Artificial Recharge Through a Well Tapping Basalt Aquifers Walla Walla Area Washington

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1594-A

Prepared in cooperation with the State of Washington Department of Conservation

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By CHARLES E. PRICE

ARTIFICIAL RECHARGE OF GROUND WATER

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ARTIFICIAL RECHARGE THROUGH A WELL TAPPING BASALT AQUIFERS, WALLA WALLA AREA, WASHINGTON

By Charles E. Price

ABSTRACT

Declining water levels in part of the Columbia lava plateau, owing to pumping, have caused concern for several years. Therefore, the U.S. Geological Survey in cooperation with the State of Washington Department of Conservation carried out an experiment to determine the feasibility of artificial recharge to halt the decline of water levels in part of the Walla Walla basin, Washington. During the experiment 71.3 acre-feet (23 million gallons) of surface water was injected into basalt through Walla Walla city well 3 at rates ranging from 630 to 670 gallons per minute. The chemical and bacteriological quality of the injected water was excellent, and the water contained only 2 parts per million of suspended sediment. The injected water probably was nearly saturated with air when it entered the top of the well and may have entrained some additional air as it fell into the well.

The water injection caused a rise of the water level and hence increased the amount of ground water in storage in the local area. However, the subsequent yield and specific capacity of the well were impaired. The data obtained during the tests suggest that hydraulic boundaries limit the lateral movement of water. The tests indicate also that the coefficient of transmissibility of the basalt is about 400,000 gallons per day per foot and that the coefficient of storage is about 0.0002.

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

This report presents the results of an investigation to determine the feasibility of artificially recharging deep basalt aquifers by injecting surplus water from Mill Creek through one of the public-supply wells of the city of Walla Walla, Wash. The investigation was begun in 1956 as a result of conferences among the U.S. Geological Survey, the State of Washington Department of Conservation, and the city of Walla Walla; it was agreed that the Geological Survey, as a part of its cooperative program with the State, would make the investigation and would prepare a report on the findings.

With the continued withdrawal of ground water in greater and greater quantities for irrigation, industrial, and public supply, conservation practices will become of great importance in the planned development of the ground-water resources. Artificial recharge, involving the injection of surplus surface water into the ground through wells, is one form of conservation aimed at increasing the ground-water supply and lowering pumping costs in areas where heavy ground-water development currently is taking place.

The city of Walla Walla for several years has considered the possibility of introducing surface water into one of its public-supply wells in order to recharge artificially the basalt aquifer tapped by that well. The water-supply system of the city is easily adaptable to such a recharge program: excess surface water is available for recharge during a part of each year, and because one of the wells is only a few feet from the pipeline carrying Mill Creek water to the city's reservoir, the installation of piping and metering equipment was simple and inexpensive.

Because of the city's interest in salvaging surplus Mill Creek water and the interest of the State and Federal agencies in recharge as related to conservation in general, the Geological Survey undertook this project to investigate the feasibility of recharge through wells. The Survey supervised the experimental work and determined the effect of such recharge on the injection well and on the basalt aquifers tapped by the well.

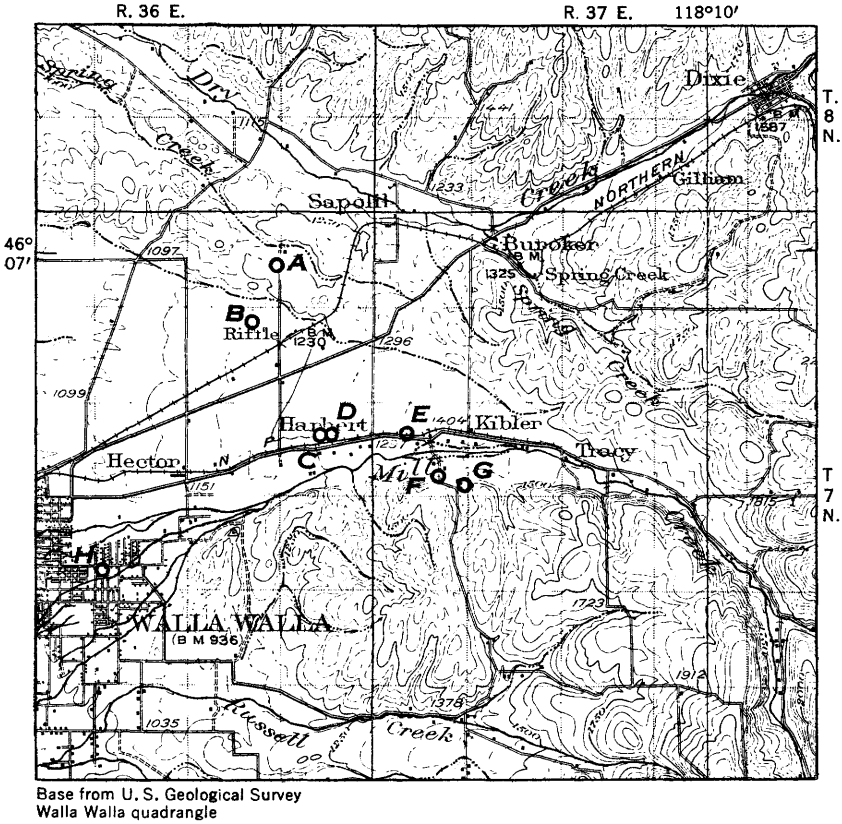
The fieldwork was done jointly by the Geological Survey and the State of Washington Department of Conservation, under the supervision of A. A. Garrett, district engineer, Ground Water Branch, and R. H. Russell, assistant supervisor, State Division of Water Resources. The section of this report dealing with the suitability of Mill Creek water for recharging the basalt aquifers has been adapted from a chapter in a report by Hart (1957).

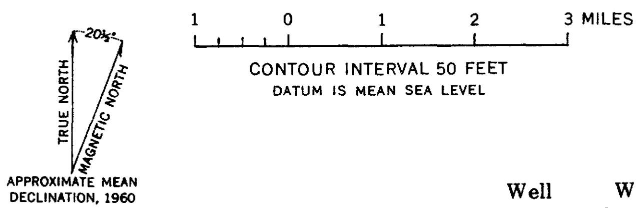
LOCATION OF THE AREA

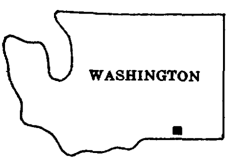
Walla Walla is in the southeastern part of the State of Washington, about 5 miles north of the boundary between Washington and Oregon and in the drainage basin of Mill Creek, a westward-flowing tributary of the Walla Walla River. The well in which the water was injected, Walla Walla well 3, is about 5 miles east-northeast of the city, near Mill Creek (fig. 1).

ACKNOWLEDGMENTS

The writer wishes to acknowledge the assistance of Mr. Paul F. Meyer, water superintendent of Walla Walla, and other of the city's personnel. Without the use of the city's facilities and the excellent cooperation of the Water Department, the collection of many important data would not have been possible.







Well	Well name
A	Robert Moore
B	Roy Frazier
C	Walla Walla well 1
D	Walla Walla well 2
E	Walla Walla well 3
F	Gerald Brunton
G	Olaus Filan
H	Walla Walla well 4

FIGURE 1.—Map of the Walla Walla areas showing locations of wells.

The writer is indebted to Mr. Harlow Barney, Walla Walla County watermaster, for making a series of water-level measurements on the injection well after the period of recharge.

GEOLOGIC AND HYDROLOGIC FEATURES

Walla Walla basin is an east-trending topographic and structural basin that lies astride the Washington-Oregon boundary. This basin, about 1,300 square miles in area, is bounded on the north by the Touchet slope, on the east by the Blue Mountain uplift, on the south by the Horse Heaven uplift, and on the west by a rimrock ledge in the lower valley of the Walla Walla River. All these features are beyond the extent of figure 1, which shows only a part of the eastern part of this basin.

The Walla Walla basin is underlain by a series of lava flows that are a part of the basaltic materials designated the Columbia River basalt by Russell (1893). The Columbia River basalt extends in general from the Okanogan highlands south to the eastward-trending mountain systems of central Oregon, and from the Cascade Mountains eastward to the Rocky Mountains in Idaho. The Walla Walla basin lies southeast of the geographic center of that vast basaltic area, and the sequence of lava flows in it is of unknown thickness. At Walla Walla well 3, used as the injection well in the recharge experiment, the basalt is at least 1,169 feet thick (table 1). In Mill Creek Canyon, east of well 3, a thickness of about 2,000 feet of basalt is exposed. The rock on which the basalt rests is not exposed, nor has it been reached by drilling in the Walla Walla basin. About 35 miles northeast of Walla Walla, in the Tucannon River canyon, a few small inliers of Paleozoic(?) and Mesozoic(?) sedimentary and igneous rocks are exposed from beneath the basalt, according to Huntting (written communication, 1942). In that vicinity the basalt is at least 3,000 feet thick. About 50 miles southwest of Walla Walla, in the Umatilla River basin, the basalt lies upon sedimentary rock of Eocene age (Hogenson, 1957, p. 15, pl. 2a) and other older rocks.

TABLE 1.—*Abridged drillers' logs of wells*

Well 1, city of Walla Walla

[Altitude, about 1,260 ft. Drilled by A. A. Durand & Son, 1942. Casing, 10-in to 363 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil	8	8	Basalt, brown	5	560
Gravel, clay, boulders	51	59	Basalt, black	190	750
Gravel, brown clay	79	138	Basalt, gray	5	755
Basalt, black, with clay seams	143	281	Basalt, brown	7	762
Basalt, gray	33	314	Basalt, black	15	777
Basalt, black	133	447	Basalt, gray	4	781
Basalt, gray	57	504	Basalt, black	21	802
Basalt, black	51	555	Basalt, gray	8	810

TABLE 1.—*Abridged drillers' logs of wells*—Continued

Well 2, city of Walla Walla

[Altitude, about 1,273 ft. Drilled by A. A. Durand & Son, 1942. Casing, 16-in to 140 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil and gravel, cemented	15	15	Basalt, brown	2	477
Gravel and boulders	57	72	Basalt, black and gray (alternating layers)	91	568
Gravel, some brown clay	38	110	Basalt, brown	9	577
Basalt, black	89	199	Basalt, black and gray	189	766
Basalt, brown	14	213	Basalt, brown	5	771
Basalt, black	262	475	Basalt, black	37	808

Well 3, city of Walla Walla

[Altitude, about 1,317 ft. Drilled by A. A. Durand & Son, 1947. Casing, 20-in to 178 ft, 16-in from 1,063 to 1,102 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil	2	2	Basalt, black, red, brown, and gray layers	139	539
Gravel and boulders	6	8	Basalt, black and gray layers	289	828
Gravel and clay	137	145	Basalt, black; gray and brown layers	287	1, 115
Basalt, black and brown, and clay	26	171	Basalt, black, and light-brown clay	5	1, 120
Basalt, black and gray	92	263	Basalt, brown	49	1, 169
"Shale," blue	7	270			
Basalt, black, porous; some broken layers	119	389			
Clay, brown and black	11	400			

Well 4, city of Walla Walla

[Altitude, about 1,045 ft. Drilled by A. A. Durand & Son, 1953. Casing, 24-in to 400 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil, sand, clay, and gravel	5	5	Basalt, black, hard	321	718
Gravel and boulders	19	24	Basalt, dark-gray, very hard	45	763
Gravel and clay, yellow	270	294	Basalt, black, hard	26	789
Clay, blue, hard	103	397			

Gerald Brunton well

[Altitude, about 1,350 feet. Drilled by W. E. Ruther & Son, 1957. Casing, 6-inch to about 30 feet]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil	17	17	Gravel, black, cemented, and yellow clay	13	39
Cobbles, black	9	26			

Olaus Filan well

[Altitude, about 1,400 ft. Drilled by George E. Scott, 1951. Casing, 12-in to 102 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil	12	12	Basalt, black	101	175
Gravel	5	17	Basalt, gray	6	181
Basalt, black	32	49	Basalt, black, gray, hard	589	770
Basalt, gray	25	74			

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TABLE 1.—*Abridged drillers' logs of wells*—Continued

Roy Frazier well

[Altitude, about 1,190 ft. Drilled by George E. Scott, 1947. Casing, 16-in to 170 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Clay, yellow	13	13	Clay, yellow	6	161
Gravel, dirty	84	97	Gravel, cemented	9	170
Clay, yellow	11	108	Basalt, black, gray	431	601
Gravel	6	114	Shale, dark, sticky	3	604
Clay and gravel	41	155	Basalt, black, gray	203	807

Robert Moore well

[Altitude, about 1,225 ft. Drilled by A. A. Durand & Son, 1955. Casing, 12-in to 164 ft]

Materials	Thickness (feet)	Depth (feet)	Materials	Thickness (feet)	Depth (feet)
Soil	36	36	Clay, blue	18	580
Gravel, yellow, and brown clay	44	80	Basalt, broken, and brown and blue clay	40	620
Clay, yellow, and cemented gravel	90	170	Lava, red, broken	37	657
Basalt, black and blue	392	562	Basalt, gray	153	810

East of the injection well the Columbia River basalt is arched to form the Blue Mountains. The west side of the Blue Mountains is essentially a monocline dipping 3°–5° toward the Walla Walla basin. The Blue Mountains slope is dissected by steep-sided, narrow canyons as much as 1,500 feet deep; Mill Creek canyon is one of the deepest of these. The gradient of the streams in general is less than the slope of the basalt beds; therefore, the outcrop pattern of each individual lava flow, as viewed from above, is V-shaped and points downstream. This outcrop pattern favors natural recharge of ground water into the permeable layers cropping out in the stream channels.

In the area adjacent to the well, however, replenishment is less than withdrawal, as shown by the long-term decline in ground-water levels in the city wells 1, 2, and 3 (p. A'–8). That insufficient recharge reaches this area is obvious. This isolation from natural recharge no doubt is caused by the existence of hydraulic boundaries.

In the Walla Walla area the basalt is dark gray, brown, or black and contains finely felted microscopic crystallites in a glassy groundmass (Newcomb, 1951, p. 24). Individual lava flows range in thickness from about 5 to 100 feet and average about 40 feet.

The two common systems of cooling joints in the lava are the columnar and the cubical. The columnar system cuts the lava into rude 6-sided and 4-sided joint columns, and the cubical divides it into irregular boulder- or cobble-size straight-sided blocks. Both types of jointing can occur in one flow, though one or the other usually predominates in any one part of a flow.

Regional joints and faults locally cut the basalt; the faults contain crushed and sheared rock that forms a barrier to the lateral movement of ground water. The location of a few of these faults is known; other faults are suspected to be in certain places, and many others undoubtedly exist.

OCCURRENCE OF WATER IN BASALT

GROUND-WATER MOVEMENT

The water obtained by wells in the basalt almost invariably comes from the zone of contact between one basalt flow and another. According to Newcomb (1951, p. 41), the openings in these contact or interflow zones are mainly cracks or crevices produced primarily by the incomplete closure of one flow over another and by fragmentation of the basalt at the top of some of the flows. Although these interflow zones may be fairly extensive, their transmissibilities differ greatly from place to place.

From areas of recharge, where the basalt is at or near the surface, such as the Blue Mountains, rainwater and snowmelt percolate downward into the porous zones between the tabular flows of basalt. The water in these porous zones moves by gravity down the dip of the basalt toward the center of the Walla Walla basin, a few miles southwest of Walla Walla, where the basalt aquifers locally contain water under considerable hydraulic head. Here, water flows at the surface or stands but a few feet below the surface in wells tapping these aquifers.

Planning a successful program of artificial recharge requires knowledge of whether conditions are favorable for the recovery of the water after it has been injected into the aquifers. Water introduced into an aquifer by means of an injection well raises the water level or artesian pressure in the aquifer adjacent to the well and creates a mound of water, or a piezometric high, around the well. As a result of the recharge, local hydraulic gradients are established that allow water to spread out through the aquifer, away from the well, at the same rate it is injected into the well. If injection is discontinued and the well is pumped, the hydraulic gradients in the vicinity of the well will be reversed, so that the water will then move toward the well. In this manner part of the water recharged can be recovered by pumping the injection well or nearby wells. Some of the water injected usually cannot be recovered because it has passed beyond the area of influence of the pumped well; the amount so lost depends upon the rate of movement, the physical characteristics of the aquifer, the natural hydraulic gradients in the vicinity of the well, and the time that has elapsed since injection. However, part of any water not removed by pumping the injection well may be recovered by pumping wells downgradient from the recharge well.

In the eastern part of the Walla Walla basin, ground-water movement is, in general, from east to west; that is, from high to low parts of the basin. Immediately adjacent to city well 3, however, the direction of water movement has not been determined accurately. Wells in which reliable water-level elevations could be obtained are insufficient to warrant constructing a meaningful water-level contour map. When virtually simultaneous determinations of static water levels were made in wells 1 and 3 on May 27 and 28, October 1, and December 11, 1957, and on January 11, 1958, the levels in the two wells were about equal.

Hence, so far as these measurements showed, no hydraulic gradient existed between well 3 and well 1 on those dates. Earlier measurements had shown that for at least a part of the period of record a slight westward gradient existed; however, all those water levels were measured by means of air gages, which have too low a sensitivity to indicate small differences in altitude. Because these water-level comparisons were made on only two wells, they represent conditions only along a straight line connecting city well 3 with well 1. Obviously the two points are insufficient control for determining whether a gradient exists in the local area. Possibly either a northerly or a southerly component of gradient exists here.

The existence of impermeable boundaries adjacent to the recharge area seems probable, and they may have an appreciable, but unevaluated, effect on the direction of water movement. Elsewhere in the Walla Walla area there are hydraulic boundaries (Newcomb, 1951, p. 48).

WATER-LEVEL FLUCTUATIONS

Because the introduction of water into a well will raise the water level in the area around the well, an analysis of information concerning depth to water in and near a recharge well is important. The total distance between land surface and water level in a well is the maximum hydraulic head that can be utilized when introducing recharge water by gravity flow at the top of the casing. If a closed system is used, of course, water can be injected under pressure.

Information on the long-term fluctuations of water level in this area is scant. Records of water-level measurements show that the level in well 3 declined about 38 feet during the period April 1942–May 1957.

There is a relatively large seasonal fluctuation of water levels in city wells 1, 2, and 3 and in wells adjacent to them. For example, from May to October 1957 the level in city well 1 declined 16 feet, and that in well 3 declined 17 feet. From August 1957 to January 1958 the level in the Roy Frazier well recovered 25 feet, from 74 to 49 feet below the measuring point. However, a small part of this recovery may have been caused by the recharge operations. Although this well is a little more than 2 miles northwest of city well 3 (fig. 1), the short-term hydrograph shown on figure 2 for the Frazier well strongly suggests that the two are hydraulically interconnected.

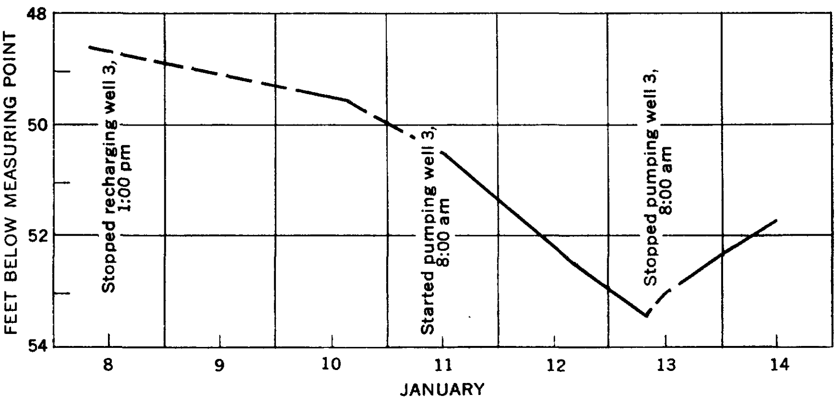

FIGURE 2.—Hydrograph of Roy Frazier well for Jan. 8–14, 1958.

The long-term decline in levels points out the need for conservation measures, for it indicates that there is more water being pumped from the basalt aquifers in the immediate area than is being replaced by natural recharge or movement of water from adjoining areas.

WATER SUPPLY OF WALLA WALLA

The public water-supply system of the city of Walla Walla is served from both surface- and ground-water sources. The city has an established water right to withdraw 14 mgd (million gallons per day) from Mill Creek. However, during a part of the year the city's demand is greater than this maximum withdrawal rate; furthermore, for short periods when Mill Creek receives storm runoff, the water in that stream is too turbid for public supply without treatment by costly filtration facilities. During such periods the city's demand is satisfied by pumping ground water to the extent that the Mill Creek supply is inadequate.

SURFACE-WATER SUPPLY

Mill Creek, a perennial stream, rises in the Blue Mountains and flows north and then west to join the Walla Walla River about 6 miles west of Walla Walla. The water supplying the city is withdrawn from Mill Creek at a diversion dam and is then led into a settling basin (not shown in fig. 1) about 3,000 feet north of the Oregon-Washington boundary and about 11 miles southeast of Walla Walla. This settling basin removes only a moderate amount of the sediment present in the water and contains screens that stop larger debris such as pine needles. The settling basin also enables the operator to maintain a visual check on the turbidity of the water. When the water is too turbid to use, it can be bypassed. When being used by the city, it is chlorinated as it leaves the settling basin. From the settling basin the water flows westward by gravity through a 20-inch pipeline about 7 miles to the reservoir and from there into the distribution mains. The rate of flow through the 20-inch line is controlled by gates at the settling basin.

At the reservoir the 20-inch line terminates in a standpipe; the water spills over the top of this standpipe into a vertical annular duct that leads to the reservoir. The height of the standpipe is such that a positive pressure exists in the pipeline through at least part of its length. For example, at well 3, about 5,000 feet east of the reservoir, the pressure in the 20-inch line is about 18 pounds per square inch.

GROUND-WATER SUPPLY

Four wells, ranging in depth from 789 to 1,169 feet, are used by the city to supplement the Mill Creek supply (table 1). The maximum combined installed-pump capacity of the four wells is about 7,500 gpm (11 mgd). A fifth well had been drilled but had not been put into operation at the time of this study. City well 3, the deepest of the four and the well into which water was injected, was drilled to a depth of 1,169 feet, more than 1,000 feet of which was in basalt.

City wells 1, 2, and 3, near the reservoir, pump directly into the reservoir through separate discharge pipes. Orifice plates and manometers at the ends of these discharge pipes enable the operator to determine the rate at which each well is yielding water. City well 4, which is at the eastern edge of the city, pumps directly into the city mains. The water from the wells is not chlorinated.

SUITABILITY OF MILL CREEK WATER FOR RECHARGE

Many factors determine whether a given water will be suitable for injection underground. Some of these factors can be evaluated, others are more difficult to determine. Even under the best of conditions, where the chemical and physical characteristics of both the ground water and the injection water are known within rather narrow limits, it is often impossible to predict how the hydraulics of a recharge system will function.

Hart, in his preliminary study (1957), and the author of this report thoroughly investigated the quality of Mill Creek water and evaluated the suitability of this water for injection underground.

CHEMICAL COMPATABILITY

For the purpose of this report it has been arbitrarily accepted that two waters will be chemically compatible for mixing in artificial recharge operations if they are similar in proportions of constituents and if the concentration of constituents in the recharge water is not appreciably greater than that which would be acceptable for domestic use.

Chemical analyses of water from Mill Creek and from city wells 1, 3, and 4 are given in table 2 (p. A–12). Of the 7 analyses there shown, 4 were made by the Geological Survey, and 3 were made by private laboratories. The analyses in this table show a marked difference between the amount of total solids in water from Mill Creek and the amount in the water pumped from the three wells. The table also shows that, of the three wells, city well 4 yields water in which the total solids content is considerably greater than that from either well 1 or well 3.

Although, in table 2, all the available quality data are given, of chief interest is the comparison of the quality of water from Mill Creek with that of water from well 3—the one in which injection of water from Mill Creek is contemplated. This comparison can be effected by expressing the analyses of both in terms of percentage equivalents per million of total cations and total anions.[1] For the purpose of this comparison the analysis of water from well 3 and that of the Mill Creek water sample collected December 19, 1957, in percentage equivalents per million, are shown in the following table.

Constituent	Percentage equivalents per million	
	Mill Creek water	Well 3 water
Calcium	51	46
Magnesium	28	29
Sodium and potassium	21	25
Bicarbonate	94	94
Sulfate	1	3
Chloride	4	2
Fluoride	1	1

It is obvious from a comparison of the constituents in the two waters, in equivalents per million, that both are of the same type, for the dissolved solids in both are predominately alkaline earth (Ca and Mg) bicarbonates. The silica present is equivalent to 46 and 42 percent of the dissolved solids in the two waters.

[1] Equivalents per million for any constituent (or ion) can be obtained by dividing the concentration of the constituent in parts per million by the chemical equivalent weight of the constituent.

TABLE 2.—*Chemical analyses, in parts per million, of water from city wells 1, 3, and 4, and from Mill Creek*

[Analyst: CLP, Charlton Laboratory, Portland, Oregon; USGS, U.S. Geological Survey]

Source of sample	City well 1	City well 1	City well 3	City well 4	Mill Creek [1]	Mill Creek [2]	Mill Creek [2]
Date of collection	11-26-46	4-23-53	1-28-57	10-9-53	4-23-53	3-26-57	12-19-57
Silica (SiO_2)	54	43	56	55	26	33	28
Iron (Fe)		.10	.0	.17	.03	.04	.04
Manganese (Mn)						0	0
Calcium (Ca)	17	16	17	17	5.9	4.8	6.0
Magnesium (Mg)	8.2	7.5	6.5	6.1	2.6	2.1	2.0
Sodium (Na)	7.1	7.4	9.3	29	6.4	1.8	1.8
Potassium (K)			2.6			1.5	1.9
Aluminum (Al)		.1		.4	.6		
Bicarbonate (HCO_3)	96	98	106	152	33	30	33
Carbonate (CO_3)	0	0		12	0	0	0
Sulfate (SO_4)	9.7	3.1	2.5	6.6	3.2	.7	.1
Chloride (Cl)	1.8	2.8	1.0	5.6	0	1.0	1.0
Fluoride (F)	.2	.2	.2	.7	.05	.1	.1
Nitrate (NO_3)	.2	.2	.2	.04	.05	.0	.2
Boron (B)			.04			.04	.03
Dissolved solids	145	144	132	[3] 208	86(?)	60	61
Hardness as $CaCO_3$	76	69	69	[3] 68	25	21	23
Specific conductance (micromhos at 25°C)	150		169			54.5	62
pH		7.6	8.0			7.3	7.1
Temperature (°F)			59				39
Analyst	USGS	CLP	USGS	CLP	CLP	USGS	USGS

[1] Sample collected at diversion dam. [2] Chlorinated sample from Mill Creek pipeline. [3] Calculated by Geological Survey.

In general, although the proportions of all determined constituents are much the same in both waters, the dissolved-solids content in water from well 3 is more than twice that in water from Mill Creek, (table 2). Because the chemical character of both waters is nearly identical, however, as described above, the only effect that could take place from blending the two would be a dilution of the ground water. The greater mineralization of the natural ground water probably is due to the greater period of time during which the water has been in contact with rock materials.

SEDIMENT

Because of economic considerations, the ground-water recharge program at Walla Walla was carried out with unfiltered surface water. Inasmuch as surface water may contain a considerable quantity of sediment, particularly during periods of high runoff, it was necessary to determine the magnitude of the sediment load carried by Mill Creek and to evaluate the extent to which that sediment load would plug the well and the aquifers.

In order to determine the sediment load carried by Mill Creek at different times, 60 samples of water were taken at the city's settling basin by the city's personnel in April, May, and June 1956, and 50 were taken in January, February, March, and December 1957. These 110 samples, collected on separate days, were analyzed in the laboratory of the Geological Survey in Portland, Oreg. The samples collected in 1956 contained 4 to 6 ppm of sediment. Of those collected in 1957, 44 contained 2 ppm of sediment, and 6 contained 12 to 16 ppm.

During February 23–28, 1957, when the 6 samples were collected, the water was not considered clear enough for public supply and was returned to Mill Creek. The samples of December 1957, collected immediately before and during recharge, all contained 2 ppm of suspended sediment of silt and clay size, which represents the sediment concentration of the water injected into city well 3.

A visual check on the turbidity of the Mill Creek water is made several times each day by the operator at the settling basin. According to him, if the turbidity is great enough to obscure the bottom of the settling basin, the water no longer can be used and is then returned to Mill Creek. This degree of opacity is reached when the sediment content exceeds about 6 ppm.

It can be assumed, therefore, that the highest concentration of sediment in Mill Creek water that would be available for recharge is about 6 ppm. Hence, the greatest amount of sediment that could be carried into the well would be about 16 pounds for each acre-foot of water injected.

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AIR CONTENT

When surface water is being used for artificial recharge through wells, air from two different sources can enter the aquifers tapped by the well: air carried into the well in solution in the water, and air entrained in the flow of recharge water during transit.

Air introduced into a well during recharge may lessen the water-carrying capacity of an aquifer by both physical and chemical processes. Air entrapped in the interstices of the aquifer materials, in the form of minute bubbles, may impede the flow of water in the aquifer. Also, under certain conditions air may react chemically with native ground water to produce insoluble precipitates that can clog an aquifer. For example, iron contained in ground water is usually present in the partly oxidized ferrous state; upon further oxidation by contact with injected air, the iron may precipitate as a ferric iron compound. In addition, carbon dioxide from the atmosphere, brought into contact with dissolved silica in alkaline solution, can precipitate a siliceous cementing material (Uren, 1939).

With regard to the possibility that aeration might result in the formation of precipitates in the ground water tapped by well 3, it should be pointed out that no precipitate was observed in a blended sample of water from Mill Creek and city well 3 after it was allowed to stand for some time in an open container. Therefore the possibility of harmful chemical reaction resulting from the addition of air, at least air in solution, cannot be considered of prime concern, although it cannot be disregarded completely on the basis of this one simple test. The two methods by which air can be introduced into the well will be discussed separately to the extent that they apply to Mill Creek water and to the particular type of artificial-recharge system tried in Walla Walla city well 3.

DISSOLVED AIR

Water in contact with air will take into solution certain quantities of oxygen, nitrogen, and other atmospheric gases. The amount of these dissolved gases depends on pressure, temperature, and length of time involved. Water flowing in a stream invariably takes some air into solution. In deciding whether a surface water is suitable for artificially recharging a ground-water body, consideration should be given to the amount of dissolved air in the water, inasmuch as it is a potential source of trouble.

The following discussion evaluates the possibility of the dissolved air coming out of solution from Mill Creek water after injection into the well. The evaluation must be purely qualitative because it is impossible to assign values to all the variables that control the solubility of air in water under the conditions that exist within the aquifers.

Three samples of water from Mill Creek and one sample of water from city well 3 were collected by the city Health Department for determination of dissolved oxygen. The results of these tests, made by the Geological Survey, are shown in the following table. Because the oxygen-nitrogen ratio in air dissolved in fresh surface water that contains no oxidizable material in solution or in suspension is a constant under a given set of physical conditions, the amount of air in solution in water from Mill Creek can be computed easily if the amount of dissolved oxygen in solution is known.

TABLE 3.—*Dissolved oxygen in water from Mill Creek and city well 3*

Source	Sampling point	Date of collection in 1957	Dissolved oxygen (ppm)
Mill Creek	Settling basin	May 29	8.3
Mill Creek	Settling basin	May 30	10
Mill Creek	Tap in pipeline, near well 3	June 13	14
City well 3	Tap in discharge line	June 13	2.3

Because the temperatures of the samples were not taken, it is not possible to determine whether the water samples from Mill Creek were saturated with air. However, if the temperature of the sample taken from the pipeline to the reservoir on June 13 was within the range of 45°–50°F, the observed dissolved-oxygen content of 14 ppm probably represented a near-equilibrium, or near-saturated, condition. Although this assumed temperature range is an estimate, a review of table 4 suggests that in the months of May and June, Mill Creek water is commonly within this temperature range.

At 45°F the air in solution in fresh water contains about 34.6 percent oxygen and 65.4 percent nitrogen (Hodgman, 1956, p. 1606–1607). Hence a dissolved-oxygen content of 14 ppm would be equivalent to a dissolved-air content of about 40 ppm.

The temperature of the water pumped from city well 3 on May 28, 1957, measured at the point where the water discharges into the city reservoir, was 59°F. This temperature resulted from a blending, during pumping, of water entering the well at different depths. Because of the almost universal existence of a geothermal gradient, the temperature of the water from deeper aquifers in most places is higher than that from shallower ones. Therefore, water from Mill Creek that enters permeable zones in the lower part of city well 3 will be warmed to a higher temperature than that which enters zones closer to the land surface. The amount of air that can be held in solution is an inverse function of the temperature of the solvent. Thus the air will have a

TABLE 4.—*Discharge and temperature of Mill Creek near Walla Walla*

[Measurements by Geological Survey]

Date	Discharge (cfs)	Temperature (°F)	Date	Discharge (cfs)	Temperature (°F)
1953			*1955*—Con.		
Aug. 21	36	70	Sept. 29	31	56
Sept. 2	39	52	Dec. 8	73	36
Oct. 6	36	49			
Oct. 7	36	48	*1956*		
			Jan. 26	134	35
1954			Mar. 15	582	42
Jan. 10	151	42	Apr. 18	226	45
Jan. 30	278	42	May 24	120	47
Mar. 19	88	40	July 4	40	59
June 12	173	50	Aug. 9	31	55
July 15	40	79	Sept. 20	33	51
Sept. 2	36	70	Oct. 25	42	45
Oct. 9	36	49	Dec. 11	459	40
Nov. 18	54	56			
Dec. 29	42	41	*1957*		
			Jan. 18	39	33
1955			Feb. 21	58	34
Jan. 28	69	33	Feb. 26	655	38
Mar. 10	112	37	Feb. 27	525	38
May 26	134	49	Mar. 14	143	39
July 12	40	54	Apr. 27	143	39
Aug. 25	28	67			

greater tendency to be expelled from solution in that part of Mill Creek water entering the deeper aquifers than in that part entering the shallower ones, provided that the pressures were identical. After injection, however, the pressure to which the recharged water will be subjected may range from slightly more than 1 to as much as 30 atmospheres, and the water that is warmed the most (in the deepest water-bearing zones) will be subjected to the greatest hydrostatic pressure. Because the effect of temperature increase in forcing air out of solution will be dominated by the effect of pressure increase in forcing the air to remain in solution, it seems very unlikely that bubbles from air in solution in the recharge water will form within the aquifers.

ENTRAINED AIR

The entrainment of air in the recharge water could be far more important than dissolved air in introducing air into the recharge system. As indicated in the foregoing section of the report, there is a definite upper limit on the amount of air that can be carried in solution. On the other hand, there is a much higher limit on the amount of air that can be carried along by the water column in the form of bubbles. This limit is a function of the mechanical characteristics of the recharge system.

The city officials of Walla Walla decided that Mill Creek water will be led into city well 3 through the pump column. This decision was made chiefly to enable water-level measurements to be made in the well during recharging.

In designing the recharge system it was necessary, therefore, to limit the rate of recharge to a value below which the pump column could act as a water barometer and could produce a pressure differential of 1 atmosphere on that part of the piping system. If a strong negative pressure should exist, all leaks in that section of the piping would allow air to enter. The air entering any leaks doubtless would be entrained because of the high linear velocity of the water falling through the column by gravity. At the planned rate of recharge, which is about 500 to 600 gpm, the pump column could run full only if the linear velocity of the water in the column were less than 4 to 7 fps (feet per second). The velocity will be much greater under the conditions of free fall due to gravity. Therefore, although conditions will be favorable for the entrainment of air, there should be little possibility of air entering the system to be captured by the falling water.

BIOLOGICAL SUITABILITY

The water injected into city well 3 was withdrawn from the city's pipeline downstream from the point where chlorine is added for sanitation purposes. The injection of chlorine is adjusted to maintain a residual chlorine content of 0.35 ppm. This residual is adequate to destroy pathogenic bacteria, but it is not sufficiently high to destroy the organisms that could cause difficulty when water is introduced underground.

These nuisance bacteria, although not disease-producing in humans, are generally undesirable in that they may color the water, produce slimes or other objectionable products, and cause unpleasant taste and odor. Several types of such organisms can exist in water. Of these, the iron bacteria and sulfur bacteria are common (Starkey, 1945); they can develop in water containing little or no organic material, but in which incompletely oxidized mineral substances occur. None of these bacteria exist in Mill Creek water in quantities great enough to be objectionable; otherwise it could not be used for public supply without heavy chlorination. However, if they were present to some extent and were introduced into the underground environment, where iron likely occurs in the ferrous state and where some sulfur may occur in an incompletely oxidized state as well, they could become abundant enough to plug the well and aquifer interstices.

To obtain information concerning the existence of these bacteria in Mill Creek water, a sample of the water was shipped to the Sanitary Engineering Section of the Washington State Institute of Technology at Pullman. The water sample was studied by Mitsuru Nakamura of that organization; neither the odor-producing bacteria nor the hydrogen sulfide producing and iron-depositing bacteria could be isolated, but, cultivation in the laboratory did produce a stringy growth.

The State of Washington Department of Health was requested by both the city of Walla Walla and the State of Washington Department of Conservation to examine the recharge plans and to provide an opinion on whether injection of Mill Creek water underground would be practicable with regard to the possible harmful effects of bacteria. That agency set forth the opinion that although *Sphaerotilus* (iron-producing) organisms are sometimes present in chlorinated Mill Creek water, they would not continue to flourish underground after recharge of Mill Creek water ceased.

These two reports were considered by the city to be adequate justification for minimizing the possible effects of well damage or water deterioration by nuisance bacteria.

ADEQUACY OF SUPPLY

During part of the year, the city of Walla Walla does not withdraw as much water from Mill Creek as it is entitled to, because of the seasonal variation in demand. During periods of peak demand, exceeding 14 mgd, the additional requirement is supplied by wells; and when Mill Creek water is too turbid to use, usually for only a few days at a time, ground water is substituted for the entire surface-water supply. During the rest of the year, some water from Mill Creek is available for injection into wells.

During the years 1954–57, the period for which water-use data were collected from the city, the city's water demand exceeded 14 mgd (Walla Walla's allotment) only during the 3- or 4-month period June to August or September.

Because of the sharp rise and decline of the demand curve prior to and after the seasonal peak, recharging could be undertaken for 8 to 9 months a year, which would result in a total yearly increment to the ground-water body of as much as 1,600 acre-feet. However, during short periods of storm runoff the flow of Mill Creek would be too turbid for recharge purposes.

No estimate of the city's water demand in future years has been made. Probably at least 1,000 gpm would be available for recharging no less than 9 months of the year, for many years in the future. Hence, a recharge program could become a valuable part of the city's water-supply system.

YIELD CHARACTERISTICS OF CITY WELL 3

As a part of the data-collection program, pumping tests were run on city well 3 to determine its yield and other hydraulic characteristics before the start of the artificial-recharge test. In all, 3 tests were made, 2 on May 28 and 29, 1957, and 1 on October 1 and 2.

During the pumping tests of May 28 and 29, city well 3 yielded about 1,800 gpm with a drawdown of about 52.5 feet, which represents a specific capacity (yield divided by drawdown) of about 35 gpm per ft. For the test of October 1 and 2, city well 3 yielded 1,630 gpm with a drawdown of about 45 feet—a specific capacity of 36 gpm per foot. The smaller yield for the October test resulted from a greater pumping lift, nearly 10 feet more than during the previous tests. In the period between the May and October tests a decline of 16 feet in static level had occurred.

Throughout these tests the levels in well 3 were measured by using a steel tape, but the levels in adjacent city wells 1 and 2, about three-quarters of a mile west, and the Olaus Filan well, three-quarters of a mile southeast (fig. 1), were measured by means of air gages. During the May tests, the level in well 1 declined about 2 feet and that in the Filan well declined about half a foot. During the pumping tests of October 1 and 2, the level in well 1 declined about 3.5 feet, but the Filan well was not affected to the extent that a water-level change could be detected by the air gage. In both the May and October tests, air-gage readings at well 2 were erratic, and no interpretation of them could be made.

Because of the inherent inaccuracies of measurements made by means of the air gages on the Filan and city wells, there is doubt about the amount of water-level decline actually due to the pumping of well 3. Any small regionwide trends of the water level that may have existed are unkown.

RECHARGE OF CITY WELL 3 WITH MILL CREEK WATER

Injection of water from Mill Creek into city well 3 was started on December 11, 1957, and terminated on January 8, 1958, after 71.3 acre-feet had been injected. Mill Creek water entered the well through a 6-inch branch line from the 20-inch city conduit. The rate of injection was measured by means of a displacement-type meter. Some adjustment of the valve in the 6-inch line was required to regulate the rate of flow into the well. Within 30 minutes after the start of injection at 8:29 a.m. the rate was adjusted at 630 gpm. Only slight deviation from this rate was noted during the progress of the experiment.

In 24 minutes the water level rose 10.65 feet and remained within 0.03 foot of that height for at least another 22 minutes. (See fig. 3.) The specific capacity for this short period was calculated from the figures 10.65 feet and 630 gpm to be 59 gpm per ft, more than half again as great as the specific capacity calculated from the pumping

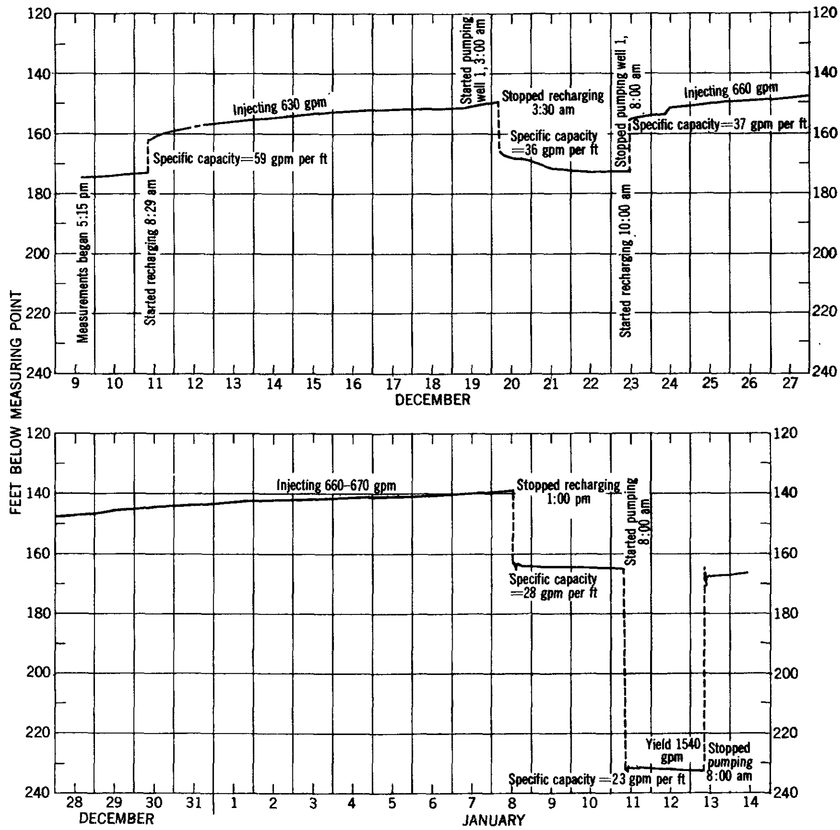

FIGURE 3.—Hydrograph of Walla Walla well 3 for the period Dec. 9, 1957–Jan. 14, 1958.

test, which was made at a greater rate and drawdown. The difference in specific capacity is probably due to the length of time involved and to the difference in the rates of pumping and recharging, or due to the effect this difference has on the entrance loss of the well.

After about a day of recharging, the water level in well 3 rose at a fairly constant rate. Because the rate should have diminished appreciably with time, possibly some progressive decrease in the water-receiving capacity was occurring. However, according to E. W. Reed (written communication, 1958) the linear relation of water-level rise to time may be only coincidental, or it may result from the existence of a complex set of hydraulic boundaries within the basalt aquifers.

On December 20, at 3:30 a.m., recharging was discontinued, because Mill Creek became turbid as a result of storm runoff. About half an hour before recharging was stopped, well 1 was turned on to supply the city's demand. Half an hour after recharging was stopped the water level in well 3 declined about 17.3 feet. During the next 3-day period the water level declined an additional 6 feet, partly because of the pumping of well 1.

The specific capacity of well 3 was computed by using 17.3 feet as the water-level change and 630 gpm as the flow rate, and a value of 36 gpm per ft was obtained, which is 23 gpm per ft less than that obtained on December 11 shortly after artificial recharging commenced.

By December 23 the flow in Mill Creek had cleared, and recharging at a rate of 660 gpm, was resumed at 10:00 a.m., 2 hours after well 1 was shut down. After 135 minutes (at 12:15 p.m.) the water level had risen 17.7 feet. The indicated specific capacity at that time was 37 gpm per ft. After 16 days of recharging, the water level had risen to a level of 33.2 feet above that held before the second period of recharging commenced.

On January 8 recharging was stopped, which caused a drop in water level of about 24 feet. By using 670 gpm as the flow rate near the end of the test, the specific capacity was found to be 28 gpm per ft at the time the recharging was ended. The water level in the well held nearly constant for the next 3 days while the pump was idle.

As part of the recharging test, periodic water-level measurements were made in well 1. These measurements are shown graphically on figure 4. As the graph shows, the level in the well was rising prior to the start of recharging. Possibly this represents a residual recovery of the water level from the drawdown caused by the pumping of all three wells on December 6 to 8. At the end of the first recharging period, on December 20, the level in well 1 had risen almost 7 feet; doubtless a substantial part of this rise can be attributed to the recharge at well 3.

Very few measurements of the water level in well 1 were made during the second recharging period. At the end of the second recharging period, on January 8, the level in well 1 had risen an additional 4 feet to about 105.5 feet below the measuring point, but it showed a reversal and a decline within 20 minutes after recharging was stopped (fig. 4). Because of outside effects, that part of the water-level rise due solely to recharging cannot be identified.

A few scattered measurements made in the Roy Frazier well indicate that the water level in that well may be affected by both pumping and artificial recharge of well 3 (fig. 2).

EFFECT OF RECHARGE ON THE YIELD CHARACTERISTICS OF CITY WELL 3

To permit evaluation of the effect of the recharging on city well 3, the well was pumped for a 48-hour period beginning at 8:00 a.m. on January 11, 1958.

Although the static level just prior to the start of pumping was

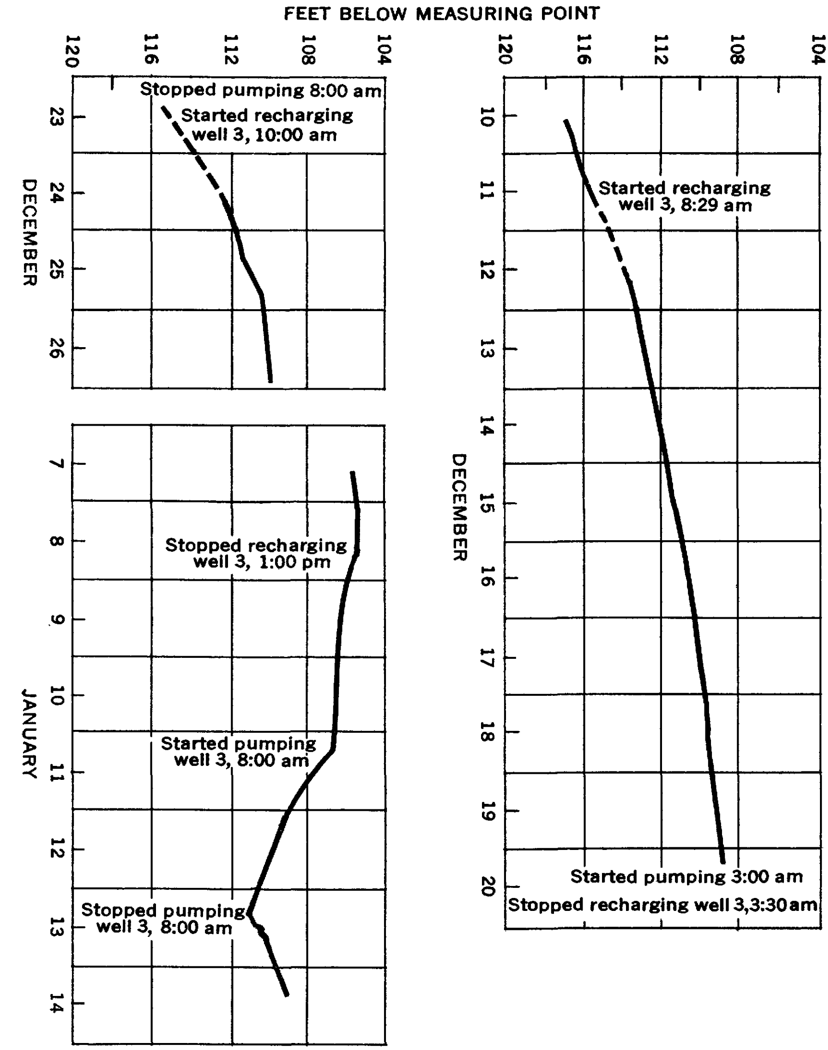

FIGURE 4.—Hydrograph of Walla Walla well 1 for the period Dec. 10, 1957–Jan. 14, 1958.

about 164 feet below the measuring point, or about 9 feet higher than before the recharge tests were run, the yield of the well was less, only 1,540 gpm, and the pumping level was 231 feet below the measuring point. The observed yield together with the drawdown of 67 feet represents a specific capacity of 23 gpm per ft, which is only about 65 percent of the pretest average specific capacity of 35. The yield was 95 percent of that (1,630 gpm) observed during the October test.

The lower specific capacity after recharging indicates that some deterioration in yield characteristics of the well occurred as a result of the artificial recharge experiment. At the beginning of the experiment the specific capacity was 59. As the experiment continued, the successive specific-capacity values were 36, 37, and 28. The drop from 59 to 36 represented a 40-percent decline during the first recharge period, when 24.3 acre-feet of water was introduced into the well. During the second period, in which 47.0 acre-feet was injected, a further decline of only 19 percent occurred. There is evidence, then, by using specific capacity as the criterion, that deterioration of the well was not linear and that if the recharge had been continued over a longer period less and less reduction would have accrued per unit quantity of water injected.

A water sample collected from the discharge pipe of well 3 on January 11, 1958, 30 minutes after pumping started, contained 76 ppm of suspended sediment. The water pumped before this time doubtless contained much more sediment. However, because of the arrangement of piping, it was not possible to sample the first water pumped. Within three-quarters of an hour after the start of pumping, the sediment content had dropped to 3 ppm. It is estimated that about 390 pounds of sediment was carried into the well by the 71.3 acre-feet of water recharged, and that somewhat less than half this amount, or about 150 pounds, was removed during the post-recharge pumping and surging period.

Well 3 was started again at 1:32 p.m. on January 14 and was then alternately stopped and started in a surging operation. This surging was done in an effort to restore the well's prerecharge specific capacity; however, no significant increase was detected.

RECOVERY OF INJECTED WATER

The difference between the specific conductance of Mill Creek water and that of native ground water from city well 3 was used to determine the approximate amount of injected water that was recovered during pumping of the well after completion of the recharge experiment. The specific conductance of water from well 3 was about 169 micromhos per centimeter at 25°C (table 2). That of Mill Creek water ranged from 53 to 64 micromhos in the samples collected December 11 to 28 from a faucet on the 20-inch line a few feet from the pumphouse at city well 3. (See table 5.)

The observed difference in specific conductance between the two waters results from their difference in concentration of dissolved solids. The relation between concentration of aqueous solutions and specific conductance is not exactly linear. However, within the limits

TABLE 5.—*Partial chemical analyses of water from Mill Creek*

[Where two or more samples are grouped, the analyses are averaged. Analyses by C. E. Price and A. A. Garrett]

Date	Time	Bicarbonate (HCO_3) (ppm)	Hardness as $CaCO_3$ (ppm)	Specific conductance (micromhos at 25°C)	Temperature (°F)
1957					
Dec. 11	12:40 p. m. 2:45 p.m.	38	21	58	40.5
Dec. 12	10:42 a.m. 1:45 p.m. 3:18 p.m. 4:22 p.m.	37	21	59	41.5
Dec. 13	8:30 a.m. 10:15 a.m. 11:40 a.m. 4:05 p.m.	37	23	63	----------
Dec. 14	10:45 a.m. 12:06 p.m.	37	22	61	----------
Dec. 16	9:10 a.m. 2:16 p.m.	39	23	64	44
Dec. 17	9:35 a.m. 12:35 p.m.	42	24	63	42
Dec. 18	9:02 a.m.	39	----------	60	41.5
Dec. 19	12:45 p.m.	38	22	57	39
Dec. 19	12:50 p.m.	33	23	62	39
Dec. 23	12:20 p.m.	34	22	54	----------
Dec. 26	8:00 a.m.	36	20	54	----------
Dec. 28	8:00 a.m.	33	20	53	----------

of accuracy of the specific conductance determinations, a linear relation is assumed. The deviation resulting from this assumption is of little consequence, because specific conductance for most of the samples is reported here to only two significant figures.

The range in the specific conductance of the samples of recharge water—from 53 to 64 micromhos—doubtless resulted in part from day-to-day changes in the concentration of dissolved solids in the water. Some of the variation may have been caused by differences in the length of time between the collection and the analysis of each sample. For example, the samples dated December 23, 26, and 28 were collected by the city's personnel and were not analyzed until January 11. The specific conductances of these samples are less than those of the samples that were collected and analyzed during the period December 11 to 19.

The ratio of the specific conductance of Mill Creek water to that of native ground water from well 3 was 60:169, or 0.36, at the time of the test, based on an approximate average specific conductance of 60 micromhos for Mill Creek water and on 169 micromhos for native ground water from well 3.

During the time that the well was pumped continuously from January 11 to 13, 1958, and also during three subsequent pumping periods, samples of water were collected from the pump discharge. The chemical analysis of these are listed in table 6.

TABLE 6.—*Partial chemical analyses of water from Walla Walla city well 3 after completion of recharge*

[Analyses by C. E. Price and A. A. Garrett; analytical results in parts per million]

Date	Time	Temperature (°F)	Bicarbonate (HCO_3)	Hardness as $CaCO_3$	Specific conductance (micromhos at 25°C)
1958					
Jan. 11	8:35 a.m.	39.5	40	24	64
	8:45 a.m.	39.5	38	24	63(?)
	9:00 a.m.		39	23	64
	9:25 a.m.	39.5	38	23	64
	10:00 a.m.		38	25	65
	1:30 p.m.	40.5	39	23	65
	5:38 p.m.		40	23	68
	10:20 p.m.	42.8	42	23	69
Jan. 12	10:20 a.m.	43.5	45	23	74
	3:50 p.m.	44.0	46	27	75
	11:00 p.m.	44.0	46	26	76
Jan. 13	7:05 a.m.	45.0	49	26	79
Jan. 14	3:35 p.m.	44.5	73	48	116
Feb. 21	12:30 p.m.	54.5	93	58	148
Feb. 26	6:50 a.m.	55.0	110	64	157

Table 6 shows a progressive increase in specific conductance, from 64 to 157 micromhos, in the 15 samples collected from the discharge of city well 3 from January 11 to February 26. The specific conductance of the first sample was only slightly more than the assumed average specific conductance of Mill Creek water as determined from the data presented in table 5. The specific-conductance sample collected on February 26 was more nearly that of native ground water. The foregoing data show that, at the beginning of the pumping period, the water pumped from well 3 was a blend of Mill Creek water and native ground water, with a very high proportion of Mill Creek water. As pumping continued, the proportion of native ground water in the well effluent became greater and greater, until on February 26 the effluent consisted largely of native ground water.

The specific conductances of the samples collected during the period of continuous pumping, which ended with the collection of the sample at 7:05 a.m. on January 13, show a roughly linear decrease with time in the amount of Mill Creek water recovered from the well. During this period of 2,825 minutes, about 13.5 acre-feet of water had been pumped from the well. Table 7 shows that by the end of this period about 12 acre-feet of Mill Creek water had been recovered, or about 17 percent of the amount injected during the experiment.

TABLE 7.—*Quantities of water pumped from Walla Walla city well 3 after completion of recharge*

Time pumping interval ended	Duration of interval (minutes)	Estimated average specific conductance during interval (micromhos at 25° C)	Cumulative yield [1]		
			Mill Creek water (acre-ft)	Native ground water (acre-ft)	Total (acre-ft)
9:25 a.m., Jan. 11	85	62	0. 400	0. 007	0. 407
10:00 a.m.	35	64. 5	. 561	. 014	. 575
1:30 p.m.	210	65	1. 52	. 06	1. 58
5:38 p.m.	248	66. 5	2. 64	. 13	2. 77
10:20 p.m.	282	68. 5	3. 88	. 24	4. 12
10:20 a.m.	720	71. 5	6. 97	. 60	7. 57
3:50 p.m., Jan. 12	330	74. 5	8. 34	. 81	9. 15
11:00 p.m.	430	75. 5	10. 1	1. 1	11. 2
7:05 a.m., Jan. 13	485	77. 5	12. 0	1. 5	13. 5
3:35 p.m., Jan. 14	[2] 178	97. 5	12. 6	1. 8	14. 4
12:30 p.m., Feb. 21	[3] 17, 515	137	37. 2	61. 1	98. 3
6:50 a.m., Feb. 26	[4] 1, 970	156	38. 4	70	108

[1] Computed by assuming an average pumping rate of 1,560 gpm.
[2] Pump idle from 8:00 a.m. Jan. 13 to 1:32 p.m. Jan. 14.
[3] Pump idle from 11:00 a.m. Jan. 15 to 9:00 a.m. Jan. 17 and from 8:00 a.m. Jan. 20 to 3:00 a.m. Feb. 13.
[4] Pump idle from 1:00 a.m. Feb. 21 to 10:00 p.m. Feb. 24.

The three random samples collected from city well 3 on January 14, February 21, and February 26, each during a separate pumping period, show a still further increase in specific conductance.

However, because these three pumping periods were interrupted by rather long intervals of inactivity, the average specific conductance of the effluent during the times that the well was being pumped (table 7) could be estimated only very roughly. Some change in the ratio of Mill Creek water to native ground water in the aquifers tapped by city well 3 doubtless occurred while the pump was idle. The magnitude of such change, is, of course, largely proportional to the rate of lateral ground-water movement within the aquifers. At least some of the increase in specific conductance of the sample collected at 3:35 p.m. on January 14 over that of the sample collected at 7:05 a.m. on January 13 no doubt occurred during the 1,772-minute shutdown between these two sampling times.

During the whole period of discontinuous pumping, which began at 8:00 a.m. on January 11 and ended at 6:50 a.m. on February 26, city well 3 yielded 108 acre-feet of water (table 7). About 38 acre-feet of Mill Creek water was recovered in that time. This amount is about 53 percent of the 71.3 acre-feet injected into city well 3 during the artificial-recharging experiment.

Incidental to the recharging test, water samples were collected from several wells near the injection well for partial analysis. Table 8 is a compilation of the partial analyses of these samples.

TABLE 8.—*Chemical analyses of water from selected wells in the Walla Walla basin*

[Analyses by C. E. Price]

Well	Date sampled, in 1958	Bicarbonate as HCO_3 (ppm)	Hardness as $CaCO_3$ (ppm)	Specific conductance (miromhos at 25°C)
Gerald Brunton well	Jan. 14	154	85	256
Robert Moore well	Jan. 13	134	79	230
Walla Walla well 1	Feb. 26	141	84	208
Do	Apr. 14	137	82	197
Walla Walla well 2	Feb. 26	112	74	180
Do	Apr. 14	121	77	181
Walla Walla well 4	Jan. 14	154	64	237

The quality of water pumped from city well 1, the nearest well to well 3 for which data are available for the period prior to the time of the recharge experiment, is known only from two analyses made in 1946 and 1953 (table 2). The water pumped from well 1 after the end of the experiment (table 8) was considerably higher in bicarbonate and was slightly harder than were the earlier samples. The increase in the concentration of dissolved solids between 1953 and 1958 demonstrates a significant change in quality of water, but it is probably not due to any effects of the artificial recharge.

The water sample from the Gerald Brunton well, which taps the gravel aquifer overlying the basalt, contained a high concentration of dissolved solids as compared with that of the samples taken from those tapping basalt aquifers (table 8). This fact suggests that the increase in dissolved solids observed in the samples taken from well 1 between 1953 and 1958 may be due to mixing of the water from the gravel with that from the underlying basalt aquifers. The increase also may be due, in part, to the drawing in of water from different parts of the basalt as the level of water in the well declined.

AQUIFER TRANSMISSIBILITY AND BOUNDARIES

Data obtained during the first pumping test, May 28, 1957, and during the recovery after the postrecharge pumping, January 11 to 13, 1958, were used to compute aquifer transmissibility (field permeability, in gallons per day per square foot, multiplied by aquifer thickness, in feet). The other pumping and recharging data seemed to be unsuitable for this purpose, because they were complicated by factors that cannot be evaluated quantitatively. The transmissibility as calculated from the first pumping test was 400,000 gpd per ft, and the transmissibility as computed from the postrecharge pumping test was 370,000 gpd per ft. Water-level measurements obtained from well 1 during the postrecharge pumping test suggest that the coefficient of storage was about 0.0002.

The indicated postrecharge transmissibility is only 8 percent less than the prerecharge transmissibility. However, the accuracy in transmissibility evaluations does not warrant conclusive interpretation from this one determination.

The water-level measurements obtained during the first recharge period, December 11 to 20, 1957, and during the recovery after the postrecharge pumping, January 11 to 13, 1958, suggest the existence of at least two nearly impermeable ground-water boundaries (possibly structural barriers) that restrict the movement of ground water in the vicinity of the city wells. The nearest boundary may trend about N. 80° W. and may pass through a point about 1.5 miles N. 10° E. of city well 3. The other boundary probably trends in a northerly direction and may pass through a point about 4 or 4.5 miles west of city well 3.

The long-term decline in water levels in the vicinity of city wells 1, 2, and 3 may be due in part to the presence of these two as well as other possible boundaries, which may restrict lateral percolation of water toward the wells.

CONCLUSIONS

The basalt aquifers tapped by city well 3 accepted 71.3 acre-feet of water from Mill Creek during a 26-day period of artificial recharge. Data obtained during the recharging experiment show that the performance of city well 3 deteriorated somewhat during this period, for a decline in both yield and specific capacity was noted. Three potential causes of yield deterioration have been recognized in this report: (a) sediment in the injected water, (b) dissolved air in the injected water, and (c) entrained or entrapped air that originated from leaks or undetected openings in the piping system. The relative importance of the three in causing the observed deterioration cannot be evaluated on the basis of the data now available. Possibly the decrease in yield and in specific capacity resulted from a combination of two or more of the potential causes cited above.

The continuous blast of air emanating from the measuring port during the artificial-recharge period suggests that large amounts of entrained air were being carried into the well with the recharge water. This premise is based on the fact that an internal source of air in such quantity is extremely difficult to postulate.

Although the source of the air could not be determined the air doubtless was carried into the casing by entrainment in the water falling in the pump column. If upon impact near the bottom of the well column many of these bubbles were broken into others so small that further entrainment downward could occur within the well, many of these would enter the aquifer interstices and cause substantial plugging.

Repeated surging of the well did not improve its performance characteristics, even after almost half the estimated 390 pounds of sediment carried into the aquifer with the injection water was recovered. Thus the sediment content of the injected Mill Creek water probably was not a prime cause of plugging. Also, there seems to be no obvious way for the dissolved air to impair the well or aquifer, inasmuch as it is not likely to be released from solution. It is true, of course, that oxidation of ferrous salts in solution to the insoluble ferric hydroxide would be a possible cause of aquifer plugging if enough ferrous iron were present to yield large quantities of precipitate. However, analytical data presented earlier show that the amount of iron in solution in native ground water from city well 3 is extremely small.

On the other hand, the sediment remaining in the well or in the aquifer immediately adjacent to the well may have a deleterious effect far greater than might be supposed from the small amount of sediment involved. Further, the oxidation of ferrous iron in the ground water by the air entering the aquifer, if it occurs at all, may have a much greater effect than is now suspected.

The air entrapped in the Mill Creek water could be removed by passing the water through deaeration equipment prior to its injection into the well. Use of a regulator foot valve at the bottom of the pump column would prevent the free fall of water and would virtually eliminate the problem of air coming out of solution above the water level in the pump column. Filter beds could be used to remove the sediment prior to injection of the water into the well.

The decision to continue experiments at city well 3 must be based on a realistic appraisal of all pertinent factors. The inherent risk of ultimate permanent damage to the well conceivably could be a strong deterrent to the continuation of the experiments. Three of the important factors that should be considered in arriving at a decision are:

1. Periodic redevelopment of the well by the use of chemical agents and other techniques might become an integral part of any long-term program of recharge. A chemical washing agent proved satisfactory in the redevelopment of an injection well in the Grand Prairie region of Arkansas (Sniegocki, 1957). Although the aquifers involved are different lithologically, a similar redevelopment procedure might be employed at city well 3 in the event that considerable loss in yield occurred.
2. A definite need for recharge exists in the general area of city wells 1, 2, and 3. Water-level gradients here seem to be consistently low, of which one cause could be the existence of the hydraulic bound-

aries detected during the recharging experiment. These boundaries may limit the natural recharge of this area. Therefore the small long-term water-level decline indicated by the series of water-level measurements that were begun in the early forties likely indicates local overdraft. If an overdraft is occurring, water will have to be pumped from increasingly greater depths with consequent increased pumping costs. Artificial recharge could be used to augment the supply.

If the air entrapment and sediment problem can be resolved, as described, alternate recharging and pumping of city well 3 could be tried, for this procedure might help sustain the highest possible specific capacities. Recharge water could be injected into the well for a selected period of time, and then the well could be pumped for a short while. Experimentation of this type probably would determine the most effective periods of alternate recharge and pumping. For example, it is suggested that recharge water be injected for about 2 days and that the well be pumped for about 2 hours to determine any change in yield and drawdown. If no appreciable deterioration occurs, a longer period of recharging could be tried.

3. The water system of the city of Walla Walla is ideally arranged to supply large quantities of water from Mill Creek for artificial recharge with a minimum of attention. During the test 71.3 acre-feet (23.2 million gallons) was injected in city well 3 at virtually no cost except that for the installation of the crossover piping. Because of the readily available supply of Mill Creek water for recharging and the definite gain that would be derived by the city from a recharge program, provided that a technique having no serious adverse effect on well or aquifers could be developed, continuation of the experiments seems worthwhile.

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