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The dynamic relationship between ground water and the Columbia River: using deuterium and oxygen-18 as tracers

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ABSTRACT

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Deuterium and oxygen-18 were used as natural tracers to investigate the hydraulic relationship between the Columbia River and the Blue Lake gravel aquifer near Portland, Oregon. A time series of stable-isotope data collected from surface and ground waters during a March 1990 aquifer test confirms that the river and aquifer are hydraulically connected. Calculations based on simple mixing show that the river contributed 40–50% of the yield of three wells after 5–6 days of pumping. Data collected during August 1990, show that the river contributed 65–80% of the yield of one well after 22 days of pumping and indicate that the contribution of the river was still increasing.

INTRODUCTION

Well fields commonly are constructed in highly transmissive aquifers located adjacent to streams. Part of the water extracted from such wells may be derived from induced infiltration of the nearby surface water. Knowledge of the fraction of well water derived from the stream is important for identifying potential sources of contaminants, understanding problems of scaling and corrosion, and predicting the effects of pumping on groundwater levels. Although several analytical and numerical models of groundwater/surface-water interactions have been developed, there are few methods for actually measuring the fraction of ground water derived from the stream.

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Traditionally, the field approach to investigating the hydraulic relationship between an aquifer and a stream has involved comparing water levels in the aquifer and stream to determine the direction of the hydraulic gradient, and measuring discharge at various points along the stream to determine the magnitude of the stream's gain or loss. Other tools that have been used include flow-net analysis, seepage meters, and river-bed piezometers. In most cases, however, the limited number of data-collection points results in a lack of detailed data on subsurface heterogeneities and anisotropy. Because of the broad assumptions involved in interpreting such data, these techniques generally yield only qualitative results with a high degree of uncertainty. Chemical tracers provide yet another option, but data interpretation can be complicated by chemical reactions, changes in natural background levels of the compound of interest, and dilution due to hydrodynamic dispersion.

An alternative approach is to use the stable-isotopic composition of water as a natural tracer to study the interaction between ground water and surface water. This relatively quick, simple and inexpensive technique is useful as a preliminary investigative tool and as an independent means for corroborating or refuting hypotheses based on more traditional investigations. Stichler and Moser (1977) used deuterium and oxygen-18 measurements to demonstrate hydraulic communication between ground water and a small lake in the Upper Rhine Valley, Germany. By examining seasonal variations of the lake's isotopic composition and corresponding variations in ground water, they were able to estimate groundwater velocity. Exploiting the isotopic fractionation of water which occurs owing to evaporation from a surface-water reservoir, Iacovides (1988) employed stable isotopes to study the relationship between a reservoir and underlying aquifers in Cyprus. Darling et al. (1990) used stable-isotope data to trace the subsurface outflow of a Rift Valley lake and to confirm that the lake was the source of much of the steam used by a local geothermal power station. Krabbenhoft et al. (1990) demonstrated a method for estimating groundwater exchange with lakes based on a stable-isotope mass-balance technique. Payne (1981), Ferronsky and Polyakov (1982), and Payne (1983) give additional examples of the stable-isotope technique applied to the study of groundwater/surface-water interactions.

In this study, the stable isotopes of hydrogen and oxygen are used as natural tracers to investigate the hydraulic relationship between the Blue Lake gravel aquifer and the Columbia River in northwestern Oregon. Time-series sampling during two aquifer tests allowed the determination of the effects of groundwater pumping on this relationship.

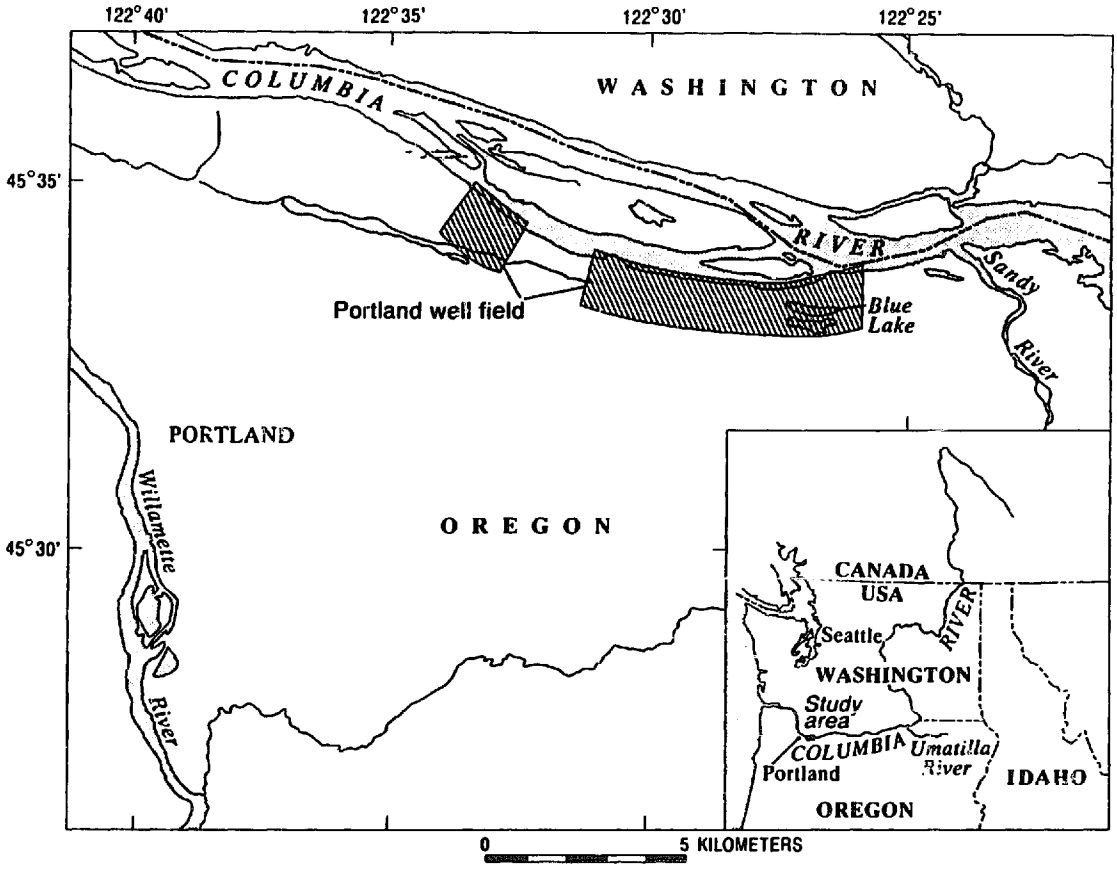

Fig. 1. Location map with insert showing Columbia River basin.

BACKGROUND

During the late 1970s and 1980s, the City of Portland, Oregon, constructed a well field adjacent to the Columbia River (Fig. 1) as a back-up source for municipal water needs. The wells are completed in various hydrogeologic units; those completed in the Blue Lake gravel aquifer are particularly productive. In March 1990, and again in August 1990, the City of Portland conducted aquifer tests in the Blue Lake gravel aquifer to determine the effect on adjacent hydrogeologic units.

The aquifer tests provided an opportunity to independently corroborate flow-system hypotheses and to apply the stable-isotope technique as an investigative tool in a unique hydrogeologic setting. The two primary hypotheses tested were: (1) that the Blue Lake gravel aquifer and the Columbia River are hydraulically connected; (2) that a substantial part of the yield from wells completed in the aquifer comes from the Columbia River. Several factors suggested that the site was particularly well suited to the application of the stable-isotope technique. First, because the site is part of a recently constructed

municipal well field, the density of wells and piezometers is high and each was carefully constructed so as to receive water from only one hydrogeologic unit. Secondly, the site has been extensively studied in the past and the local geology is well characterized. Thirdly, the Columbia River, due to its large, geographically diverse basin (Fig. 1), was expected to have an isotopic signature easily distinguishable from local ground water. Finally, preliminary calculations using hydraulic properties of the Blue Lake gravel aquifer determined from previous aquifer tests indicated that the anticipated pumping rates and durations of the tests were adequate to draw river water into wells and piezometers.

HYDROGEOLOGIC SETTING

The Portland basin is a northwest-trending structural basin filled with nearly 600 m of sediments underlain by volcanic and marine sedimentary rocks. The basin-fill sediments (Holocene-Miocene) are the most widely used and most productive aquifers in the basin (Swanson et al., 1992). Aquifers in the Miocene and older bedrock units are less permeable than the basin-fill sediments and are not as widely used as a source of water. Holocene-Pliestocene sediments include stream alluvium, overbank deposits, and flood deposits derived from catastrophic floods that swept through the basin. Basin-fill sediments of Pliocene-Miocene age typically are more consolidated than the Holocene-Pleistocene sediments and are included in the Troutdale Formation and Sandy River Mudstone (Hartford and McFarland, 1989).

The Blue Lake area, approximately 16 km northeast of downtown Portland on the south shore of the Columbia River (Fig. 1), is underlain by an ancestral channel of the Columbia River. The channel formed an erosional surface on the Troutdale Formation and was later filled with the coarse gravel deposits. The gravel aquifer is composed primarily of boulder-, cobble-, and gravel-sized clasts in a minor matrix of clayey-sandy silt. The unit is clast supported, averaging 80–95% gravel and 5–20% matrix (Hartford and McFarland, 1989).

The extent and thickness of the Blue Lake gravel aquifer has been mapped using well data and surficial geologic maps (Hartford and McFarland, 1989). The gravel aquifer occurs beneath and north of Blue Lake and has an areal extent of approximately 1.5 km^2. The western and southern extent of the aquifer is bounded by the more consolidated, less permeable sediments of the Troutdale Formation (Fig. 2). To the east, the extent of the aquifer is poorly defined due to the lack of wells. The aquifer thickness ranges from approximately 15 m near the western end of Blue Lake to more than 65 m just north of the eastern end of Blue Lake. A hydrogeologic cross-section from north to

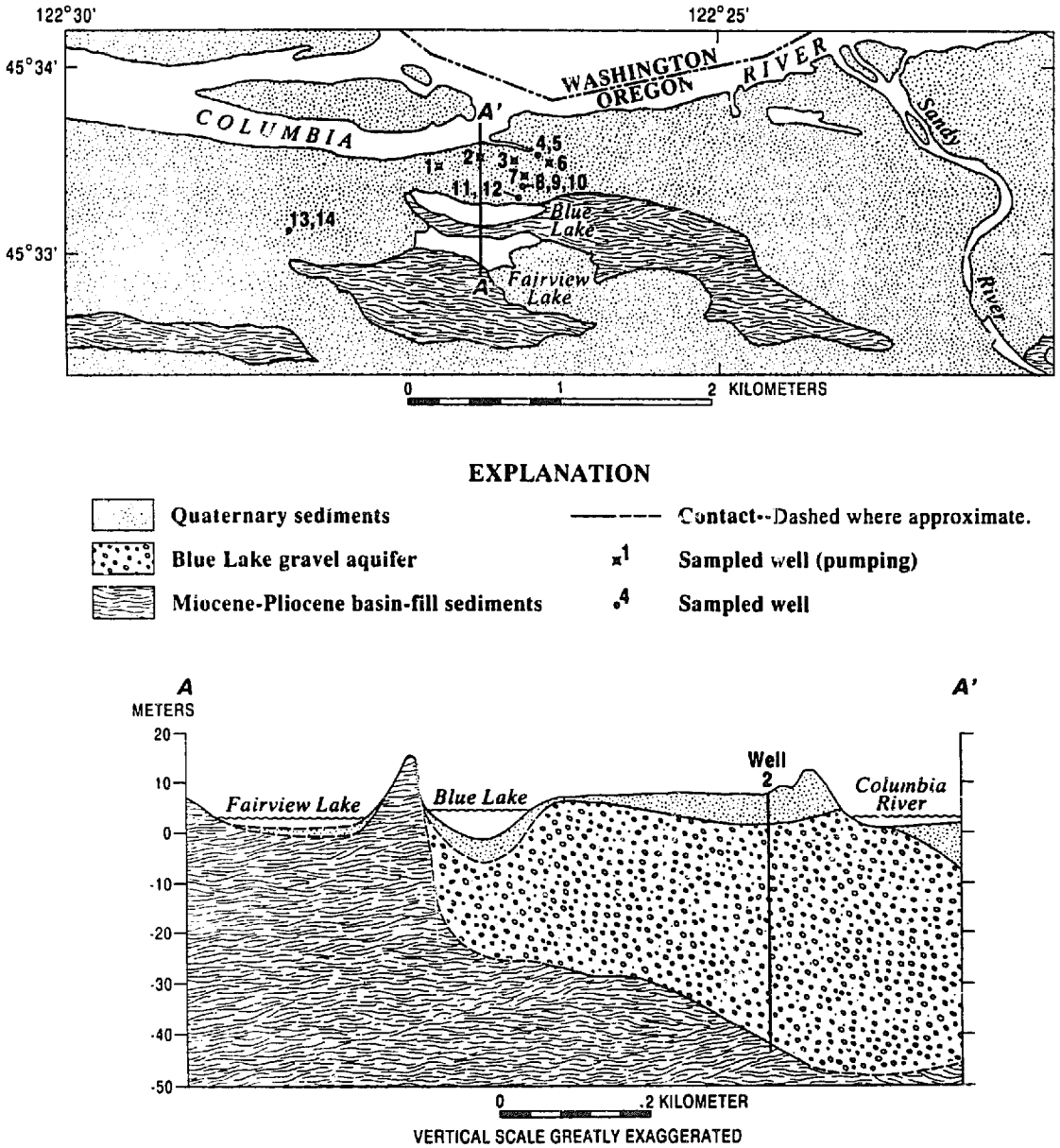

Fig. 2. Well and piezometer locations, surficial hydrogeology, and hydrogeologic section.

south (Fig. 2) suggests that the aquifer is hydraulically connected to the Columbia River. Calculations based on data from previous aquifer tests indicate that the hydraulic conductivity of the Blue Lake gravel aquifer is approximately one order of magnitude greater than that of the adjacent Troutdale Formation.

METHODS

During the March 1990 aquifer test, five municipal production wells

TABLE 1

Well and piezometer construction details

Site ID	Land surface altitude (m)	Well completed depth (m)	Depth of open interval (m)	
			Top	Bottom
1[a]	7.9	36.0	16.8	34.4
2[a]	8.5	51.5	25.9	50.3
3[a]	7.6	50.3	24.4	48.8
4	12.8	28.7	27.7	28.7
5	12.8	54.9	53.9	54.9
6[a]	4.9	58.8	26.8	57.9
7[a]	4.9	37.5	18.3	36.0
8	5.3	8.5	7.6	8.5
9	5.3	28.3	27.4	28.3
10	5.3	53.0	52.1	53.0
11	9.0	38.1	37.2	38.1
12	9.0	9.1	8.2	9.1
13	6.1	54.9	53.9	54.9
14	6.1	112.8	111.9	112.8

[a] Pumping wells.

completed in the Blue Lake gravel aquifer (sites 1, 2, 3, 6, and 7) were pumped continuously for 7 days, beginning 5 March. The total pumping rate averaged $2\,m^3\,s^{-1}$ with rates for individual wells ranging from 0.2 to $0.5\,m^3\,s^{-1}$. Beginning 7 August 1990, well 1 was again pumped for a period of 22 days at an average rate of $0.4\,m^3\,s^{-1}$. The locations of wells and piezometers that were sampled during the tests are shown in Fig. 2 and pertinent construction details are listed in Table 1. Sites 1–12 are completed in the Blue Lake gravel aquifer; sites 13 and 14 are completed in the older Pliocene–Miocene basin-fill sediments.

Prior to water-sample collection, non-pumping wells were purged until effluent pH and specific conductance stabilized. Samples for stable-isotope analyses were collected in 50 ml glass bottles which were sealed with polyseal caps. Analyses were performed at the US Geological Survey laboratory in Menlo Park, California. Oxygen-18 abundances were determined using the CO_2-equilibration method of Epstein and Mayeda (1953) followed by CO_2 analyses by mass spectrometry (SD 0.1‰). Deuterium abundances were determined using the zinc-reduction method of Kendall and Coplen (1985) followed by hydrogen analyses by mass spectrometry (SD 1.5‰). Stable-isotope ratios (D/H and O-18/O-16) are reported in per mil relative to Vienna Standard Mean Ocean Water (V-SMOW) and normalized (Gonfiantini, 1984)

on scales such that the deuterium and oxygen-18 values of Standard Light Antarctic Precipitation (SLAP) are −428‰ and −55.5‰, respectively.

RESULTS AND DISCUSSION

Deuterium and oxygen-18 concentrations for all samples collected over the course of the study are listed in Table 2. The isotopic compositions of samples collected prior to the effects of March 1990, pumping are shown in Fig. 3. With the exception of water from site 12, isotopic compositions of ground water from the aquifer and surface water from the Sandy River, a local tributary of the Columbia River, all fall within a cluster about the global meteoric water line (Craig, 1961). The isotopic composition of Blue Lake falls on a theoretical evaporation trajectory (slope ≈ 4) originating in the same cluster as other local waters. Site 12 is a shallow piezometer completed near the shore of Blue Lake. The isotopic composition indicates that ground water from this piezometer is a mixture of infiltration from Blue Lake and deeper ground water and suggests the presence of a transition zone between surface- and groundwater systems.

Water from the Columbia River is significantly depleted in deuterium and oxygen-18 as compared with other water in the Blue Lake area (Table 2). Contrasting data from the Umatilla basin (McCarthy, 1989) with data from the Blue Lake area illustrates the diverse nature of the Columbia River basin. The Umatilla River, in northeastern Oregon, is a tributary of the Columbia River (Fig. 1). Surface water in the Umatilla basin is more depleted in deuterium and oxygen-18 than precipitation runoff within the Blue Lake area (Fig. 3); this can be explained by the fact that it originates from precipitation occurring further inland. Yurtsever and Gat (1981) provide a discussion of the relationship between the isotopic composition of precipitation and distance from the ocean. This diversity within the Columbia River basin is largely responsible for the distinct isotopic signature of the river as compared with local ground water, a key factor in the success of this study.

The changes in isotopic composition that occurred over the course of the March aquifer test are illustrated in Fig. 4. The isotopic compositions at sites 1–4 (wells 1, 2, and 3, and piezometer 4) show a significant shift toward the isotopic composition of Columbia River water. On the basis of simple mixing theory, it is possible to estimate the contribution of the river to the yield of each well using:

$$PR(t) = \{[C(\mathrm{i}) - C(t)]/[C(\mathrm{i}) - CR]\} \times 100 \qquad (1)$$

where $PR(t)$ is the percent of the yield coming from the river at time t, $C(\mathrm{i})$ is the initial isotopic composition of ground water in the well, $C(t)$ is the

TABLE 2

Oxygen and hydrogen isotope ratios (per mil relative to V-SMOW)

Site ID	Date	$\delta^{18}O_{V\text{-}SMOW}$	$\delta D_{V\text{-}SMOW}$
1[a]	3/5/1990	−10.6	−78.0
	3/11/1990	−12.9	−99.0
	8/10/1990	−12.2	−94.0
	8/13/1990	−12.5	−100.0
	8/16/1990	−12.7	−102.0
	8/19/1990	−12.8	−102.0
	8/22/1990	−13.5	−106.0
	8/25/1990	−13.6	−106.0
	8/29/1990	−13.9	−109.0
2[a]	3/5/1990	−11.5	−84.0
	3/12/1990	−13.2	−100.0
3[a]	3/5/1990	−11.5	−81.0
	3/12/1990	−12.8	−98.0
4	3/2/1990	−9.2	−71.0
	3/14/1990	−11.4	−85.0
5	3/6/1990	−10.2	−71.0
	3/9/1990	−10.2	−72.0
	3/14/1990	−10.1	−75.0
6[a]	3/5/1990	−10.0	−73.0
	3/12/1990	−10.0	−77.0
7[a]	3/5/1990	−9.7	−69.0
	3/11/1990	−9.4	−68.0
8	3/2/1990	−9.3	−68.5
9	3/2/1990	−10.2	−67.5
	3/9/1990	−9.2	−66.0
	3/14/1990	−8.3	−68.0
10	3/2/1990	−9.8	−72.0
	3/9/1990	−10.2	−75.0
	3/14/1990	−10.0	−72.0
11	3/2/1990	−9.3	−70.0
	3/9/1990	−9.8	−68.0
	3/14/1990	−9.1	−71.0
12	3/2/1990	−8.0	−65.0
13	4/6/1990	−10.2	−72.0
14	3/27/1990	−9.8	−71.0
Columbia River	3/2/1990	−15.7	−116.0
	3/9/1990	−15.2	−117.0
Sandy River	3/6/1990	−11.0	−74.0
Blue Lake	3/2/1990	−4.3	−48.0

[a] Pumping wells.

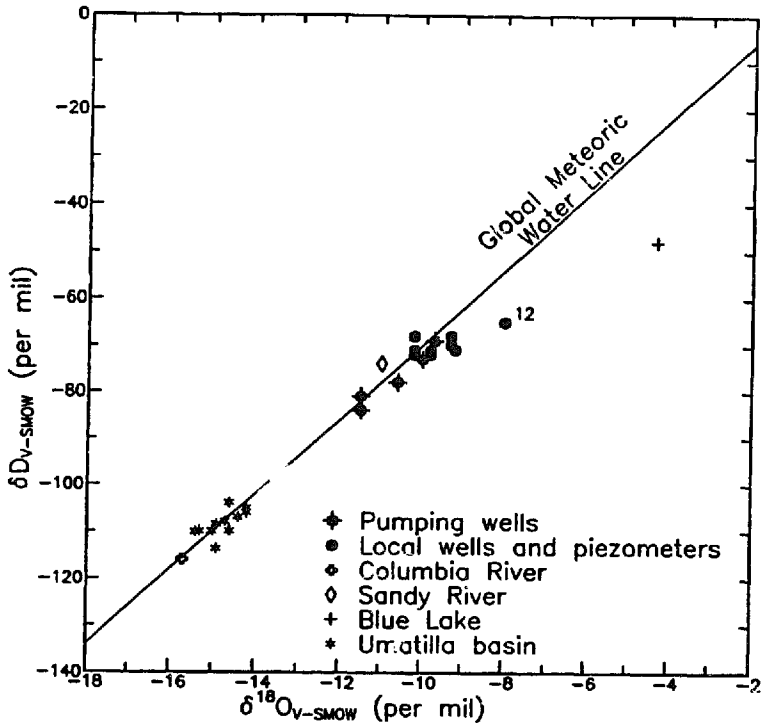

Fig. 3. Deuterium and oxygen-18 initial concentrations.

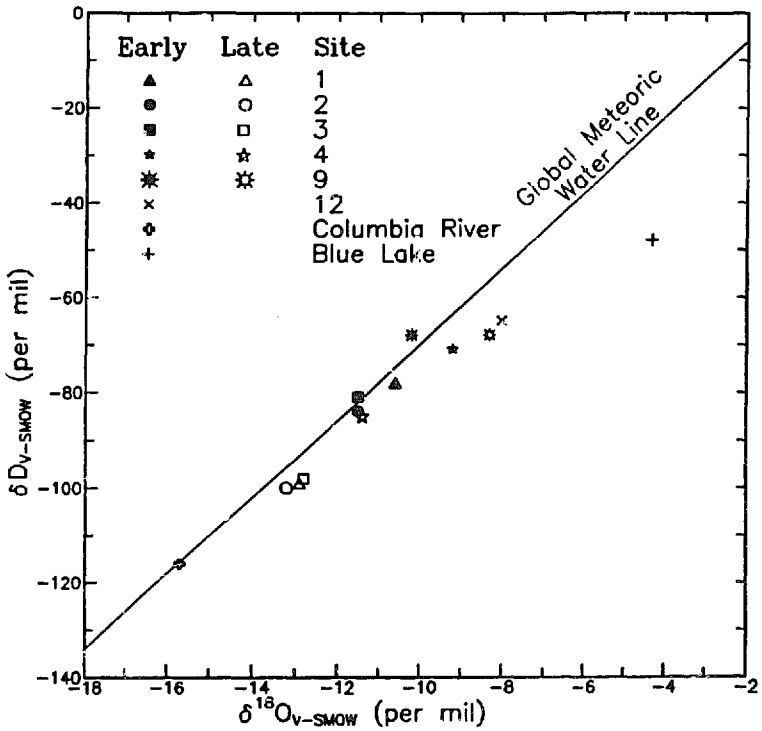

Fig. 4. Deuterium and oxygen-18 early and late concentrations for selected sites.

isotopic composition of the well water at time t, and CR is the isotopic composition of the Columbia River. This equation is based on the assumptions that (1) initially, the contribution of the river to the yield of the well is negligible, and (2) the isotopic composition of the Columbia River is constant throughout the period of interest. The second assumption is supported by data from water samples collected by the US Geological Survey, January 1985–September 1987. Ten samples from the Columbia River at Warrendale, Oregon, approximately 30 km upstream from the study area, show that for this period, the maximum seasonal variations in deuterium and oxygen-18 were 6.5‰ and 0.5‰, respectively. Calculations using eqn. (1), based on either deuterium or oxygen-18 content, indicate that the yields from sites 1, 2, and 3 were approximately 40–50% Columbia River water after 5–6 days of pumping. Two days after pumping ceased, the water from site 4 was approximately 30% Columbia River water.

The isotopic composition of water from site 9 underwent a 2% enrichment in oxygen-18 over the course of the aquifer test, approaching the initial composition of water from site 12. Owing to a water-level decline during the aquifer test, additional samples from site 12 could not be collected, but data from site 9 suggest that the transition zone between ground water and water from Blue Lake migrated toward the pumping wells during the course of the test.

Water from sites 6 and 7 (wells) and sites 5, 10, and 11 (piezometers), showed no change in isotopic composition during the aquifer test. Owing to the locations of these sites with respect to the river and the depths of their screened intervals, it is apparent that the time frame of the aquifer test was inadequate to draw river water to these wells.

The changes in the isotopic composition of water from site 1 during the 10–29 August 1990, pumping period are shown in Fig. 5. March data for site 1 also are included in Fig. 5 for reference. During pumping, deuterium and oxygen-18 concentrations again declined. The available data suggest that the initial composition was similar to the composition of the ground water prior to the March 1990 aquifer test, although ground water samples were not collected prior to August 1990 pumping. For example, D/H and O-18/O-16 ratios on the seventh day of pumping for both the March and August pumping periods were nearly identical (Fig. 5). After 22 days of continuous pumping (day 23), stable-isotope ratios had not stabilized which indicated that the contribution of water from the Columbia River to the yield of the well was still increasing. Assuming that the initial composition of the ground water in August was similar to that in March and that the isotopic composition of the Columbia River is stable over time, calculations using eqn. (1), based on deuterium, indicate that the yield from site 1 was approximately 80% river

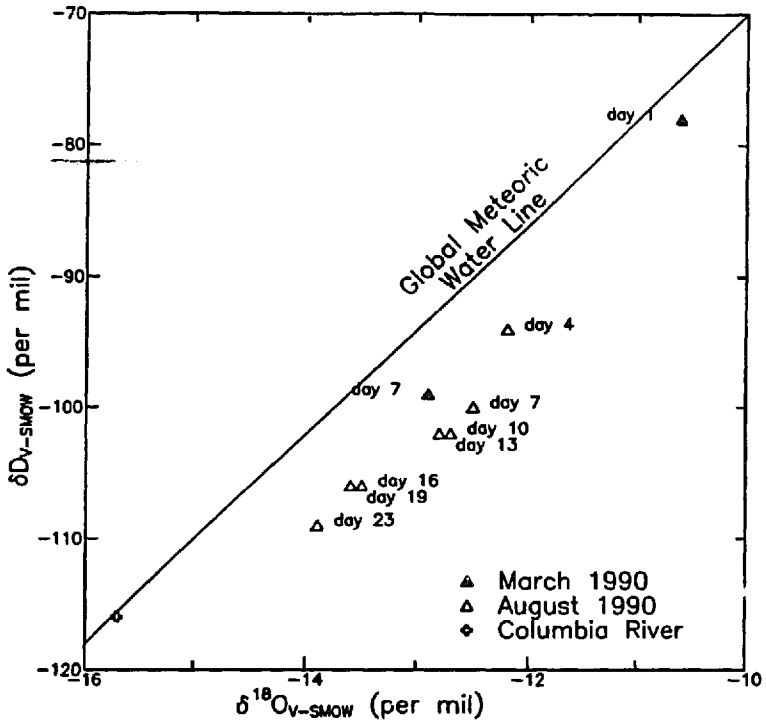

Fig. 5 Deuterium and oxygen-18 concentrations for site 1.

water after 22 days of pumping (day 23). Calculations based on oxygen-18 indicate that the contribution of the river to the yield of the well was approximately 65% after 22 days of pumping.

CONCLUSIONS

Stable-isotope data from the Blue Lake gravel aquifer and the Columbia River corroborate the hypothesis that the aquifer and river are hydraulically connected. Calculations based on simple mixing show that after 5–6 days of pumping of the aquifer, the river was contributing approximately 40–50% of the yield from three of the five production wells during the March 1990 aquifer test. After 22 days of pumping in August 1990 the yield from site 1 was approximately 65–80% river water and the contribution of the river to the yield of the well was still increasing. It is not possible to calculate the equilibrium composition of well yields without a longer time series of data, but it is apparent that the Columbia River contributes substantially to the yields of wells completed in the Blue Lake gravel aquifer during winter and summer.

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