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DIVISION OF WATER RESOURCES
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Artificial Recharge of a Well Tapping Basalt Aquifers, Walla Walla Area, Washington

By

Charles E. Price

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FOREWORD

For many years there has been a progressive water-level decline in some wells taking water from artesian zones of the Columbia River basalt of the Walla Walla basin. Because of this decline, it became apparent that the Division of Water Resources through administrative authority, must eventually limit the total annual pumpage of water from the basalt aquifers or implement a program whereby the safe sustaining yield could be materially increased. In 1951 a well spacing program was adopted designed to maintain a reasonable distance between wells pumping from the artesian zones. This, together with permitting a greater seasonal lowering of the water table, made possible an increased annual withdrawal from the basin with reasonable assurance that water withdrawn would be replaced annually by natural recharge. Hydrographs of observation wells suggest that the program was generally successful with the exception of the subbasin in which Walla Walla city wells 1, 2, and 3 are located where water levels continued to decline.

This succession of events led the Division of Water Resources to request the cooperation of the Geological Survey, Ground Water Branch, in a program to evaluate the possibility of supplementing the water supply in basalt aquifers by artificial recharge through injection wells.

We were very fortunate to receive approval from the city of Walla Walla officials to use their water supply facilities for the recharge experiment without which the project would not have been economically feasible since it would have required an expenditure of about $100,000 to duplicate their facilities.

The results and conclusions of this experiment are gratifying and have a great economic value. These data may be used not only by the city of Walla Walla but by other cities and agencies who develop water supplies from the Columbia River basalt and to a lesser degree these data are applicable to wells penetrating other igneous and consolidated sedimentary rocks.

The Columbia River basalt of Eastern Washington contains natural reservoirs with capacities to store millions of acre-feet of water without the necessity of constructing costly dams and canals or filtering plants. The Division of Water Resources should continue its support of research toward a better understanding of these rocks and the occurrence and behaviour of ground water within them. The report just completed is a valuable contribution to our understanding of the hydrology of the State of Washington.

My association with the Geological Survey, Ground Water Branch, and officials of the city of Walla Walla, in planning and carrying out the recharge experiment has been a most pleasant experience and it is my hope that through mutual agreement the next phase of recharge can be started with the least possible delay.

I respectfully submit herewith this report entitled "Artificial Recharge of a Well Tapping Basalt Aquifers, Walla Walla Area, Washington," by Charles E. Price.

-Robert H. Russell
Assistant Supervisor
Division of Water Resources

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By Charles E. Price

ABSTRACT

Declining water levels in part of the Columbia lava plateau, due to pumping, have caused concern for a number of years. Therefore, the U. S. Geological Survey in cooperation with the Washington State 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 gpm (gallons per minute). The chemical and bacteriological quality of the injected water was excellent, and the water contained only 2 ppm (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 test 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 gpd (gallons per day) per foot, and 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, Washington. The investigation was begun in 1956 as a result of conferences among the U. S. Geological Survey, the Washington State 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 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 has considered for several years 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. During a part of each year, excess surface water is available for recharge. 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 because of the interest of the State and Federal agencies in recharge from the standpoint of conservation in general. The Geological Survey undertook this project to investigate the feasibility of recharge through wells, supervised the experimental work, and determined the effect of such recharge on the injection well and on the basalt tapped by the well.

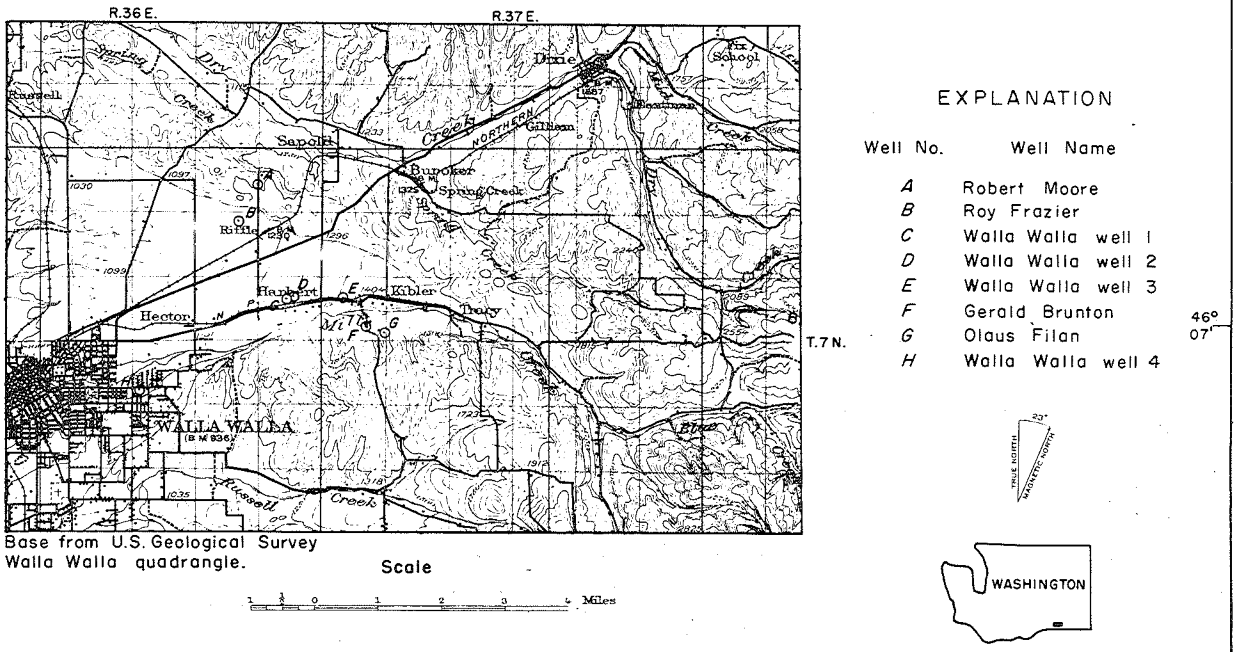
The fieldwork was done jointly by the Geological Survey and the Washington State Department of Conservation, under the supervision of A. A. Garrett, District Engineer, Ground Water Branch, and R. H. Russell, Assistant Supervisor, State Division of Water Resources. The section of this report dealing with 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).

Acknowledgements

The writer wishes to acknowledge the assistance of Mr. Paul F. Meyer, Water Superintendent of Walla Walla, and other city personnel. Without the use of the city's facilities and



Base from U.S. Geological Survey
Walla Walla quadrangle.

EXPLANATION

Well No.	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 area showing locations of wells

the excellent cooperation of the Water Department, the collection of many important data would not have been possible.

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 is an east-west-trending topographic and structural basin which 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 easternmost portion of this valley.

The Walla Walla basin is underlain by a series of lava flows which 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 east-west-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. In this basin, the sequence of lava flows 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 in drilling in the Walla Walla basin. About 35 miles northeast of Walla Walla, in the Tucannon River canyon, a few small "windows" of Paleozoic (?) and Mesozoic (?) sedimentary and igneous rocks are exposed beneath the basalt, according to Huntting (oral Communication) which in that vicinity is known to be 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 and Son, 1942.

Materials	Thickness (feet)	Depth (feet)
Soil --	8	8
Gravel, clay, boulders-----------------------	51	59

Table 1.--Abridged drillers' logs of wells (Continued)

Well 1, city of Walla Walla. Altitude about 1,260 ft. Drilled by A. A. Durand & Son, 1942 . Continued

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

Casing, 10-inch to 363 ft.

Well 2, city of Walla Walla. Altitude about 1,273 ft. Drilled by A. A. Durand & Son, 1942.

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

Casing, 16-inch to 140 ft.

Table 1.--Abridged drillers' logs of wells--Con.

Well 3, city of Walla Walla. Altitude about 1,317 ft. Drilled by A. A. Durand & Son, 1947.

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

Casing, 20-inch to 178 ft. 16-inch from 1,063 to 1,102 ft.

Well 4, city of Walla Walla. Altitude about 1,045 ft. Drilled by A. A. Durand & Son, 1953.

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

Casing, 24-inch to 400 ft.

Table 1--Abridged drillers' logs of wells--Con.

Gerald Brunton well. Altitude about 1,350 ft. Drilled by W. E. Ruther & Son, 1957,

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

Casing, 6-inch to about 30 ft.

Olaus Filan well. Altitude about 1,400 ft. Drilled by George E. Scott, 1951

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

Casing, 12-inch to 102 ft.

Roy Frazier well. Altitude about 1,190 ft. Drilled by George E. Scott, 1947

Materials	Thickness (feet)	Depth (feet)
Clay, yellow	13	13
Gravel, dirty	84	97
Clay, yellow	11	108
Gravel	6	114
Clay, gravel	41	155
Clay, yellow	6	161
Gravel, cemented	9	170

Table 1--Abridged drillers' logs of wells--Con.

Roy Frazier well. Altitude about 1,190 ft. Drilled by George E. Scott, 1947-Continued

Materials	Thickness (feet)	Depth (feet)
Basalt, black, gray	431	601
Shale, dark, sticky	3	604
Basalt, black, and gray	203	807

Casing, 16-inch to 170 ft.

Robert Moore well. Altitude about 1,225 ft. Drilled by A. A. Durand & Son, 1955.

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

Casing, 12-inch to 164 ft.

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° to 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, pointing downstream. This outcrop geometry forms a favorable situation for natural recharge of ground water into the permeable layers cropping out in the stream channels.

In the area adjacent to the recharge well, however, hydraulic boundaries seem to occur in a pattern such that insufficient natural recharge water is reaching that area. This isolation from natural recharge results in the replenishment being less than the withdrawal, as shown by long-term decline in ground-water levels in the city wells, 1, 2, and 3 (p.11).

In the Walla Walla area the basalt is dark gray, brown, or black and contains finely felted microscopic crystallites in a glassy ground mass (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 former cuts the lava into rude six-sided and four-sided joint columns, and the latter 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, others are suspected in certain places, and many others undoubtedly exist. In the area adjacent to the injection well the basalt is overlain by 145 feet of gravel, sand, and clay.

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 the unhealed fragmentation and inflated character of the basalt at the top of some of the flows. Although these interflow zones may be fairly extensive, their transmissibilities vary 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, which is a few miles southwest of Walla Walla. Beneath the valley floor here the basalt aquifers locally contain water under sufficient hydraulic head that when tapped by wells it flows at the surface or stands but a few feet below the surface.

An important factor in planning a program of artificial recharge is 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 which 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, some 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--from high to lower parts of the basin. In the area 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 construction of a meaningful water-level contour map. When virtually simultaneous determinations of static water levels were made in wells 1 and 3 on May 27, 28, October 1, and December 11, 1957, and January 11, 1958, the levels at 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, the sensitivity of which was too low 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. It is possible that either a northerly or a southerly component of gradient may exist here.

The existence of impermeable boundaries adjacent to the recharge area may have an appreciable, but unevaluated, effect on the direction of water movement. Elsewhere in the Walla Walla area hydraulic boundaries exist (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, 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.

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

There is relatively large seasonal fluctuation of water level in wells in and adjacent to city wells 1, 2, and 3. 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 suggests strongly that the two are hydraulically interconnected.

The long-term decline in levels points out the need for conservation measures; the decline indicates that there is more water pumped from the basalt aquifers in the immediate area than is 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 on 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 which 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 it is 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, over the top of which the water spills into a vertical annular duct leading 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 the location of 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 has 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

There are many factors that 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.

In the preliminary study made by Hart (1957) and in this investigation, the quality of Mill Creek water was thoroughly investigated and an evaluation was made of the suitability of this water for injection underground.

Chemical Compatibility

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.

A comparison of Mill Creek water with water from city well 3 (table 2) can be made by expressing the analyses of both in terms of percentage equivalents per million of total cations and total anions._/ For purposes of comparison, the analysis of water from well 3 and that of the Mill Creek 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 the foregoing tabular comparison that both waters are of the same type, in that the dissolved solids in both predominate in alkaline earth (Ca and Mg) bicarbonates. In addition to the dissolved constituents is silica, equivalent to 46 and 42 percent of the dissolved solids in the two waters.

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. Because the chemical character of both waters is nearly identical, the only effect that could take place from blending the two would be a dilution of the ground

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_/ 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 of water from city wells 1, 3, and 4, and from Mill Creek.
(parts per million)

Source of sample Date of collection	City well 1 11/26/46	City well 1 4/23/53	City well 3 1/28/57	City well 4 10/9/53	Mill Creek (1) 4/23/53	Mill Creek (2) 3/26/57	Mill Creek (2) 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)	(	(	9.3	(	(	1.8	1.8
	7.1	7.4		29	6.4		
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	a208	86(?)	60	61
Hardness as $CaCO_3$	76	69	69	a68	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	Charlton Lab. Portland	USGS	Charlton Lab. Portland	Charlton Lab. Portland	USGS	USGS

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

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

Sediment is one of the major problems when unfiltered surface water is injected directly into a well; therefore, water used for recharging ground-water reservoirs should be as free of sediment as possible.

Because of economic considerations, the ground-water recharge program at Walla Walla was carried out with unfiltered surface water. Consequently, it was necessary to determine the magnitude of the sediment load carried by Mill Creek and to evaluate the extent to which sediment would plug the well and 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 city 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, Oregon. 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 to 28, 1957, when the latter 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.

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 which can clog an aquifer. For example, iron contained in ground water is usually present in the partially oxidized ferrous state; upon further oxidation by contact with injected air, the iron may precipitate as a ferric iron compound. Also, 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 containing 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 (1957)	Dissolved oxygen (parts per million)
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

Table 4.--Discharge and temperature of Mill Creek near Walla Walla (Measurements by Geological Survey)

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

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° to 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 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 of its discharge into the city reservoir, was 59°F. The observed temperature of 59°F results 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. Therefore, the tendency would be greater for air 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. However, after injection, the pressure to which the recharged water will be subjected may range from slightly more than 1 to as much as 30 atmospheres, the water that is warmed the most (in the deepest water-bearing zones) being 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 will form within the aquifers because of the existence of air in solution in the recharge water.

Entrained Air

It is believed that 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.

It has been determined that Mill Creek water will be led into city well 3 through the pump column. This decision was made by city officials chiefly to enable water-level measurements to be made in the well during recharging. Although no provision is planned for measuring water pressure in the crossover line between the 20-inch supply line and the well, specifically between the control valve and the pump column, there is every reason to believe that the pressure will be nil or slightly negative. If a negative pressure should exist, which is virtually a certainty if the rate of recharge is great enough that the pump column is carrying a full cross section of water, all leaks in this section of the system would allow air to enter. The air doubtless would be entrained because of the high linear velocity of the water falling through the column by gravity.

From the foregoing consideration, it would seem imperative to limit the rate of inflow to a value below which the pump column could act as a "barometric leg" and produce a pressure differential of 1 atmosphere on that part of the piping system. In designing the recharging system, this factor was taken into consideration by limiting the rate of recharge to a point below which the pump column will be full of water at any time. At the planned rate of recharge, about 500 to 600 gpm, the pump column could run full only if the linear velocity of water in the column were less than 4 to 7 fps (feet per second). Under the conditions of free fall due to gravity, the velocity will be much greater. 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, although adequate to destroy pathogenic bacteria, 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, generally are undesirable in that they may color the water, may produce slimes or other objectionable products, and may 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). These can develop in water containing little or no organic material but in which incompletely oxidized mineral substances occur. None of these 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 these were present to some extent, their introduction 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, could enable them to develop to the point where the well and aquifer interstices would become plugged.

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. In a study of the water sample by Mitsuru Nakamura of that organization, neither the odor-producing bacteria nor the hydrogen sulfide-producing and iron-depositing bacteria could be isolated. However, cultivation in the laboratory did produce a stringy growth.

The Washington State Department of Health was requested by both the city of Walla Walla and the State Department of Conservation to examine the recharge plans and to provide an opinion on whether injection of Mill Creek water underground would be practicable, from the standpoint of 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 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 from Mill Creek as much water 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 for use, usually for only a few days at a time, ground water is substituted for the entire surface-water supply. During the remainder of the year, some water from Mill Creek is available for injection into wells.

During the years 1954 to 1957, the period for which water-use data were collected from the city, the city's water demand was in excess of 14 mgd (Walla Walla's allotment) only during the 3- or 4-month periods June to August or September.

Because of the sharp rise and decline of the demand curve prior to and after the seasonal peak, it is likely that recharging could be undertaken during 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. However, probably at least 1,000 gpm would be available for recharging during at least 9 months of the year, for many years in the future. Hence,a recharge program, if initiated, 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 and 1 on October 1 and 2, 1957.

During the pumping tests of May 28 and 29 (see table 9 for water-level measurements) city well 3 yielded about 1,800 gpm with a drawdown of about 52½ feet, which represents a specific capacity (yield divided by drawdown) of about 35 gpm per foot. During the test of October 1 and 2, city well 3 yielded 1,630 gpm with a drawdown of about 45 feet, representing a specific capacity of 36 gpm per foot. The smaller yield during the test in October resulted from a greater pumping lift, nearly 10 feet more than during the previous tests. During the period between the May and October tests, a decline of 16 feet in static level had occurred.

Although during these tests the levels in well 3 were measured by a steel tape with a precision of 0.01 foot, 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 3½ 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 unknown.

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 and table 9.) From the figures 10.65 feet and 630 gpm, the specific capacity for this short period is calculated to be 59 gpm per foot, more than half again as great as the specific capacity calculated from the pumping test, which was made at a greater rate and drawdown. The difference in specific capacity probably is due to the length of time involved, and to the difference in the rates of pumping and recharging or to the extent that this difference affects 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, it is possible that some progressive decrease in water-receiving capacity was occurring. However, according to E. W. Reed (personal 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 17.30 feet (see table 9). During the next 3-day period the water level declined an additional 6 feet, partly because of the pumping of well 1.

Using 17.30 feet as the water-level change and 630 gpm as the flow rate, a specific capacity of 36 gpm per foot is obtained. This value is 23 gpm per foot less than that obtained on December 11, shortly after artificial recharging commenced. However, it is realized that this apparent decrease is due in small part to the pumping of well 1.

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 foot. 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. Using 670 gpm as the flow rate near the end of the test, the specific capacity was found to be 28 gpm per foot 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 listed in table 9 and 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.

During the second recharging period, very few measurements of the water level in well 1 were made. 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.

Within 20 minutes after cessation of recharging the water level in well 1 showed a reversal and a decline (fig.4). Because of outside effects, that part of the water-level rise due solely to recharging cannot be identified.

A few scattered measurements 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 IN 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 about 164 feet below the measuring point, about 9 feet higher than that 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 foot, 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, using specific capacity as the criterion, that deterioration of the well was not linear, and that, had the recharge 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, or about 150 pounds, was removed during the postrecharge pumping and surging period.

Well 3 was started again at 1:32 p.m. on January 14, and then was 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

Advantage was taken of the difference in specific conductance of Mill Creek water and native ground water from city well 3 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 on the basis of samples collected through the period 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.)

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.	38	21	58	40.5
	2:45 p.m.				
Dec.12	10:42 a.m.	37	21	59	41.5
	1:45 p.m.				
	3:18 p.m.				
	4:22 p.m.				

Table 5.--Partial chemical analyses of water from Mill Creek. Continued

Date	Time	Bicarbonate (HCO_3) (ppm)	Hardness as $CaCO_3$	Specific conductance (micromhos at 25°C)	Temperature °F
1957					
Dec. 13	8:30 a.m.				
	10:15 a.m.				
		37	23	63	--
	11:40 a.m.				
	4:05 p.m.				
Dec.14	10:45 a.m.				
		37	22	61	--
	12:06 p.m.				
Dec.16	9:10 a.m.				
		39	23	64	44
	2:16 p.m.				
Dec.17	9:35 a.m.				
		42	24	63	42
	12:35 p.m.				
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	--

The observed difference in specific conductance of the two waters results from the difference in concentration of dissolved solids in the two. The relationship between concentration of aqueous solutions and specific conductance is not exactly linear. However, within the limits of accuracy of the specific conductance determinations, a linear relationship 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 specific conductance of the samples of recharge water--from 53 to 64 micromhos--doubtless resulted in part from day-to-day changes in 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 analysis of each sample. For example, the samples dated December 23, 26, and 28 were collected by city 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.

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 at the time of the test, the ratio of the two was 60/169, or 0.36.

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 analyses 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; chemical constituents 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 trend in specific conductance, from 64 to 157 micromhos, in the 15 samples collected from the discharge of city well 3 through the period 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.

Pumping interval ended	Duration of interval (minutes)	Estimated average specific conductance during interval (micromhos)	Cumulative yield[a]		
			Mill Creek water (acre-feet)	Native ground water (acre-feet)	Total (acre-feet)
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	178[b]	97.5	12.6	1.8	14.4
12:30 p.m. Feb.21	17,515[c]	137	37.2	61.1	98.3
6:50 a.m. Feb.26	1,970[d]	156	38.4	70	108

a Assuming an average pumping rate of 1,560 gpm
b Pump idle from 8:00 a.m., Jan. 13, to 1:32 p.m.,Jan. 14
c 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.
d 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 of course, is 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, doubtless 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). During this period about 38 acre-feet of Mill Creek water was recovered. 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, Geological Survey)

Owner	Date sampled	Bicarbonate (HCO_3) (ppm)	Hardness as $CaCO_3$ (ppm)	Specific electrical conductance (micromhos at 25°C)
Gerald Brunton	1-14-58	154	85	256
Robert Moore	1-13-58	134	79	230
Walla Walla well 1	2-26-58	141	84	208
Do.	4-14-58	137	82	197
Walla Walla well 2	2-26-58	112	74	180
Do.	4-14-58	121	77	181
Walla Walla well 4	1-14-58	154	64	237

The quality of water pumped from city well 1, the nearest 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 water character but 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 to the samples taken from nearby wells tapping basalt aquifers. This suggests that the difference in dissolved solids observed in samples from well 1 from 1953 to 1958 may be due to mixing of the water from the gravel with that from the underlying basalt aquifers, or 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 not to be suitable 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 foot, and the transmissibility as computed from the postrecharge pumping test was 370,000 gpd per foot. 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 groundwater 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 1½ 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 4½ 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 some deterioration in performance of city well 3 occurred during this period; a decline in both yield and specific capacity was noted. Three potential causes of yield deterioration have been recognized in this report: (1) sediment in the injected water, (2) dissolved air in the injected water, and (3) 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. It is possible, of course, that 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. If, during free fall of water in the pump column, water bubbles were of such size that further entrainment downward could occur within the well, many of those bubbles 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 present 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. However, there are three important factors that should be considered in arriving at a decision:

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

If the air entrapment and sediment problem can be resolved, as described above, alternate recharging and pumping of city well 3 could be tried, as this procedure might help sustain the highest possible specific capacities. Recharge water might 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 has occurred, 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 because of the definite gain that would be derived by the city from a recharge program, provided that a technique could be developed having no serious adverse effect on well or aquifer, continuation of the experiments would seem worthwhile.

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Table 9.--Water-level measurements in observation wells in the recharge area.

(Measurements, in feet below measuring point, by Geological Survey, except as noted.)

City of Walla Walla well 1

(Altitude of measuring point, 1,260 feet above mean sea level.)

Time	Depth to water (feet)	Remarks
		May 27, 1957
3:45 p.m.	[a]107	
		May 28, 1957
7:18 a.m.	[a]108	
8:25	[a]108	
8:30	..	Started pumping well 3
9:17	[a]108	
10:15	[a]108	
1:04 p.m.	..	Stopped pumping well 3
6:00	..	Started pumping well 3
		May 29, 1957
5:41 a.m.	[a]110	
6:00	..	Stopped pumping well 3
7:05	[a]109	
9:06	[a]109	
		Sept. 30, 1957
4:35 p.m.	[a]123	
		Oct. 1, 1957
10:16 a.m.	[a]123	
1:39 p.m.	[a]123	
2:00	..	Started pumping well 3
6:05	[a]124	
9:20	[a]125	
		October 2,1957
12:53 a.m.	[a]125	
9:44	[a]126+	
11:20	[a]126+	
1:43 p.m.	[a]126.5	
2:00	..	Stopped pumping well 3
		Dec. 6, 1957
3:55 p.m.	[a,b]114	
4:00	..	Started pumping wells 1, 2, and 3.
4:10	..	Yield 1,800 gpm.
		Dec. 7, 1957
..	[a,b]145	Yield 1,780 gpm.
		Dec. 8, 1957
9:00 a.m.	..	Stopped pumping wells 1, 2, and 3.
		Dec. 10, 1957
2:00 p.m.	116.88	
5:03	116.69	
5:20	116.69	
		Dec. 11, 1957
8:07 a.m.	115.99	

[a] See footnotes at end of table.

Table 9.--Water-level measurements in observation wells in the recharge area.--Con.

City of Walla Walla well 1--Con.

Time	Depth to water (feet)	Remarks
		Dec. 11, 1957--Con.
8:29 a.m.	..	Started recharging well 3.
9:30	116.06	
9:32	115.78	
9:34	115.80	
10:45	115.62	
12:16 p.m.	115.45	
1:20	115.36	
3:00	115.25	
4:26	115.11	
10:26	113.99	
		Dec. 12, 1957
8:35 a.m.	114.05	
11:20	113.83	
1:58 p.m.	113.74	
4:08	113.64	
10:26	113.37	
		Dec. 13, 1957
8:05 a.m.	113.00	
10:25	112.90	
11:27	112.82	
1:22 p.m.	112.79	
4:12	112.78	
		Dec. 14, 1957
10:23 a.m.	112.19	
1:22 p.m.	112.13	
4:27	112.07	
		Dec. 16, 1957
8:58 a.m.	110.82	
1:55 p.m.	110.69	
4:53	110.63	
		Dec. 17, 1957
9:10 a.m.	110.32	
1:17 p.m.	110.25	
4:10	110.18	
		Dec. 18, 1957
8:53 a.m.	109.92	
11:06	109.93	
11:11	109.95	
1:10 p.m.	109.91	
3:21	109.87	
5:12	109.90	
		Dec. 19, 1957
8:39 a.m.	109.53	
12:30 p.m.	109.45	
5:37	109.40	
		Dec. 20, 1957
2:55 a.m.	[b]109.29	
3:00	..	Started pumping
3:30	..	Stopped recharging well 3.
8:29	127.83	Yield 1,850 gpm.
		Dec. 23, 1957
8:00 a.m.	..	Stopped pumping.

Table 9.--Water-level measurements in observation wells in the recharge area.--Con.

City of Walla Walla well 1--Con.

Time	Depth to water (feet)	Remarks
		Dec. 23, 1957--Con.
10:00 a.m.	..	Started recharging well 3.
11:55 a.m.	b115.33	
		Dec. 24, 1957
12:30 p.m.	b112.39	
		Dec. 25, 1957
8:20 a.m.	b111.45	
8:20 p.m.	b110.51	
		Dec. 26, 1957
7:45 a.m.	b110.32	
7:45 p.m.	b110.17	
		Jan. 7, 1958
5:19 p.m.	105.91	
		Jan. 8, 1958
11:16 a.m.	105.49	
1:00 p.m.	..	Stopped recharging well 3.
1:13 p.m.	105.48	
1:16	105.49	
1:20	105.50	
1:31	105.52	
1:40	105.52	
1:50	105.54	
2:00	105.55	
3:00	105.66	
4:02	105.77	
4:04	105.75	
6:15	105.88	
		Jan. 8, 1958--Con.
8:53 p.m.	106.04	
		Jan. 9, 1958
12:10 a.m.	106.20	
6:22	106.22	
11:21	106.34	
12:35 p.m.	106.36	
4:18	106.39	
4:23	106.39	
10:24	106.39	
10:29	106.38	
		Jan. 10, 1958
8:11 a.m.	106.40	
8:12	106.40	
2:18 p.m.	106.56	
2:22	106.55	
6:02	106.51	
		Jan. 11, 1958
12:03 a.m.	106.57	
7:51	106.65	
7:55	106.65	
8:00	..	Started pumping well 3.
8:05	106.67	
8:07	106.66	
8:10	106.66	
8:15	106.70	
8:20	106.73	

Table 9.--Water-level measurements in observation wells in the recharge area.--Con.

City of Walla Walla well 1 --Con.

Time	Depth to water (feet)	Remarks
		Jan. 11, 1958--Con.
8:25 a.m.	106.75	
8:30	106.78	
8:40	106.84	
8:50	106.91	
9:00	106.95	
9:15	107.02	
9:30	107.08	
9:45	107.14	
10:00	107.21	
10:18	107.29	
11:11	107.43	
11:15	107.44	
12:00 m.	107.56	
12:35 p.m.	107.65	
1:01	107.72	
1:32	107.81	
5:25	108.34	
5:28	108.34	
10:05	108.71	
10:09	108.71	
		Jan. 12, 1958
10:11 a.m.	109.49	
10:13	109.49	
4:10 p.m.	109.84	
4:13	109.83	
10:46	110.25	
		Jan. 12, 1958-Con.
10:49 p.m.	110.24	
		Jan. 13, 1958
7:00 a.m.	110.74	
7:05	110.74	
7:42	110.79	
7:44	110.79	
7:56	110.82	
8:00	..	Stopped pumping well 3.
8:03	110.82	
8:05	110.82	
8:10	110.78	
8:15	110.79	
8:20	110.76	
8:25	110.75	
8:30	110.73	
8:40	110.68	
8:50	110.64	
9:00	110.60	
9:15	110.55	
9:30	110.52	
9:45	110.45	
10:00	110.41	
10:15	110.38	
10:30	110.33	
11:03	110.26	
11:30	110.18	

Table 9.--Water-level measurements in observation wells in the recharge area.--Con.

City of Walla Walla well 1--Con.

Time	Depth to water (feet)	Remarks	Time	Depth to water (feet)	Remarks
		Jan. 13, 1958--Con.			
12:00 m.	110.13				
12:21 p.m.	110.08				
1:27	109.98				
1:59	109.94				
2:53	109.87				
3:30	109.83				
4:32	109.80				
5:59	109.72				
11:52	109.27				
11:55	109.27				
		Jan. 14, 1958			
9:05 a.m.	108.78				
9:11	108.78				
11:37	108.68				
11:39	108.67				

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3

(Altitude of measuring point, 1,317 feet above mean sea level.)

Time	Depth to water (feet)	Remarks
	May 27, 1957	
4:18 p.m.	164.05	
4:26	164.04	
4:35	164.04	
4:44	164.03	
4:56	164.03	
5:02	164.02	
7:05	164.00	
7:06	164.00	
8:58	164.03	
9:02	164.02	
	May 28, 1957	
6:51 a.m.	164.03	
6:55	164.03	
7:06	164.04	
8:19	164.07	
8:30	..	Started pumping
8:50	a205	
9:20	..	Yield 1,810 gpm
9:45	a207	
10:05	a207	
10:18	..	Yield 1,810 gpm
11:24	c217.03	Yield 1,810 gpm
11:31	c217.08	
11:40	216.50	
11:44	216.24	
	May 28, 1957	
11:48 a.m.	216.39	
1:04 p.m.	..	Stopped pumping
1:24	166.21	
1:27	166.02	
1:33	165.84	
1:37	165.72	
1:40	165.65	
1:45	165.55	
1:50	165.47	
2:00	165.31	
2:15	165.14	
2:30	165.02	
2:45	164.92	
3:00	164.84	
3:15	164.77	
3:30	164.73	
3:46	164.67	
4:00	164.64	
4:30	164.56	
5:30	164.46	
5:33	164.46	
5:50	164.44	
5:55	164.44	
5:59	164.43	
6:00	..	Started pumping

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks
		May 28, 1957--Con.
6:25 p.m.	..	Yield 1,810 gpm;Temp 59°F
9:36	..	Yield 1,810 gpm.
10:08 p.m.	216.47	
10:10	216.48	
		May 29, 1957
5:28 a.m.	217	
5:33	216.99	
5:47	..	Yield 1,795 gpm
6:00	..	Stopped pumping
6:01	169.70	
6:12	167.77	
6:19	167.32	
6:22	167.16	
6:23	167.09	
6:26	167.01	
6:28	166.93	
6:30	166.81	
6:34	166.80	
6:40	166.61	
6:50	166.41	
6:55	166.35	
7:00	166.27	
7:05	166.21	
7:16	166.13	
7:25	166.06	
7:30	166.04	
7:45	165.79	
		May 29, 1957--Con.
7:50 a.m.	165.96	
7:55	165.94	
8:00	165.93	
8:05	165.92	
8:10	165.90	
8:20	165.87	
8:30	165.85	
8:40	165.83	
9:00	165.80	
10:00	165.76	
11:00	165.73	
11:05	165.73	
12:00 m.	165.69	
2:30 p.m.	165.57	
6:15	165.41	
6:18	165.41	
		Aug. 22, 1957
..	186.44	
		Sept. 30, 1957
4:09 p.m.	181.01	
4:17	181.00	
4:21	181.01	
8:46	180.95	
8:49	180.93	
8:53	180.92	
8:55	180.94	
11:53	180.89	

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks	Time	Depth to water (feet)	Remarks
		Sept. 30, 1957--Con.			Oct. 1, 1957--Con.
11:58 p.m.	180.90		2:05 p.m.	a222	
		Oct. 1, 1957	2:10	a223	
12:03 a.m.	180.89		2:15	a223	
6:14	180.78		2:20	a223	
6:19	180.78		2:30	a223	
9:29	180.72		2:50	..	Yield 1,655 gpm.
9:41	180.72				temp. 55.5°F.
10:45	180.66		3:34	a224	
11:08	180.63		4:00	a225	
12:00 m.	180.61		4:18	225.10	
12:16 p.m.	180.60		5:25	225.6	
1:06	180.58		5:48	..	Yield 1,645 gpm.
1:10	180.58				temp. 57°F.
1:16	180.56		9:27	..	Yield 1,640 gpm.
1:21	180.55				temp. 57.2°F
1:30	180.54		9:35	a225	
1:43	180.55		11:50	a225	
1:52	180.54				October 2, 1957
2:00	..	Started pumping.	12:35 a.m.	a226	
2:00:20	a210		1:00	..	Yield 1,635 gpm.
2:00:40	a217				temp. 57°F.
2:01	a219		6:48	a226	
2:01:20	a221		7:28	..	Yield 1,625 gpm.
2:02	a221		9:21	a226	
2:03	a222		9:24	225.94	
2:04	a222		9:48	..	Yield 1,625 gpm.
					temp.57.5°F.

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks	Time	Depth to water (feet)	Remarks
		Oct. 2, 1957--Con.			Dec. 6, 1957
11:05 a.m.	226.16		4:00 p.m.	..	Started pumping wells
11:21	..	Yield 1,635 gpm.			1, 2, and 3.
1:35 p.m.	226.16				Dec. 8, 1957
1:40	226.23	Yield 1,630 gpm. temp.57°F.	9:00 a.m.	..	Stopped pumping wells
1:42	226.20				1, 2, and 3.
1:56	226.16				Dec. 9, 1957
2:00	..	Stopped pumping	5:15 p.m.	174.65	
2:12	183.32				Dec. 10,1957
2:16	184.09		4:25 p.m.	173.25	
2:20	184.98		4:30	173.24	
2:25	183.73				Dec. 11,1957
2:30	183.52		8:20 a.m.	172.50	
2:35	183.41		8:29	..	Started recharging
2:41	183.25		8:34	..	Injecting 1,035 gpm.
2:45	183.15		8:53	161.85	
2:50	183.06		8:56	..	Injecting 524 gpm.
2:55	182.98		8:58	..	Injecting 632 gpm.
3:00	182.91		9:15	161.82	
3:05	182.86		10:12	161.30	
3:10	182.76		10:17	..	Temp 40.5°F
3:21	182.70		10:20	..	Injecting 620 gpm.
3:25	182.67		10:25	..	Injecting 623 gpm.
3:30	182.64		10:30	..	Injecting 658 gpm.
3:35	182.62		12:30 p.m.	160.62	
3:40	182.61	Started pumping well 1.	12:33	..	Injecting 624 gpm.
3:55	182.64		1:27	160.48	
4:00	..	Started pumping	2:43	160.24	Injecting 623 gpm.

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks
		Dec. 11, 1957--Con.
4:35 p.m.	160.00	Injecting 623 gpm
10:00	159.43	Injecting 629 gpm
		Dec. 12, 1957
8:17 a.m.	158.24	
8:20	..	Injecting 624 gpm
10:25	..	Temp 41°F
11:54	157.93	
12:00 m.	..	Injecting 626 gpm
1:45 p.m.	..	Temp 42°F
2:08	156.67	
2:13	..	Injecting 630 gpm
3:03	156.72	
3:05	157.61	
3:12	157.62	
3:16	157.70	
3:20	..	Injecting 616 gpm
4:16	157.70	
10:00	..	Injecting 629 gpm
10:07	156.40	
		Dec. 13, 1957
8:13 a.m.	156.44	
8:15	..	Injecting 624 gpm
10:15	156.30	Injecting 634 gpm
11:21	156.30	
1:29 p.m.	156.01	
4:02	156.0	Injecting 623 gpm
		Dec. 14, 1957
10:31 a.m.	154.92	
10:35	155.03	
10:36	154.97	
10:38	155.00	Injecting 627 gpm
12:10 p.m.	154.92	
4:40	..	Injecting 626 gpm
4:43	154.68	
		Dec. 16, 1957
9:06 a.m.	152.70	
2:14 p.m.	152.71	
2:20	..	Injecting 616 gpm temp 44°F
5:04	152.58	
5:07	..	Injecting 621 gpm
		Dec. 17, 1957
9:20 a.m.	151.71	
9:24	151.71	
9:26	..	Injecting 623 gpm; temp 42°F
12:27 p.m.	151.65	
12:30	..	Injecting 621 gpm; temp 42.5°F
4:18	151.45	
4:24	151.37	
4:26	151.30	
4:30	151.39	

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks	Time	Depth to water (feet)	Remarks
		Dec. 18, 1957			Dec. 20, 1957--Con.
9:07 a.m.	150.83	Temp 41.5°F	3:40 a.m.	b153.90	
9:12	150.88		4:00	b166.07	
10:51	..	Injecting 629 gpm	4:30	b166.40	
10:54	150.86		6:00	b167.16	
1:00 p.m.	150.91		7:00	b167.48	
1:31	..	Injecting 622 gpm	8:01	167.65	
3:28	..	Injecting 636 gpm	10:00 a.m.	168.10	
3:31	150.80		11:00	168.28	
3:34	150.88		12:00 m.	168.43	
4:24	151.17		1:00 p.m.	168.72	
4:29	150.79		2:00	168.72	
5:04	..	Injecting 625 gpm	3:00	168.86	
		Dec. 19, 1957			Dec. 21, 1957
8:46 a.m.	150.13		1:00 p.m.	b170.91	
8:49	150.05				Dec. 22, 1957
8:54	..	Injecting 626 gpm	12:00 m.	b172.59	
12:41 p.m.	149.85				Dec. 23, 1957
12:51	..	Temp 39°F	8:00 a.m.	..	Stopped pumping well 1
1:08	149.65		9:55	b172.55	
1:11	..	Injecting 628 gpm	10:00 a.m.	..	Started recharging
4:11	149.62		12:15 p.m.	b154.87	
4:20	..	Injecting 627 gpm			Dec. 24, 1957
		Dec. 20, 1957	8:00 a.m.	b153.40	
3:00 a.m.	..	Started pumping well 1	12:15 p.m.	b151.66	
3:30	b148.77	Injecting 633 gpm			Dec. 25, 1957
		Stopped recharging	8:00 a.m.	b150.64	

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks
		Dec. 25, 1957--Con.
8:00 p.m.	b149.90	
		Dec. 26, 1957
8:00 a.m.	b148.50	
8:00 p.m.	b149.05	
		Dec. 27, 1957
8:00 a.m.	b148.60	
8:00 p.m.	b147.77	
		Dec. 28, 1957
8:00 a.m.	b147.38	
8:00 p.m.	b147.12	
		Dec. 29, 1957
8:00 a.m.	b145.54	
8:00 p.m.	b144.46	
		Dec. 30, 1957
8:00 a.m.	b144.01	
8:00 p.m.	b143.75	
		Dec. 31, 1957
8:00 a.m.	b143.24	
		Jan. 1, 1958
8:00 a.m.	b142.58	
		Jan. 2, 1958
8:00 a.m.	b142.00	
		Jan. 3, 1958
8:00 a.m.	b141.91	
		Jan. 4, 1958
8:00 a.m.	b141.15	
		Jan. 5, 1958
8:00 a.m.	b140.63	
		Jan. 6, 1958
8:00 a.m.	b140.25	
		Jan. 7, 1958
1:25 p.m.	b139.81	
5:10	..	Injecting 661 gpm
11:23	139.64	
		Jan. 8, 1958
10:52 a.m.	c142.78	
11:05	140.22	
12:59 p.m.	139.35	
1:00	..	Injecting 6 gpm
1:00	..	Stopped recharging
1:01	148?	
1:11	161?	
1:15	162?	
1:20	162?	
1:25	161?	
1:29	162?	
1:38	163?	
1:46	163?	
1:50	163?	
1:57	163?	
2:12	164?	
2:15	163?	
2:23	163?	
2:26	164?	

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks
		Jan 8, 1958--Con.
2:30 p.m.	166?	
3:16 p.m.	164?	
3:19	163?	
3:22	165?	
4:15	164?	
4:20	163?	
6:03	164?	
6:08	163.30	
8:44	163.31	
11:54	163.31	
12:00 m.	163.32	
		Jan. 9, 1958
6:11 a.m.	163.34	
10:24	163.40	
12:16 p.m.	163.42	
12:25	..	Temp 40°F
4:03	163.49	
5:28	163.48	
10:02	163.47	
		Jan. 10, 1958
8:00 a.m.	a162	
1:55 p.m.	163.55	
6:30	163.57	
		Jan. 11, 1958
12:12 a.m.	163.58	
7:43	163.66	
		Jan. 11,1958 Con.
8:00 a.m.	..	Started pumping
8:01	a219	
8:01:45	a227	
8:02:25	a228	
8:02:50	a232	
8:04	a230	
8:05	a230	
8:07	a230	
8:10	a231	
8:13	a231	
8:17	a231	
8:22	a231	
8:26	a232	
8:27	a232	
8:40	a231	Temp 39.5°F
8:45	a230	Temp 39.5°F
8:53	..	Yield 1,520 gpm
9:00	a231	
9:01	..	Yield 1,520 gpm
9:15	a232	
9:25	..	Yield 1,600 gpm; temp 39.5°F
9:30	a231	
9:39	..	Yield 1,540 gpm
9:45	a231	
9:58	..	Yield 1,540 gpm

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks
		Jan. 11, 1958--Con.
10:00 a.m.	a231	
10:17	..	Yield 1,540 gpm
11:15	a231	Yield 1,540 gpm
11:56	a231	Yield 1,540 gpm
12:40 p.m.	..	Yield 1,540 gpm
1:28	a231	
1:37	..	Yield 1,540 gpm;temp 40.5°F
5:34	a231	Yield 1,540 gpm
10:20	c231.20	Yield 1,540 gpm;temp 42.8°F
		Jan. 12, 1958
10:22 a.m.	c231.24	Yield 1,530 gpm;temp 42.5°F
3:45 p.m.	c231.57	Temp 44°F
4:10	..	Yield 1,540 gpm
10:55	c231.52	Yield 1,540 gpm;temp 44°F
		Jan. 13, 1958
7:05 a.m.	c231.68	Temp 45°F
7:30	c231.65	Yield 1,530 gpm
7:45	c231.68	
8:00	..	Stopped pumping
8:01	172.6	
8:05	164.0	
8:15	169.20	
8:19	170+	
8:21	171.0	
8:28	168.8	
8:32	170	
8:36	168.39	
		Jan. 13, 1958-Con.
8:39 a.m.	168.31	
8:42	168.15	
8:45	168.23	
8:50	168.01	
8:55	168.01	
9:00	167.95	
9:10	167.8	
9:22	167.70	
9:30	167.64	
9:45	167.54	
9:50	167.60	
10:00	167.50	
10:10	167.40	
10:20	167.39	
10:30	167.31	
10:40	167.29	
10:50	167.26	
11:00	167.21	
11:10	167.17	
11:20	167.15	
11:30	167.13	
11:40	167.11	
11:50	167.07	
12:00 m.	167.06	
12:10 p.m.	167.05	
12:20	167.01	

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks
		Jan. 13, 1958-Con.
12:30 p.m.	167.00	
12:45	166.97	
1:00	166.95	
1:18	166.92	
1:30	166.90	
1:45	166.87	
2:53	166.78	
3:40	166.73	
4:00	166.72	
4:20	166.70	
4:47	166.67	
5:00	166.66	
5:20	166.64	
		Jan. 14, 1958
12:03 a.m.	166.18	
10:26	165.65	
10:30	165.65	
11:46	165.62	
11:49	165.62	
1:30 p.m.	a164	
1:32	..	Started surging (intermittent pumping)
2:34	..	Stopped surging
2:35	..	Started pumping
2:37	a224	
2:41	a225	
2:50	a226	
		Jan. 14, 1958-Con.
3:00 p.m.	a227	
3:20	a227	
3:30	a227	Temp 44.5°F
3:48	..	Yield 1,590 gpm
		Jan. 15, 1958
10:55 a.m.	ab228	Yield 1,600 gpm
11:00	..	Stopped pumping
		Jan. 17, 1958
8:55 a.m.	ab164	
9:00	..	Started pumping
9:05	ab227	
11:00	..	Started pumping wells 1 and 2
		Jan. 20, 1958
7:55 a.m.	ab234	Yield 1,540 gpm
8:00	..	Stopped pumping wells 1, 2, and 3
		Jan. 23, 1958
	d167.90	
		Jan. 30, 1958
2:55 p.m.	d164.66	
		Feb. 6, 1958
3:05 p.m.	d164.42	
		Feb.13, 1958
2:55 a.m.	ab163	
3:00	..	Started pumping wells 1, 2, and 3

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

City of Walla Walla well 3--Con.

Time	Depth to water (feet)	Remarks	Time	Depth to water (feet)	Remarks
		Feb. 13, 1958-Con.			
3:05 a.m.	..	Yield 1,600 gpm.			
		Feb. 14, 1958			
3:20	ab230				
		Feb. 21, 1958			
12:30 p.m.	..	Temp 54.4°F			
12:50	d236.64				
1:00	..	Stopped pumping wells 1, 2, and 3.			
		Feb. 22, 1958			
8:40 a.m.	d179.31				
		Feb. 24, 1958			
10:00 p.m.	..	Started pumping wells 1, 2, and 3.			
		Feb. 26, 1958			
8:00 a.m.	..	Stopped pumping wells 1, 2, and 3			
		Feb. 27, 1958			
1:50 p.m.	d174.58				
		Mar. 5, 1958			
4:00 p.m.	d169.73				

Table 9.--Water-level measurements in observation wells in the recharge area--Con.

Roy Frazier Well

(Altitude of measuring point, 1,190 feet above mean sea level.)

Time	Depth to water (feet)	Remarks
		Aug. 22, 1957
5:45 p.m.	73.82	
		Jan. 8, 1958
8:55 a.m.	48.64	
9:02	48.74	
1:00 p.m.	..	Stopped recharging well 3
		Jan. 10, 1958
3:42 p.m.	49.50	
3:45	49.50	
		Jan. 11, 1958
8:00 a.m.	..	Started pumping well 3
12:36 p.m.	50.40	
12:40	50.38	
		Jan. 12, 1958
5:11 p.m.	52.49	
5:14	52.49	
		Jan. 13, 1958
7:23 a.m.	53.39	
7:32	53.43	
8:00	..	Stopped pumping well 3
12:45 p.m.	53.06	
12:51	53.05	
4:59	52.77	
5:02	52.77	
		Jan. 14, 1958
12:18 a.m.	52.27	
12:21	52.27	
10:20	51.77	
10:23	51.77	

a/ Air-line measurement.
b/ Measurement by Walla Walla Water Department.
c/ Electric tape measurement.
d/ Measurement by Washington Department of Conservation.

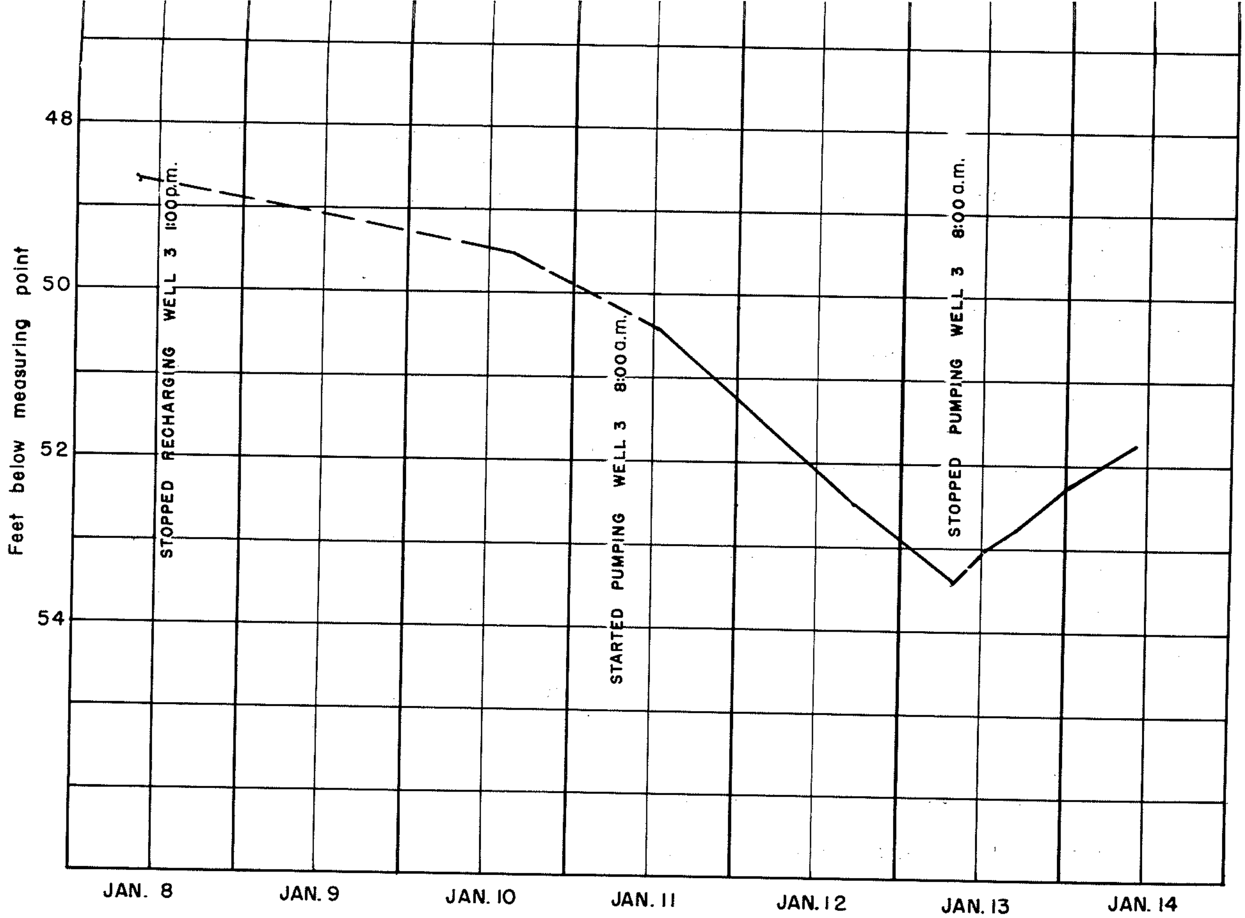

Figure 2.-- Hydrograph of Roy Frazier well for the period January 8-14, 1958.