:		
Basalt, black, hard	55	100
Basalt, black	17	117
Basalt, gray, hard	7	124
Basalt, black	11	135
Basalt, gray, hard	26	161
Basalt, gray, fractured, decomposed	6	167
Basalt, black	21	188
Basalt, gray, hard	78	266
Basalt, gray	25	291
Basalt, brown to black	28	319
Basalt, black, hard	21	340
Basalt, vesicular, carbonated	12	352
Basalt, black	16	368
Marine sedimentary rocks:		
Clay, yellow and white	19	387
Shale, gray, soft	11	398
Shale, gray, hard, "crystalline"	44	442
Shale, gray, hard; gray, white, and yellow granules of calcite, opal, quartz, and garnet	23	465
Shale, sandy	33	498
Sandstone, quartz and opal; calcite "binder"	97	595
Shale, gray, soft, sticky	22	617

TABLE 3.—*Drillers' logs of wells*—Continued

Materials	*Thickness (ft)*	*Depth (ft)*
8/3W-10K2		
[Salem Heights Water Dist. (Park well 1). Altitude 385.6 ft. Drilled by Duffield Bros., 1954]		
Soil and weathered Columbia River Group:		
Clay, red	65	65
Ash, volcanic, compacted	32	97
Columbia River Group:		
Basalt	23	120
Basalt, fractured	8	128
Basalt, layered, solid, fractured and broken	51	179
Basalt	8	187
Cinders (basaltic); water level 45 ft	2	189
Basalt	71	260
Andesite	25	285
Basalt, vesicular; water level dropped to 192 ft	7	292
8/3W-10K4		
[Salem Heights Water Dist. (Park well 2). Altitude 386.0 ft. Drilled by Duffield Bros., 1959]		
Soil and weathered Columbia River Group:		
Clay, surface	3	3
Clay, red and yellow	57	60
Columbia River Group:		
Basalt, black, hard	101	161
Basalt, gray, hard	56	217
Basalt, vesicular; static water level 123 ft	5	222
Basalt, black	34	256
Cinders, basaltic; pieces of calcified basalt, smooth, rounded	27	283
Basalt "rocks," ¼-in. to 1½-in	12	295
Basalt, black	33	328
Basalt, black, soft like coal	3	331
Marine sedimentary rocks:		
Clay, yellow	9	340
Shale, gray, soft	5	345
8/3W-11N1		
[Salem Heights Water Dist. (Hall well 12). Altitude about 425 ft. Drilled by Duffield Bros., 1960]		
Soil and weathered Columbia River Group:		
Clay, soil	3	3
Clay, yellow	15	18
Boulders and red clay	28	46
Columbia River Group:		
Basalt, black, hard; yielded 75 gpm at 60-ft depth	59	105
Basalt, black, hard	67	172
Basalt, brown, vesicular, medium-grained, weathered	8	180
Basalt, black, hard, fine-grained	12	192
Basalt, light-brown, weathered	16	208
Basalt, black, coarse-grained	18	226
Basalt, vesicular, weathered	26	252
Marine sedimentary rocks:		
Shale, reddish-brown	8	260
Shale, blue-gray, squeezes	10	270

TABLE 4.—*Chemical analyses of waters*

[Milligrams per liter except as noted. Samples collected at sampling tap in pipeline at recharge well 8/3W–
including recharge water, was chlorinated; all recharge water was fluoridated. (See text.) *Remarks.*—
followed by test number, or by "PR" (prerecharge pumping test). See summary of tests, table 1

Source	Date and time of collection	Temperature (°C)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)
City of Salem water supply.	2-14-61	------	15	0.5	0.04	4.2	1.7	6.0	6.2	16.4	1.1
Do	10-30-61 4:45 p.m.	11.7	16	------	.01	5.0	.7	2.5	.6	22	1.6
Recharge well (8/3W-10K4).	10-30-61 4:20 p.m.	12.7	52	------	.04	4.5	1.7	7.3	2.0	37	3.6
Do	2-28-62 4:45 p.m.	11	48	------	.00	5.0	1.4	6.5	1.9	34	2.8
Do	2-28-62 5:35 p.m.	11.4	48	------	------	------	------	------	------	35	------
Do	2-28-62 8:00 p.m.	11.6	48	------	------	------	------	------	------	37	------
City of Salem water supply.	3- 2-62 4:20 p.m.	6.7	14	------	.07	4.0	.6	4.2	.5	19	.4
Recharge water	3-20-62 9:15 a.m.	8.8	14	------	.10	------	------	------	------	22	.4
Do	3-21-62 7:10 a.m.	8.8	14	------	.09	------	------	------	------	22	.0
Recharge well (8/3W-10K4).	3-21-62 12:01 p.m.	9.5	29	------	2.0	------	------	------	------	26	3.2
Do	3-21-62 12:20 p.m.	9.5	22	------	.08	4.0	1.2	3.5	.8	23	1.0
Do	3-21-62 3:05 p.m.	10	30	------	.05	------	------	------	------	24	1.4
Do	3-21-62 4:45 p.m.	10	32	------	.06	4.0	1.3	4.3	1.1	26	1.4
Recharge water	4-16-62 7:00 p.m.	9.5	13	------	.15	5.5	.6	3.9	.6	24	.0
Do	4-17-62 6:50 p.m.	9.5	13	------	------	------	------	------	------	24	.4
Do	4-19-62 6:30 a.m.	9.5	14	------	------	------	------	------	------	24	.2
Do	4-21-62 8:52 a.m.	------	14	------	------	------	------	------	------	24	.2
Recharge well (8/3W-10K4).	4-24-62 9:12 a.m.	10.5	21	------	------	------	------	------	------	28	.2
Do	4-24-62 10:20 a.m.	10	24	------	.14	5.5	1.1	4.1	.9	27	1.6
Recharge well (8/3W-10K4).	4-24-62 11:15 a.m.	10	------	------	------	------	------	------	------	------	------
Do	4-24-62 12:15 p.m.	10.2	------	------	------	------	------	------	------	------	------
Do	4-24-62 12:50 p.m.	10	------	------	------	------	------	------	------	------	------
Do	4-24-62 2:07 p.m.	10	29	------	------	------	------	------	------	27	3.4
Recharge water	5- 1-62 6:00 p.m.	10.5	18	------	------	------	------	------	------	26	.8
Do	5- 8-62 5:05 p.m.	10.5	13	------	------	------	------	------	------	21	.6

from the Salem Heights area

10K4 except as noted. Analyses by the U.S. Geological Survey except as noted. All city of Salem water, Tests during which samples were collected are designated by "P" (pumping test) or "R" (recharge test)

Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180°C	Hardness as $CaCO_3$	Total alkalinity	Specific conductance (micromhos at 25°C)	pH	Color	Dissolved oxygen: Milligrams per liter	Dissolved oxygen: Percent saturation	Remarks
6.7	0.0	0.1	------	32	17.5	------	------	6.9	------	------	------	Data from City of Salem.
2.0	.2	.2	40	41	15	------	45	7.0	0	------	------	Sampled at booster-pump station.
2.5	.2	.5	92	92	18	------	75	7.5	5	------	------	Sampled after pumping 10 min.
2.2	.3	.4	86	83	18	------	72	7.4	0	9.3	84	PR, after pumping 1¼ hr.
2.5	------	------	------	------	18	------	74	7.4	------	8.3	76	PR, after pumping 2 hr 5 min.
2.5	------	------	------	------	19	------	80	7.3	------	6.8	62	PR, after pumping 4½ hr.
1.8	1.8	.0	37	43	12	------	47	6.9	5	11.7	95	Sampled at booster-pump station after fluoride was added.
------	------	------	------	------	------	18	51	7.3	------	10.8	93	R1, after injecting 55 min.
------	------	------	------	------	------	18	47	7.1	------	10.9	93	R1, after injecting 23 hr.
------	------	------	------	------	------	21	59	7.1	------	------	------	P1, after pumping 2 min; water turbid.
1.8	.5	.1	46	42	15	19	49	7.2	5	11.1	97	P1, after pumping 21 min.
------	------	------	------	------	------	20	52	7.3	------	10.0	87	P1, after pumping 3 hr 6 min.
2.0	.4	.1	60	58	16	21	54	7.2	5	8.6	76	P1, after pumping 4¾ hr.
1.0	1.3	.3	38	38	16	20	52	6.9	5	13.2	115	R2, after injecting 7⅛ hr.
1.2	1.3	------	------	------	------	20	51	6.9	------	9.0	78	R2, after injecting 31 hr.
1.2	1.4	------	------	------	------	20	52	6.9	------	10.5	92	R2, after injecting 67 hr.
1.2	1.3	------	------	------	------	20	51	6.9	------	------	------	R2, after injecting 117 hr.
1.2	.9	------	------	------	------	23	56	7.0	------	------	------	P2, after pumping 2 min; water turbid.
1.5	1.0	.3	53	54	18	22	59	7.0	5	9.0	80	P2, after pumping 1 hr 10 min; water contains some sediment.
------	------	------	------	------	------	------	60	------	------	8.9	79	P2, after pumping 2 hr 5 min; water contains some sediment.
------	------	------	------	------	------	------	------	------	------	9.0	80	P2, after pumping 3 hr 5 min; water clear with minor sediment.
------	------	------	------	------	------	------	61	------	------	8.7	77	P2, after pumping 3 hr 40 min; water clear with sand-size sediment.
1.2	1.0	------	------	------	------	------	61	7.2	------	8.5	75	P2, after pumping 4 hr 57 min; water clear with minor sediment.
1.2	1.1	------	------	------	------	21	55	7.3	------	------	------	R3, after injecting 1 hr; water contains sand-size sediment.
1.5	1.2	------	------	------	------	17	47	7.0	------	------	------	R3, after injecting 7 days.

TABLE 4.—*Chemical analyses of waters*

Source	Date and time of collection	Temperature (°C)	Silica (SiO_2)	Aluminum Al	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)
Recharge well (8/3W-10K4).	5-21-62 9:14 a.m.	------	41	------	------	------	------	------	------	32	1.6
Do	5-21-62 9:23 a.m.	11.6	28	------	------	------	------	------	------	28	3.2
Do	5-21-62 10:18 a.m.	11.6	24	------	------	------	------	------	------	26	3.6
Do	5-21-62 12:15 p.m.	11.6	24	------	------	------	------	------	------	25	5.6
Do	5-21-62 2:12 p.m.	11.6	24	------	.06	6.5	1.0	3.4	.9	24	6.8

TABLE 5.—*Suspended sediment in waters sampled during artificial-recharge study at Salem Heights*

[Collection points: Unless otherwise noted, samples were collected at sampling tap on injection line at pump]

Source	Date	Time	Concentration (mg/l)
Pretest conditions			
Injection line, from booster-pump station.	3-2-62	4:10 p.m.	0
		4:10 p.m.	3
Recharge test 1			
Injection line, from booster-pump station.	3-20-62	9:13 a.m.	[1] 18
		9:14 a.m.	[1] 40
		10:13 a.m.	5
		10:13 a.m.	[1] 25
		11:20 a.m.	[1] 19
		1:25 p.m.	5
		4:22 p.m.	[1] 34
	3-21-62	12:30 a.m.	5
		7:07 a.m.	[1] 27
Pumping test 1			
Blowoff line, from well 10K4	3-21-62	12:00:30 p.m.	[1] 1,290
		12:01 p.m.	[1] 371
Well 10K4	3-21-62	12:03 p.m.	[1] 162
		12:07 p.m.	[1] 53
		1:30 p.m.	2
		4:00 p.m.	2
		4:40 p.m.	[1] 8

See footnotes at end of table.

from the Salem Heights area—Continued

Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180°C	Hardness as $CaCO_3$	Total alkalinity	Specific conductance (micromhos at 25°C)	pH	Color	Dissolved oxygen: Milligrams per liter	Dissolved oxygen: Percent saturation	Remarks
2.0	.4	------	------	------	------	26	66	7.0	------	------	------	P3, after pumping 2 min; water turbid.
2.0	.6	------	------	------	------	23	62	7.0	------	8.2	75	P3, after pumping 11 min; water contains sand-size sediment.
2.0	.7	------	------	------	------	21	60	7.0	------	9.1	83	P3, after pumping 1 hr 6 min; water contains sand-size sediment.
2.0	.8	------	------	------	------	20	62	7.0	------	8.6	79	P3, after pumping 3 hr 3 min.
1.5	.8	.2	57	58	20	20	63	7.0	5	7.8	71	P3, after pumping 5 hr; water contains some sediment.

TABLE 5.—*Suspended sediment in waters sampled during artificial-recharge study at Salem Heights*—Continued

Source	Date	Time	Concentration (mg/l)
Recharge test 2			
Injection line, from booster-pump station.	4-16-62	11:50 a.m.	[1,2] 122
		1:40 p.m.	[1] 47
		3:40 p.m.	[1] 20
		6:40 p.m.	[1] 216
	4-17-62	11:45 a.m.	0
		6:50 p.m.	[1] 45
	4-18-62	6:40 p.m.	2
	4-19-62	6:30 a.m.	[1] 12
		6:10 p.m.	0
	4-20-62	11:59 p.m.	3
	4-21-62	8:52 a.m.	7
Pumping test 2			
Well 10K4	4-24-62	9:11 a.m.	[2] 18
		9:12 a.m.	[1] 120
		9:13 a.m.	[1] 678
		9:16 a.m.	[1] 155
		9:21 a.m.	[1] 292
		9:28 a.m.	[1] 48
		10:20 a.m.	[1] 7
		11:16 a.m.	[1] 5
		12:22 p.m.	[1] 50
		1:15 p.m.	[1] 16
		2:08 p.m.	[1] 12

See footnotes at end of table.

TABLE 5.—*Suspended sediment at waters sampled during artificial-recharge study at Salem Heights*—Continued

Source	Date	Time	Concentration (mg/1)
Recharge test 3			
Injection line, from booster-pump station.	5- 1-62	5:50 p.m.	[1]119
	5- 2-62	8:13 a.m.	2
	5- 3-62	8:10 a.m.	4
	5- 4-62	8:15 a.m.	0
	5- 5-62		0
	5- 6-62		0
	5- 7-62		0
	5- 8-62		0
	5- 9-62		0
	5-10-62		0
	5-11-62		0
	5-12-62		0
	5-13-62		0
	5-14-62		0
	5-15-62		2
Pumping test 3			
Well 10K4	5-21-62	8:32 a.m.	[1] 456
		9:13 a.m.	21
		9:14 a.m.	[1] 356
		9:17 a.m.	[1] 155
		9:22 a.m.	[1] 205
		10:14 a.m.	13
		11:34 a.m.	5
		12:20 p.m.	0
		1:12 p.m.	8
		2:12 p.m.	0

[1] Sample contains sand.
[2] Sample rust colored.