UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

OCCURRENCE OF DISSOLVED SODIUM IN GROUND WATERS IN BASALTS UNDERLYING THE COLUMBIA PLATEAU, WASHINGTON

By G. C. Bortleson and S. E. Cox

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4005

Prepared in cooperation with the

STATE OF WASHINGTON DEPARTMENT OF ECOLOGY

Tacoma, Washington
1986

UNITED STATES DEPARTMENT OF THE INTERIOR

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METRIC CONVERSION FACTORS

For those readers wishing to convert the inch-pound units found in this text to metric units, the following conversion factors are provided:

Multiply	By	To obtain
inches (in.)-----------------------	25.4	millimeters (mm)
	2.540	centimeters (cm)
	0.0254	meters (m)
feet (ft)--------------------------	0.3048	meters (m)
miles (mi)-------------------------	1.609	kilometers (km)
square miles (mi^2)-----------------	2.590	square kilometers (km^2)
micromhos per centimeter at 25 degrees Celsius (umho/cm at 25 °C)	1.000	microsiemens per centimeter at 25 degrees (uS/cm at 25 °C)

To change degrees Fahrenheit (°F) to degrees Celsius (°C):
°C = 5/9 (°F-32)

To change degrees Celsius (°C) to degrees Fahrenheit (°F):
°F = 9/5 (°C+32)

OCCURRENCE OF DISSOLVED SODIUM IN GROUND WATERS

IN BASALTS UNDERLYING THE COLUMBIA PLATEAU, WASHINGTON

By G. C. Bortleson and S. E. Cox

ABSTRACT

Miocene basalts are the principal source of water for agricultural, domestic, and municipal use in the Columbia Plateau of Washington State. Concern has been expressed in this agriculture-dependent region about problems associated with the use of ground water with a high dissolved-sodium concentration relative to dissolved calcium and magnesium concentrations. Continued irrigation with such water can, without adequate management practices, reduce soil permeability to the degree that water cannot effectively reach plant roots.

The spatial variations of sodium concentration and SAR (sodium-adsorption ratio) are determined by chemical reactions between ground water and aquifer material and by ground-water residence time. Ground waters evolved from a calcium-magnesium bicarbonate type in shallow and upgradient locations where residence times are relatively short to a sodium-potassium bicarbonate type in deeper and downgradient locations where ground-water residence times are longer. Most of the high SAR values (greater than 8.0) were observed in discharge areas near major streams and in pumping centers within the central part of the plateau. The pumping of ground water does not appear to affect the temporal variation in SAR. In general, there was no significant difference in the distribution of SAR for the beginning as compared to the end of two pumping periods.

Ninety-six percent of the ground waters sampled had SARs less than 4, indicating that, for irrigation purposes, there is probably little danger of harmful levels of exchangeable sodium occurring on soil. However, 8 percent of these waters, although low in SAR, were classified as high in salinity (specific conductance of 750 to 1,190 micromhos per centimeter at 25^{o} Celsius), and therefore generally suitable to irrigate only light soils with good drainage.

Water from 18 of 418 wells sampled had a SAR greater than 8.0 and were classified as having a medium, high, or very high sodium hazard. Use of water with a SAR of 8 or above may produce harmful levels of sodium in many types of soil, especially those that are fine-textured and have a high cation-exchange capacity.

INTRODUCTION

Background

The Columbia River Basalt Group underlies about 25,000 square miles of Washington State (pl. 1). In much of this area, generally referred to as the Columbia Plateau, basalts are the principal source of ground water for irrigation, stock, domestic, and municipal use. The economy of the area is dependent in large measure on irrigated crops. In recent years, a sodic soil condition has occurred in some irrigated fields requiring costly reclamation measures, such as the application of gypsum (calcium sulfate). This sodic soil condition usually results from using irrigation water that has a high sodium content relative to calcium and magnesium content. With time, and without adequate management, clays in soils being irrigated will disperse, reducing soil permeability and preventing moisture from reaching the roots of the plants (Ayers, 1977, p. 136).

In 1982, the U.S. Geological Survey, in cooperation with the State of Washington Department of Ecology, began a 2 1/2-year study of the Washington part of the Columbia Plateau to define the spatial and temporal variation of sodium in the ground water of the Columbia River Basalt Group and relate this to the ground-water flow system and its geologic environment. The objectives of this study were to determine (1) the spatial and temporal variation of sodium concentration, sodium-adsorption ratio (SAR), and specific conductance (an estimate of dissolved solids) in ground waters of the major aquifers, (2) the effect of pumping on the temporal distribution of sodium concentration and SAR, and (3) the salinity and sodium hazard, based on a general classification system, of water used for irrigation. Samples from 418 wells were collected for water-quality analyses at least once during one of the following periods: summer 1982, spring 1983, and summer 1983.

This report includes five maps (1:500,000 scale) that show the occurrence of sodium, SAR, and related constituents in the ground waters of eastern Washington. For the purpose of this report, the major aquifers were identified that correspond to the basalt formations that underlie the area. Water-quality data are presented for each of these formations. In addition, most wells in the basalts are open to more than one formation and a considerable number of wells open to either the Grande Ronde and Wanapum Basalts or the Wanapum and Saddle Mountains Basalts were also sampled. Results of this sampling are presented on plates 3 and 5.

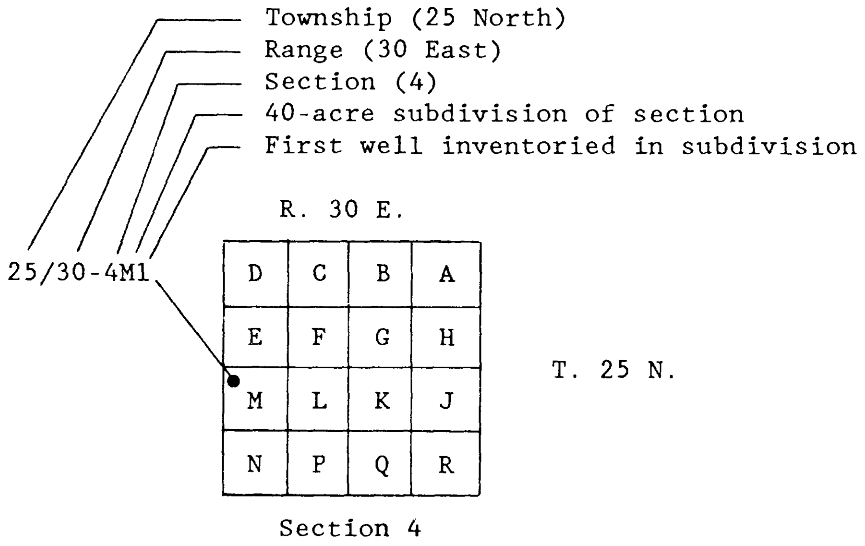
This report is one in a series that, collectively, describe (1) the geologic framework (Drost and Whiteman, 1986), (2) the ground-water flow system (Bauer and others, 1985), and (3) the occurrence of dissolved sodium underlying the Columbia Plateau (Hearn and others, 1985; Steinkampf and others, 1985; and this report).

Previous Studies

Reports describing the occurrence of ground water in eastern Washington have been completed by a number of investigators. Notable among these are reports by Garrett (1968), Luzier and Burt (1974), Tanaka and others (1974), and Cline (1984). Regional studies of ground-water quality were completed by Van Denburgh and Santos (1965) and Newcomb (1972).

Well-Numbering System

The well-location numbering system used in this report is shown in the figure below.



Acknowledgments

The authors extend their gratitude to farmers, ranchers, and others who made their privately owned wells available for water sampling and water-level measurements. Also acknowledged are agencies that provided personnel and special assistance to gain access to publicly owned wells.

QUALITY REQUIREMENTS FOR IRRIGATION WATER

While all natural waters contain some dissolved constituents, the suitability of water for irrigation generally depends on the types and amounts of the constituents in solution. Irrigators must deal with the effects that water quality and irrigation practices have on the salinity and sodium content of soil, as these factors can significantly reduce crop production.

Use of irrigation water with a high ratio of sodium to calcium plus magnesium can, without mitigating treatment, saturate the exchange sites of soil clays with sodium ions. When such sodic soil is wet it becomes sticky and nearly impervious to water; when the soil is dry it can form hard clods that are difficult to till.

While many of the various soil particles can adsorb dissolved materials, the particles usually having the highest adsorptive capacities are clay minerals. When clays adsorb divalent ions, such as calcium and magnesium, soil properties are optimal for plant growth and cultivation. If sodium is the primary adsorbed cation, clays can disperse when wetted, decreasing soil permeability. Irrigation water having a high proportion of sodium relative to total cations tends to place sodium ions in the adsorption sites in soils. Calcium and magnesium can displace sodium (ion exchange) if a water high in calcium and magnesium concentrations relative to sodium concentrations is applied to the soil. This exchange is a reversible process. Because the cation exchange process is reversible, a sodic soil can be improved by applying gypsum ($CaSO_4 \cdot 2H_2O$), which, upon dissolving, yields a more calcic soil.

The sodium-adsorption ratio is a means of determining whether the sodium concentration in water is likely to affect soil properties adversely. The U.S. Salinity Laboratory Staff (1954) defined SAR as follows:

$$SAR = \frac{(Na)}{\sqrt{\frac{(Ca) + (Mg)}{2}}} ,$$

where Na, Ca, and Mg are the concentrations of sodium, calcium, and magnesium, respectively, expressed in milliequivalents per liter. Experiments show that the SAR predicts reasonably well the degree to which irrigation water will enter into cation-exchange reactions in soil. A high SAR indicates a greater potential that sodium will replace adsorbed calcium and magnesium on the clay fraction of soil.

SODIUM AND SALINITY CLASSIFICATION OF IRRIGATION WATER

On the basis of specific conductance and SAR values, the U.S. Salinity Laboratory Staff (1954) developed a general classification to illustrate the salinity hazard and sodium hazard of water used for irrigation. Specific conductance is a convenient measure of the salinity, or dissolved-solids concentration, of water. It is defined as the capacity of water to conduct an electrical current, and is expressed in micromhos (umho) per centimeter at 25^{o} Celsius. The greater the amount of dissolved solids, the easier an electrical current will be conducted. Typically, the concentration of dissolved solids, in milligrams per liter, can be estimated by multiplying specific conductance by a factor ranging from 0.55 to 0.80, depending on the chemical composition of water.

The salinity and sodium hazard diagram (fig. 1) shows at a glance the range of usefulness of irrigation waters, but does not provide a comprehensive method of classifying irrigation water. First, no adjustment is made for different crops, which vary in their tolerance to the salinity and SAR of water. Second, because of the complex assemblage of most soils, a user cannot depend exclusively upon any classification system based solely on the composition of water. Therefore, individual users are cautioned to apply corrections as needed, according to current research, to supplement information here.

The data plotted in figure 1 are from 418 sampled wells in the Columbia Plateau--352 samples collected during summer 1982 and 66 samples collected during either spring or summer 1983. For the last set, the earliest sample taken was used if more than one sample was available. The stippled area in figure 1 indicates numerous data points of equal value.

Sixty-six percent of the ground waters sampled were in the medium salinity-low sodium hazard category (fig. 1). In general, there is little probable danger of harmful levels of exchangeable sodium accumulation in soils when using such waters. Plants with moderate salt tolerance can be grown in most instances without special salinity-control practices, but a moderate amount of leaching is generally needed (California Fertilizer Association, 1980, p. 26).

Twenty-two percent of the water samples were in the low salinity-low sodium hazard category. This type of water can be used for irrigation with most crops on most soils with little likelihood of soil salinity buildup, or little danger of development of harmful levels of exchangeable sodium accumulating in soils. However, water with very low salinity may cause leaching of calcium from the soil. Soils may then break down, disperse, and seal, and poor water penetration often results (Ayers, 1977, p. 149).

Eight percent of the waters were in the low sodium-high salinity hazard category. Exchangeable sodium is not likely to cause a problem, but because of high salinity this water should be used only on light soils with good drainage. In addition, irrigation practices should provide for appreciable leaching. Plants with good salt tolerance should be considered.

Eleven water samples (2.5 percent) were in the medium salinity-medium sodium hazard category. Use of this water may produce harmful levels of sodium in most soils, especially those that are fine-textured and with a high cation-exchange capacity. Soils high in gypsum (calcium sulfate) or lime (calcium carbonate), however, may not be affected.

Seven samples (1.5 percent) were in either high or very high sodium hazard categories and are generally considered unsatisfactory for irrigation purposes. These samples all show a medium salinity hazard, indicating that as the SAR increases the total amount of salts in solution remains about the same.

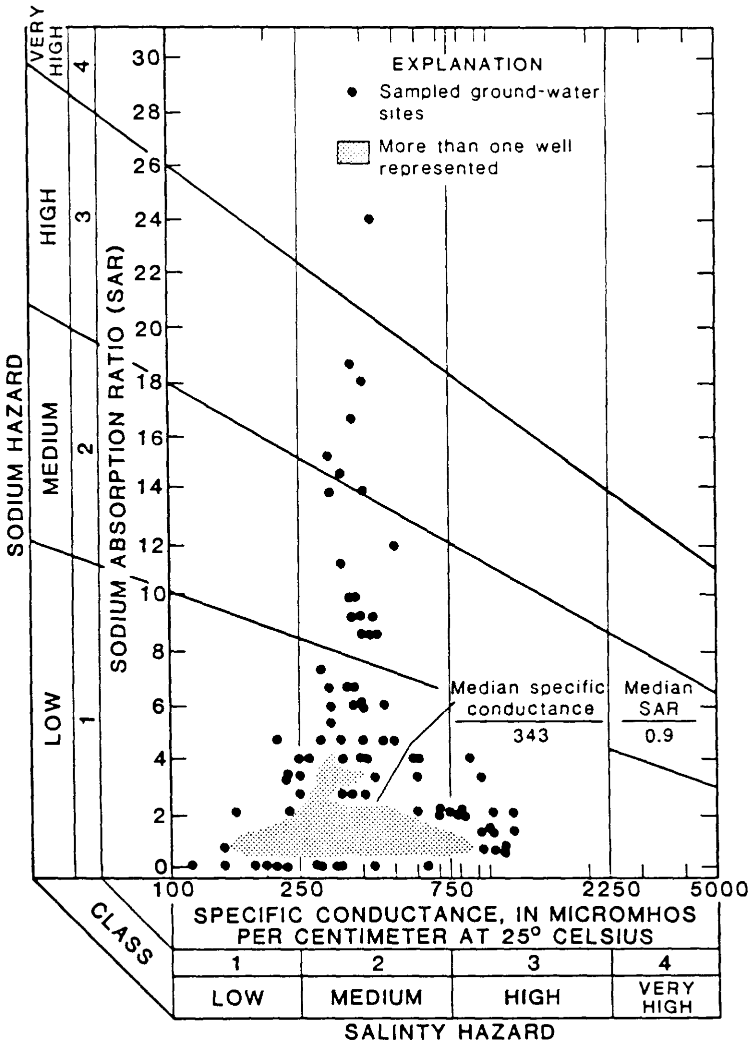


FIGURE 1.--Salinity and sodium hazard for classification of irrigation waters. (Adapted from U.S. Salinity Laboratory Staff, 1954.)

GEOHYDROLOGIC SETTING

Geology

The Columbia Plateau was formed by numerous lava flows of Miocene Age (between 17 and 6 million years ago), referred to as the Columbia River Basalt Group. Three formations in the Columbia River Basalt Group predominate in the study area. The oldest, the Grande Ronde Basalt, makes up roughly 85 percent of the total basalt accumulation in the plateau. It is generally covered by the next oldest formation, the Wanapum Basalt, over most of the area. The Saddle Mountains Basalt, the youngest formation, overlies the Wanapum Basalt over the southwestern part of the Columbia Plateau. The Saddle Mountains Basalt forms less than 1 percent of the basalt accumulation in the plateau, and is exposed only in the southwestern part of the study area.

Individual basalt flows within a formation range in thickness from less than 1 foot to as much as 300 feet, and average 100 feet. For example, the Grande Ronde Basalt comprises at least 30 and perhaps as many as several hundred individual flows. Total basalt thicknesses in excess of 10,000 feet have been reported in the central regions of the plateau, thinning in the marginal areas and interfingering with sediment derived from the surrounding highlands. The wide range in accumulated thickness is attributed to the fact that the earliest flows covered a surface with as much as 3,000 feet of relief and subsidence occurred during flow accumulation. Much of the existing basalt surface is covered with a veneer of either fluvial, glacial, lacustrine, or eolian deposits. The general dip of the basalt flows roughly parallels the plateau surface where it is unmodified, producing a northeast to southwest gradient.

The plateau is incised by the Columbia and Snake Rivers, and much of the surface topography in the eastern half of the study area has been modified by glacial outwash and catastrophic flooding associated with Pleistocene glaciation. In the southwestern part of the plateau, regional compression has produced a series of east-west anticlinal folds with broad synclinal valleys and associated faulting. These structures have a significant effect on local patterns of ground-water movement.

Hydrology

The principal water-bearing zones in the Columbia River Basalt Group are the fractured or rubbly rocks lying at the contacts of basalt flows. Ground-water flow is both vertical and lateral in the highly permeable zones near the tops and bottoms of most basalt flows. Vertical movement through the dense flow centers is facilitated by characteristic columnar and other types of jointing. Ground-water flow is roughly parallel to the slope of the land surface; however, subsurface structures that cause changes in permeability and transmissivity alter this pattern locally. Sedimentary interbeds serve as aquifers in those areas where their lithologies and extent facilitate the storage and transmission of significant quantities of water; they otherwise serve as semiconfining beds.

Most of the water in the basalts originates as precipitation, which varies throughout the area and is somewhat related to land-surface altitude. Rainfall ranges from 8 inches in the central lowlands to 20 inches in the uplands to the northeast, and occurs mainly during the cooler winter months.

After entering the ground, water tends to move downward through the basalts and laterally from areas of high recharge (generally the northeastern part of the study area) to areas of discharge (primarily in the southwestern part of the study area), where it tends to flow upward and into the Columbia, Snake, and Yakima Rivers (fig. 2). Locally, this generalized flow pattern is complicated by recharge from irrigation water applied to the land surface and by discharge to pumping wells. Ground-water movement is both vertical and lateral in interbeds and flow tops, but primarily vertical in the tight, thick, central part of most basalt flows. The many uncased wells in the study area tend to increase the vertical hydraulic conductivity between basalt flows by allowing water to move freely from one flow to another without having to travel through intervening layers.

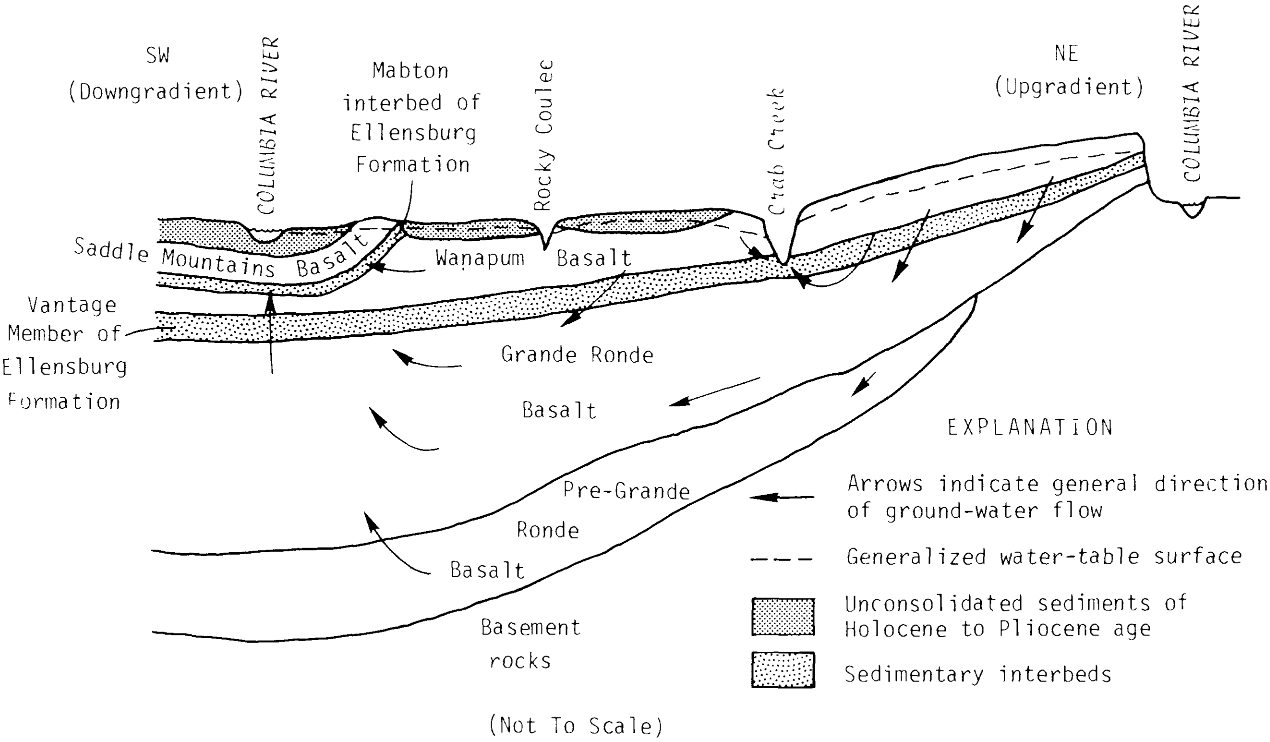


FIGURE 2.--Generalized pattern of ground-water movement in part of the study area.

AREAL VARIATION OF SODIUM CONCENTRATION, SODIUM-ADSORPTION RATIO, AND SPECIFIC CONDUCTANCE IN GROUND WATER

Areal variations of sodium concentration, sodium-adsorption ratio, and specific conductance (estimate of dissolved solids) are shown in ground waters within the Grande Ronde Basalt, plate 2; Wanapum Basalt, plate 4; and Saddle Mountains Basalt, plate 5. Some wells tap more than one formation and are thus presented as finished in the Wanapum-Grande Ronde Basalts (pl. 3) and Saddle Mountains-Wanapum Basalts (pl. 5). For purposes of discussion in this report, a SAR above 8.0 is considered high and below 4.0, low; values between 4.0 and 8.0 are considered intermediate. When more than one analysis was available for a well, average values of SAR, specific conductance, and sodium are shown.

Grande Ronde Basalt

The Grande Ronde Basalt, the oldest unit, underlies virtually all of the study area. It is exposed along the northern margin and in a few deeply incised stream channels in the central and southwestern parts of the study area. Its thickness ranges from a few feet along the northern margin, where it pinches out against "basement" rocks, to greater than 4,000 feet in the Pasco area. As can be seen in plate 2, very few wells in the central part of the plateau are cased through the Wanapum Basalt to tap only the Grande Ronde Basalt.

Water with intermediate to high SAR was observed in wells in the Grande Ronde Basalt in the central part of the plateau, and low SARs were observed in the rest of the study area, except for wells 4 and 325 (pl. 2). These two wells are located in discharge areas where ground waters are generally sodium-enriched because of a longer residence time (see beyond).

Wanapum-Grande Ronde Basalts

Few wells are cased to the great depths that would be required to obtain single-aquifer samples from the Grande Ronde Basalt, and therefore composite samples from wells tapping both the Grande Ronde and the Wanapum Basalts were needed for areal coverage. The majority of these composite samples are from wells located in the central part of the plateau (pl. 3). The proportion of water entering a well from the Grande Ronde or Wanapum Basalts is difficult to estimate, but is known to vary from well to well because of a number of factors such as aquifer permeabilities, pumping patterns, and well construction. The primary contributing aquifer is designated on plate 3 for composite samples with sufficient information. Determination of the primary aquifer was based on permeability estimation from geophysical logs, reports of water-bearing characteristics from driller's logs, and from the relative depth of well penetration into respective formations. Verification of this information is not sufficient to determine whether composite waters are more representative of a designated aquifer, but if the well has a high yield and has been continuously pumped prior to sampling, the designated primary aquifer is a reasonable determination.

Composite ground-water samples had a low SAR (less than 1.0) in the upgradient areas of the plateau, and generally an intermediate to high SAR (between 4.0 and 7.9) in the central part of the plateau.

Wanapum Basalt

The Wanapum Basalt has the most extensive surface exposure of the three major formations. Consequently, wells that draw exclusively from this formation are more widely distributed throughout the study area than wells drawing from other formations.

Water in the Wanapum Basalt had generally low SARs (pl. 4). Water with a SAR of less than 1.0 was observed in upgradient areas, and about 8 percent of the wells sampled had a SAR in the 2.0 to 3.9 range, mostly in downgradient areas. Three wells had a SAR in the 4.0 to 7.9 range and three wells had a SAR exceeding 8.0. These wells are widely scattered, and five of them are either deep wells or are located in probably discharge areas.

Saddle Mountains-Wanapum Basalts

Composite samples from wells tapping both Wanapum and Saddle Mountains Basalts were needed for adequate areal coverage in the southwestern part of the plateau. Here the Saddle Mountains Basalt, the youngest formation, overlies the Wanapum Basalt. Water samples from 11 composite wells had a low SAR, except for two wells, 54 and 106, which had SARs exceeding 4.0 (pl. 5). These wells were more than 950 feet deep and located in areas of probable ground-water discharge.

Saddle Mountains Basalt

Water samples from most wells tapping this formation had a low SAR. Only two wells had a SAR exceeding 4.0 (pl. 5), and both are located near the Columbia River in a discharge area.

VARIATION OF SODIUM CONCENTRATION, SODIUM-ADSORPTION RATIO, AND WATER TYPE WITH RESIDENCE TIME

The residence time of water, with some exception, generally increases downgradient and with depth. Radiocarbon determinations of the waters sampled provided an estimate of the approximate residence times to facilitate the evaluation of changes in sodium and SAR with time. The sample data were divided into three groups on the basis of carbon-14 concentrations: less than 25 percent modern carbon (oldest waters), 25 to 65 percent modern carbon, and more than 65 percent modern carbon (youngest waters). A cation plot of dissolved sodium, magnesium, and calcium (fig. 3) shows a progressive enrichment of sodium with residence time. Progressive enrichment of SAR with residence time is also suggested because of the concurrent depletion of calcium and magnesium. Scatter of data between sodium concentration and groups of carbon-14 concentration can be partly attributed to ground-water samples from wells tapping multiple formations. Thus, the sampled water varies in the percentage of older and younger waters. The degree of mixing of waters is dependent on well construction, pumping patterns, and hydrologic conditions.

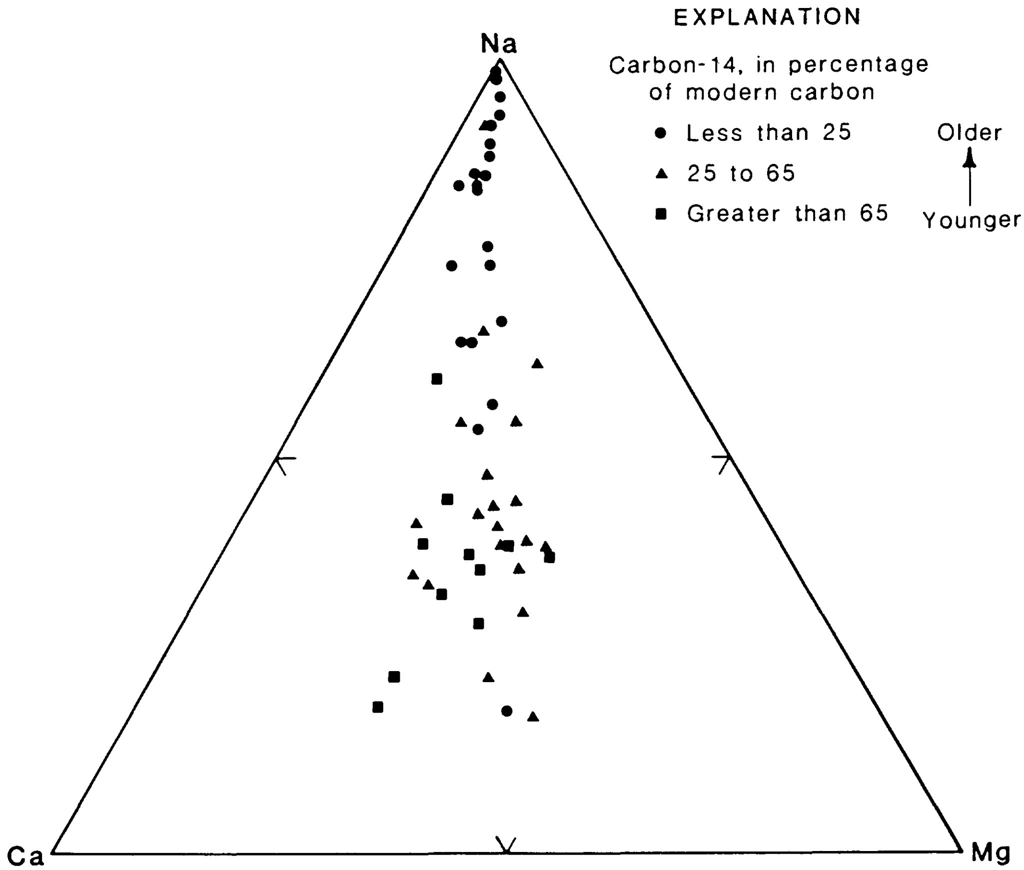


FIGURE 3.--Plot of Na, dissolved sodium; Ca, calcium; and Mg, magnesium concentrations (equivalent percentages) in ground water, grouped by carbon-14 values.

Samples taken from two piezometer sites (at Davenport, 24/36E-16A, and Odessa, 20/33E-16; see plates 2 and 4) provide evidence of increased SAR and sodium concentration with increased well depth at given locations (table 1). Ground water sampled from piezometers is drawn from aquifers at specific screened intervals. At the Davenport site, SAR values ranged from 0.5 at the top to 3.0 at the bottom. With the exception of a Grande Ronde sample at 635 feet, sodium concentration and SAR increased gradually with depth. Likewise, at the Odessa site, sodium concentration and SAR increased with depth, with the exception of a Grande Ronde sample at 704 feet. No explanation can be given for these exceptions to the general pattern of increasing sodium concentration and SAR values with increasing depth.

TABLE 1.--Sodium concentration and sodium-adsorption ratio with depth at two piezometer sites

Formation	Bottom of screen, in feet below land surface	Sodium concentration, in milligrams per liter	Sodium-adsorption ratio
	Davenport Site (24/36E-16A)		
Wanapum Basalt	160	12	0.5
Do.	224	14	.7
Do.	262	17	1.0
Do.	365	38	2.3
Grande Ronde Basalt	635	34	1.8
Do.	750	40	3.0
	Odessa Site (20/33E-16E)		
Wanapum Basalt	310	43	2.2
Do.	366	[a]49	[a]3.5
Grande Ronde Basalt	616	75	11
Do.	704	62	5.4

[a]Data from G. S. Hunt, Rockwell International, Richland, Wash., written commun., September 14, 1983.

Chemical Gradients in Regional Flow Path

Variations of sodium concentration, SAR, and water type are illustrated by examining data along approximate ground-water flow lines that represent the regional flow system of the Columbia Plateau (fig. 4). Water-level contours for the basalt formations show the direction of regional ground-water flow to be generally northeast to southwest discharging to the Columbia and Snake Rivers (fig. 4). The exception is the northwest part of the regional flow system, where basalts dip slightly to the southeast, resulting in ground-water movement, particularly in the Wanapum Basalt, towards Moses Lake and Potholes Reservoir (fig. 4).

Parallel fence diagrams (presented on plate 1) are oriented in the general direction of flow where the basalt layers are essentially horizontal, have few structural deformities, have a long flow path, and where data from numerous sampled wells are available. Superimposed on these diagrams are A--sodium concentration; B--SAR; and C--cation water type based on analyses of water samples from 199 wells. Most of these wells are within 8 miles of the trace of the line to which they are projected. Because of the scale, it is not possible to show localized variations within or between shaded zones, where the sodium concentrations or SAR can be more or less than that indicated.

In the study area, shallow ground water tends to have low sodium concentrations and SAR values. Both parameters increase downgradient and with depth. For example, the highest values of SAR were observed in waters from deep wells near the discharge end of the flow path. Because the longer residence time permits more extensive chemical evolution, these waters are sodium enriched. A progressive enrichment of sodium is also reflected in the cation type of ground waters along the regional flow path. The predominantly calcium-sodium ground waters in shallow and upgradient locations evolved to sodium-calcium and sodium-potassium ground waters in deeper and downgradient locations.

Most waters upgradient or in areas where formations are near the surface were 50 to 90 percent calcium-plus-magnesium chemical equivalents. In contrast, most waters downgradient and in deeper formations were 50 to 90 percent sodium-plus-potassium, and the deepest waters in fence diagram A-A′ and B-B′ were 90 to 100 percent sodium-plus-potassium equivalents. Throughout the flow path, most waters had 50 to 90 percent bicarbonate as the predominant anion. Most waters sampled from deeper aquifers were predominantly bicarbonate, but in the shallower aquifers sulfate plus chloride dominated in some samples. Shallow aquifers may have been affected by man's activities. For example, the higher sulfate-plus-chloride concentrations in the upper aquifers may represent flushing from soils of semiarid basins of salts accumulated since the start of surface-water importation and irrigation in the early 1950's. Higher nitrate concentrations in shallow aquifers indicate possible infiltration of fertilizer residues. Typical analyses of water at various positions along the flow path are shown in table 2.

TABLE 2.--Selected analyses of waters from Grande Ronde, Wanapum, and Saddle Mountains Basalts

[Values in milligrams per liter unless otherwise indicated]

Location[a]	Fence diagram	Index No.	Date of collection	Depth of well (ft below land surface)	Specific conductance (micromhos at 25 °C)	pH, in units	Temperature (°C)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Sodium-adsorption ratio
				Grande Ronde Basalt							
25/37-21L4	B-B'	413	7-21-82	975	288	8.2	22.3	15	5.8	40	2.3
25/32-35P1	A-A'	407	9- 9-82	1,140	270	8.2	21.3	12	5.3	39	2.4
24/41-14D1	C-C'	400	7-19-82	775	213	7.7	15.7	19	8.4	17	.8
23/41-24P2D1	D-D'	377	7-20-82	300	481	7.7	14.7	48	26	22	.7
21/30-23J1D1	A-A'	331	9- 8-82	1,335	372	8.6	23.1	16	2.4	55	3.5
21/38-23L1	C-C'	342	7-21-82	502	248	8.4	21.4	15	3.6	34	2.1
18/31-33D1	B-B'	257	5-19-83	2,400	400	9.3	36.6	1.8	.1	89	18
17/33-12F2	C-C'	232	8-10-82	1,020	300	7.8	19.2	9.0	2.2	52	4.2
15/32-7J1	C-C'	170	5-20-83	1,900	348	8.3	25.4	9.3	4.9	57	3.9
15/36-33A2	D'D'	177	9- 8-82	510	410	7.7	19.9	29	19	40	1.5
				Wanapum Basalt							
23/43-6G1	D-D'	379	7-19-82	125	196	7.4	11.8	30	6.7	8.1	.4
22/38-2D1D1	C-C'	359	7-21-82	300	315	7.7	12.9	37	11	14	.5
24/38-2D1	C-C'	396	7-20-82	85	430	7.2	9.7	38	12	26	1.0
25/35-3E1D1	A-A'	410	7-22-82	200	400	6.7	11.6	37	11	23	.9
15/35-2D1	D-D'	175	8- 7-82	342	301	8.1	15.1	17	13	25	1.1
18/33-12C2	C-C'	259	8-11-82	500	325	8.0	17.7	21	10	27	1.3
20/32-15D2	B-B'	311	8-13-82	220	353	8.2	14.4	37	12	19	.7
19/36-5B1	C-C'	293	8- 9-82	155	804	7.4	12.6	63	25	69	1.9
10/32-3R1	D-D'	74	7-19-83	540	728	7.9	19.1	46	25	61	1.8
14/30-10P1	C-C'	142	8-31-82	433	375	7.7	16.5	30	19	22	.8
17/29-24C1	B-B'	225	8-11-82	210	590	7.8	16.6	13	15	86	3.9
				Saddle Mountains Basalt							
14/29-5A1	B-B'	140	8-31-82	305	560	8.2	18.8	38	30	32	1.0
13/30-31N1	C-C'	117	9- 1-82	235	925	7.9	16.1	86	41	52	1.2
12/28-23H1D1	C-C'	105	8-30-82	413	395	8.2	18.5	15	3.7	62	3.9
11/30-36M1	D-D'	87	5-17-83	237	630	7.8	16.3	60	57	25	.6
9/29-2G2	D-D'	55	5-18-83	473	445	7.9	22.1	5.2	2.4	90	8.4
9/30-2R1	D-D'	57	8-27-82	211	575	8.0	17.6	47	24	31	.9

[a] Location, fence diagram, and index number shown on plate 1

Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Silica (SiO_2)	Dissolved iron (ug/L)
4.8	174	0.0	11	4.3	0.9	0.1	50	18
4.8	151	.0	7.0	4.6	.8	.1	57	21
3.1	136	.0	8.0	.2	.4	.1	50	91
2.5	336	.0	5.0	2.4	.3	.1	51	94
11	124	5.0	35	20	.9	.1	68	8
5.0	140	5.0	5.0	3.0	.9	.2	63	11
7.1	127	44	12	13	4.1	.1	110	62
7.5	160	.0	7.0	10	1.9	.2	66	3
7.0	172	.0	18	9.8	1.8	.2	66	12
7.1	281	.0	11	6.1	.8	.1	76	8
1.4	116	.0	5.0	1.1	.3	2.2	51	4
2.3	156	.0	11	6.1	.3	4.7	47	7
2.9	177	.0	28	15	2	7.6	38	20
3.8	150	.0	19	13	.2	12	48	6
7.1	177	.0	7.0	4.2	.4	.5	44	3
9.1	148	.0	22	6.1	.5	3.2	47	3
3.8	153	.0	31	17	.4	.5	45	3
3.5	285	.0	70	49	.3	10	39	3
9.4	139	.0	92	74	.4	11	58	10
4.8	190	.0	28	7.7	.4	1.2	53	3
7.4	226	.0	67	22	.5	5.5	47	3
5.9	190	.0	76	32	.5	4.0	57	3
4.8	280	.0	150	49	.3	8.0	48	4
9.6	193	.0	11	19	.8	.1	62	35
2.1	248	.0	120	55	.3	8.1	50	14
12	262	.0	.2	26	1.5	.1	62	73
4.8	206	.0	76	26	.5	4.0	41	3

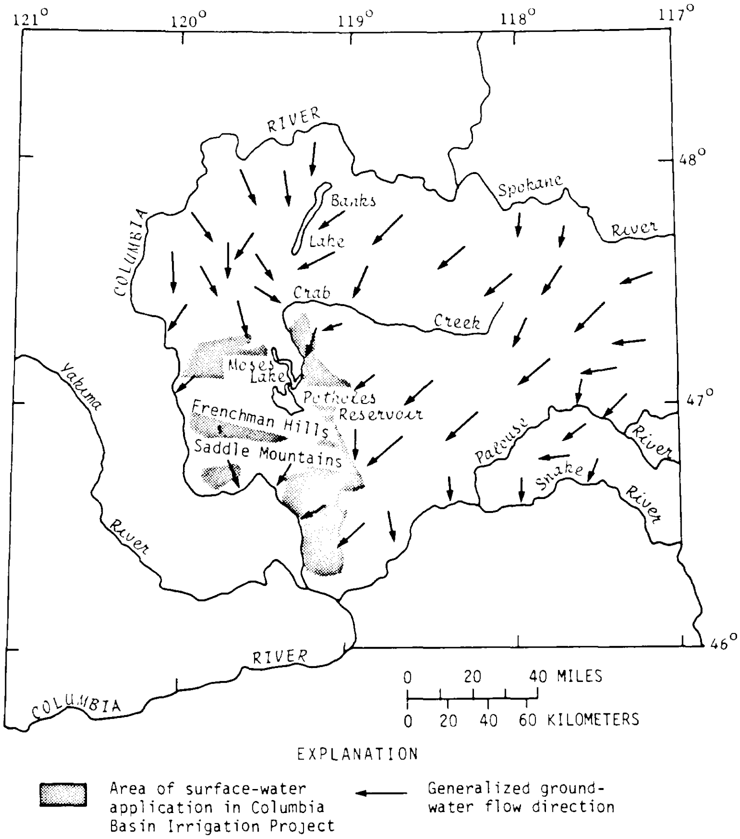


FIGURE 4.--Generalized ground-water flow in Wanapum-Grande Ronde Basalts in part of study area. Flow directions inferred from potentiometric maps (Bauer and others, 1985).

Mechanism for Sodium Enrichment

The nature of water-rock interactions and the chemical evolution of ground water along a flow path in the Columbia Plateau are described as a conceptual model by Hearn and others (1985) and Warren Wood (U.S. Geological Survey, written commun., 1982). In one such model, parent rock is dissolved by carbon-dioxide-charged water. The volcanic rocks being considered are partly altered to clay minerals and amorphous iron oxide. Sodium, potassium, magnesium, calcium, and bicarbonate are added to the ground water in the course of this initial alteration. Calcium is precipitated as calcite as the pH increases. The precipitation of calcite and iron-magnesium-rich clay minerals lowers calcium and magnesium concentrations. Since the rate of release of sodium exceeds its removal by precipitation, the concentration of sodium increases. Eventually, the sodium in solution increases to where the solubility limits of the locally most common zeolite, clinoptilolite, are exceeded and it is precipitated from solution. Additional sodium is perhaps added to solution by the replacement of exchangeable sodium on clays by calcium and magnesium. The above process favors a high SAR because sodium concentration increases and calcium and magnesium concentrations decrease.

EFFECTS OF GROUND-WATER WITHDRAWALS ON SODIUM CONCENTRATION AND SODIUM-ADSORPTION RATIO

The pumping of water from uncased wells that penetrate multiple aquifers allows a 'shortcircuiting' of natural vertical leakage and, in general, enhances the opportunity for sodium dilution or enrichment, depending on the percentage of water derived from upper and lower aquifers during pumping. Most wells in the Columbia Plateau are either uncased in the interval between aquifers within a formation or are open to more than one major formation. Typically, wells that supply water for irrigation are pumped nearly continuously for 7 months and are then idle for 5 months.

The effects of pumping on the temporal variation of sodium concentration and SAR were tested by using two samples, obtained toward the beginning and toward the end of pumping periods, from the same wells to determine whether the SAR and sodium concentration change. The sampling periods were grouped into two pumping periods, summer 1982-spring 1983 and spring 1983-summer 1983 (table 3). The SAR or sodium concentration observed in the summer (toward end of pumping period) was subtracted from a SAR or sodium concentration observed in the spring (toward beginning of pumping period). A frequency plot of the differences in sodium concentration in the Wanapum Basalt for the spring 1983-summer 1983 pumping period (fig. 5) shows that the differences are an approximate normal distribution with a strong preponderance of differences near zero and the positive and negative mean differences somewhat evenly distributed. The approximate normal distribution of data in figure 5 is typical of all categories of wells shown in table 3.

The results of the evaluation of pumping effects were divided into the categories listed below. Categories 2 and 3 were chosen because they are likely to fall inside areas of greater pumpage and of long-term ground-water withdrawal.

1. Wells by geologic formation.
2. Irrigation wells only.
3. Wells within an area that has experienced steady water-level declines since the mid-1960's (Cline, 1984). The area is generally east of the the East Low Canal in western Adams and Lincoln Counties and eastern Grant County.

The mean difference in sodium concentration and SAR shown in table 3 indicate most values are near zero. This indicates, in conjunction with significant testing shown, that pumping of ground waters for the period specified do not, with two exceptions, affect sodium concentrations and SAR. For the two exceptions, sodium concentrations, but not SARs, showed a significant change in one of two pumping periods (table 3). This occurred for categories of irrigation wells ($p = 0.001$) and wells in areas of steady water-level decline ($p = 0.061$). In order for the mean differences in SAR to show a high probability of being equal to zero and sodium concentration a low probability, calcium and magnesium concentration must also be changing.

TABLE 3.--Mean difference in sodium concentrations, in milligrams per liter, and sodium-adsorption ratio toward beginning and toward end of two pumping periods

[Significance testing from Student-t test. P is the probability that the sample mean difference would deviate this far or farther from zero if the population mean difference were actually zero. The null hypothesis is rejected (that is, there is no difference) when p is small, such as p<0.10.]

Wells	Constituent	Summer 1982-spring 1983			Spring 1983-summer 1983		
		Mean differences		Number of paired observations	Mean differences		Number of paired observations
1. Wells tapping:							
Grande Ronde Basalt	Sodium	0.27	p>0.10	72	-0.37	p>0.10	63
	SAR	.027	p>.10		-.026	p>.10	
Grande Ronde-Wanapum Basalts	Sodium	-.42	p>.10	51	-.53	p>.10	61
	SAR	.066	p>.10		.17	p>.10	
Wanapum Basalt	Sodium	-.53	p>.10	112	.40	p>.10	102
	SAR	.005	p>.10		.008	p>.10	
Saddle Mountains Basalt	Sodium	1.4	p>.10	39	.050	p>.10	38
	SAR	.10	p>.10		.068	p>.10	
2. All irrigation wells tapping any formation	Sodium	-.99	p=.001	68	-.36	p>.10	77
	SAR	-.041	p>.10		-.038	p>.10	
3. In area of water-level deline	Sodium	-.57	p>.10	43	.85	p=.061	61
	SAR	.21	p>.10		.17	p>.10	

Wells with waters that showed large differences in sodium concentration or SAR between pumping periods were plotted on maps (data not shown), but no patterns in magnitude or positive and negative differences were found. Thus, ground waters that do show a large increase or decrease in sodium concentration and SAR between pumping periods are difficult to predict because the temporal variation is a function of many variables, such as aquifer characteristics, pumping patterns, water-level fluctuations, and individual well construction.

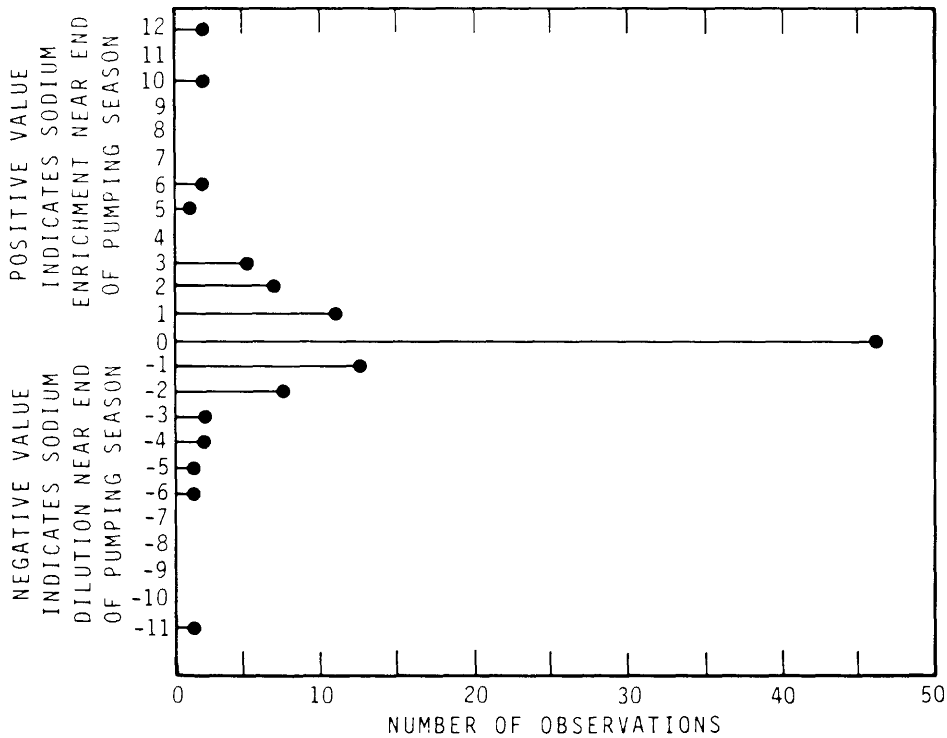


FIGURE 5.--Frequency diagram showing differences in sodium concentration (milligrams per liter) in water in the Wanapum Basalt between spring 1983 and summer 1983.

SUMMARY

The principal findings of the ground-water study are summarized below.

1. Variations of sodium concentration and SAR are determined by chemical reactions between aquifer materials through which ground water flows, and by ground-water flow patterns. Sodium concentrations and SAR were lowest in shallow aquifers and in upgradient areas where ground water has a shorter travel path. Conversely, sodium concentrations and SAR were highest in deep basalt aquifers and in downgradient areas where ground water has a long travel path. Most of the intermediate to high SAR values were in pumping centers in the central part of the plateau and in discharge areas near major streams.

2. Increasing depth and distance downgradient in the flow path favor sodium enrichment. Most ground waters upgradient or where a formation is exposed were 50 to 90 percent calcium-plus-magnesium chemical equivalents. In contrast, most waters downgradient and in deeper formations were 50 to 90 percent sodium-plus-potassium equivalents. Some of deepest waters near the end of the flow path evolved to 90 to 100 percent sodium-plus-potassium equivalents.

3. The pumping of ground water does not appear to affect the temporal variation in SAR. In general, there was no significant difference in the distribution of SAR for the beginning and the end of two pumping periods for wells tapping any basalt aquifer studied.

4. The largest percentage of ground waters sampled was classified as having a medium salinity hazard and low sodium hazard. Consequently, most sampled waters present little danger to irrigated crops with respect to harmful levels of exchangeable sodium accumulating in soils. Because of the amounts of dissolved solids present in the waters, some crops may require a moderate amount of leaching for salinity control. Eighteen of 418 wells sampled had waters with an SAR greater than 8.0 and were classified as constituting a medium, high, or very high sodium hazard to irrigated crops. Use of these waters could produce harmful levels of sodium in many soils, especially those that are fine-textured and with a high cation-exchange capacity.

REFERENCES

Ayers, R. S., 1977, Quality of water for irrigation: Journal of Irrigation and Drainage Division, American Society of Civil Engineers, v. 103, no. IR2, proceeding paper 13010, p. 135-154.

Back, William, 1961, Techniques for mapping hydrochemical facies, in Short Papers in the Geologic and Hydrologic Sciences: U.S. Geological Survey Professional Paper 424D, p. 380-382.

Bauer, H. H., Vaccaro, J. J., and Lane, R. C., 1985, Maps showing ground-water levels in the Columbia River Basalt and overlying materials, spring 1983, southeastern Washington: U.S. Geological Survey Water-Resources Investigations Report 84-4360, 4 plates.

California Fertilizer Association, 1980, Western fertilizer handbook (6th ed.): Danville, Illinois, The Interstate Printers and Publishers, Inc., 269 p.

Cline, D. R., 1984, Ground-water levels and pumpage in east-central Washington, including the Odessa-Lind area, 1967 to 1981: Washington State Department of Ecology Water-Supply Bulletin 55, 34 p.

Drost, B. W., and Whiteman K. J., 1986, Surficial geology, structure, and thickness of selected geohydrologic units in the Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 84-4326, 11 sheets (in press).

Garrett, A. A., 1968, Ground-water withdrawal in the Odessa area, Adams, Grant, and Lincoln Counties, Washington: Washington State Department of Water Resources Water-Supply Bulletin 31, 84 p.

Hearn, P. P., Steinkampf, W. C., Bortleson, G. C., and Drost, B. W., 1985, Geochemical controls on dissolved sodium in basalt aquifers of the Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 84-4304, 38 p., 1 pl.

Luzier, J. E., and Burt, R. J., 1974, Hydrology of basalt aquifers and depletion of ground water in east-central Washington: Washington State Department of Ecology Water-Supply Bulletin 33, 53 p.

Newcomb, R. C., 1972, Quality of ground water in basalt of the Columbia River Group, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Supply Paper 1999-N, 71 p.

Steinkampf, W. C., Bortleson, G. C., and Packard, F. A., 1985, Controls on ground-water chemistry in the Horse Heaven Hills, south-central Washington: U.S. Geological Survey Water-Resources Investigations Report 85-4048, 26 p.

Tanaka, H. H., Hansen, A. J., Jr., and Skrivan, J. A., 1974, Digital-model study of ground-water hydrology, Columbia Basin Irrigation Project area, Washington: Washington State Department of Ecology Water-Supply Bulletin 40, 60 p.

Van Denburgh, A. S., and Santos, J. F., 1965, Ground water in Washington - its chemical and physical quality: Washington State Division of Water Resources Water-Supply Bulletin 24, 93 p.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkaline soils: U.S. Department of Agriculture Handbook 60, 160 p.

GLOSSARY

Anions - Ions in solution that are negative in charge, such as chloride, sulfate, bicarbonate, and fluoride.

Anticline - A fold, the core of which contains stratigraphically older rocks; it is convex upward.

Aquifer - Part of a formation, a formation, or a group of formations that contain sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Basalt - A dark to medium-dark colored, usually extrusive, igneous rock composed chiefly of calcium-rich plagioclase, clinopyroxene, and minerals high in iron and magnesium.

Carbon-14 - A radioactive isotope of carbon having a mass number of 14 and a half-life of 5,730±40 years as the most recently established value. Carbon-14 is useful in estimating the age of water under the appropriate hydrologic and geochemical conditions.

Cations - Ions in solution that are positive in charge, such as calcium, magnesium, sodium, and potassium.

Dip - The angle that any planar feature makes with the horizontal, perpendicular to the trend of the feature.

Discharge - The process by which water leaves an aquifer; the quantity of water that is removed from an aquifer.

Eolian - Formed by the wind.

Fault - A fracture or fracture zone in a rock mass, along which there has been displacement or movement of the two masses relative to one another parallel to the fracture.

Fluvial - Produced by the action of moving water.

Fracture - A break in rocks as a result of intense folding, faulting, contraction, or other causes.

Head - The altitude of the water level in a well tapping an aquifer.

Joint - A fracture or parting that abruptly interrupts the physical continuity of a rock mass.

Lacustrine - Formed in a lake.

Lava - Molten extrusive material.

Mean - The mathematical average of all the values in a sample set.

Median - The middle value in a sample set, above and below which lie an equal number of values.

Null hypothesis - The assumption that no significant difference exists between two items or samples that are being compared statistically or that any observed difference is purely accidental and not due to a systematic cause.

Permeability - A measure of the relative ease with which a rock material can transmit liquid under a potential gradient. It is a property of the rock material and is dependent upon the shape, size, and interconnection of its pores or fractures.

Piezometer - A piezometer is an instrument specially designed to measure the hydraulic head within a zone small enough to be considered a point--as contrasted with a well that reflects the average head of the aquifer for the screened interval.

Recharge - The process by which water is added to an aquifer; the quantity of water that is added to the aquifer.

Residence time - Time during which a substance remains in a ground-water reservoir.

Sedimentary rock - Rock formed by the accumulation, compaction, and consolidation of sediment.

Significance level - The probability that a stated statistical hypothesis will be rejected when in fact it is true.

Student's t test - A statistical test used to compare sample and population means when the variances are unknown.

Syncline - A fold, the core of which contains stratigraphically younger rocks; it is concave downward.

Transmissivity - The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Zeolite - A generic term for a large group of white or colorless (sometimes red or yellow) hydrous aluminosilicates that are analogous in composition to the feldspars, with sodium, calcium, and potassium as their chief cations. Zeolites are known to occur as secondary minerals filling cavities and coating cracks and joints in basaltic lavas.