SUBSURFACE TRANSPORT OF RADIONUCLIDES IN SHALLOW DEPOSITS OF THE HANFORD NUCLEAR RESERVATION, WASHINGTON--REVIEW OF SELECTED PREVIOUS WORK AND SUGGESTIONS FOR FURTHER STUDY

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CONVERSION FACTORS

For use of readers who prefer to use International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

SUBSURFACE TRANSPORT OF RADIONUCLIDES IN SHALLOW DEPOSITS OF THE HANFORD NUCLEAR RESERVATION, WASHINGTON--REVIEW OF SELECTED PREVIOUS WORK AND SUGGESTIONS FOR FURTHER STUDY

EXECUTIVE SUMMARY

Operations at the Hanford Reservation, in south-central Washington, have resulted in the disposal of large amounts of radioactive wastes, some components of which have reached the ground water and are being carried to the adjacent Columbia River by the ground water, which discharges into the river as seeps and springs.

There has been considerable disagreement, as a result of different studies and monitoring attempts, as to the amounts of radioactive contaminants that are reaching the Columbia River and the rates of movement of the contaminated ground water from the waste-disposal sites to the river. The rate of travel of the radioactive substances in the ground water is important mainly in relation to radioactive decay. A relatively rapid movement allows less time for radioactive decay of the waterborne contaminants and, therefore, more total radioactivity in a given volume of ground water reaching the river, than does a slower rate of ground-water movement.

In 1985-86, a Washington-based consulting firm, SEARCH Technical Services, hereafter referred to as SEARCH, undertook an independent study of ground-water discharge from the Hanford Reservation into a selected reach of the Columbia River. As a result of its study, SEARCH concluded that ground-water discharge from the Reservation into the river was greater, and ground-water traveltime much less, than had been estimated by a U.S. Department of Energy (DOE) contractor that has been conducting the environmental monitoring at Hanford. Largely because of the disagreement as to the time required for radionuclides to be transported from disposal areas to the river, and because of the strong regional interest in possible effects of operations at the Reservation, U.S. Representative Les AuCoin of Oregon asked the U.S. Geological Survey to review the work by SEARCH. The Geological Survey also was requested to suggest methods for obtaining reliable data to fill any identified gaps in information for an adequate evaluation of radionuclide transport in the ground-water system of the Reservation and related discharge to the Columbia River.

The four principal findings of the SEARCH study were:

1. SEARCH has hypothesized the existence of a narrow buried highly permeable channel filled with boulders that provides a selected pathway for the movement of ground water from the 200-East Area of disposal to the Columbia River at about Hanford River Mile 28 (HRM 28), or about 19 miles upstream from the water-supply intake for the city of Richland.

2. SEARCH claimed to substantiate the existence of the hypothesized channel through a detailed study of streambank discharge to the Columbia River along an 852-foot reach of the river at about HRM 28, where ground-water discharge to the river was calculated to be 6.3 cubic feet per second.

3. Using the streambank discharge estimated in its detailed study, SEARCH concluded that ground-water traveltimes from the 200-East Area to the Columbia River are on the order of 2.5 years, rather than the 30 to 50 years estimated by the DOE contractor, Pacific Northwest Laboratory (PNL) of Battelle Memorial Institute, in a previous study.

4. SEARCH further concluded that the short traveltime and large ground-water discharge provided by the buried channel deposits are responsible for elevated tritium concentrations in the Columbia River downstream from HRM 28.

The Geological Survey conducted the review using information supplied by SEARCH in four short reports, in correspondence, and in oral presentations at meetings; additional information was obtained from those PNL reports that were readily available. No additional field measurements or other new data were collected by the Geological Survey.

The Geological Survey's review, conducted by a multidisciplinary team including specialists in geology, ground-water and surface-water hydrology, and water chemistry, produced the following major conclusions:

1. Available geologic, hydrologic, and water-chemistry data neither confirm nor refute the existence of a narrow, highly permeable ground-water channel connecting the Hanford 200-East Area with the Columbia River as hypothesized by SEARCH Technical Services. However, the data do suggest an alternative hypothesis that would account for a large localized ground-water discharge near HRM 28, but would result in longer average ground-water traveltimes between the 200-East Area and the river than results from the channel hypothesis.

2. The field experiment conducted by SEARCH adequately demonstrated that the streambank discharge from the Hanford Reservation into an 852-foot reach of the river was large, although the calculated discharge of 6.3 cubic feet per second may have a large undeterminable error. The existence of a large discharge can be explained by geohydrologic features other than the hypothetical channel.

3. The traveltime of 2.5 years, estimated by SEARCH for the movement of ground water through the length of the channel, cannot be supported. A more reasonable estimate of a traveltime between the 200-East Area and the river is probably on the order of 10 to 20 years but could be as low as 6 years.

4. SEARCH's estimate of the mean annual discharge of tritium in ground water to the Columbia River may be high by a factor of about three.

The foregoing conclusions, just as the SEARCH results, are estimates based on information that is incomplete and inconclusive. Reliable quantitative resolution of the important issues highlighted by the SEARCH studies can be accomplished only with additional data--planned, obtained, and evaluated under the best scientific methods available. The Geological Survey's suggestions for obtaining the minimum additional information needed to elaborate on the SEARCH studies, and for further studies needed to reliably characterize the movement of radionuclides in the ground-water system of the Hanford Reservation, are:

Hypothesized channel--Direct confirmation of the hypothesized subsurface channel on the basis of direct physical evidence (subsurface geology, water levels, water chemistry) would require the construction and sampling of an extensive array of test wells to penetrate the presumed channel along its postulated 10 to 17 miles of length. Hundreds of test wells might be required to ultimately confirm or reject the channel hypothesis; such an approach is not suggested.

Broad interconnected areas of saturated Hanford deposits are believed to exist between the 200-Areas and the Columbia River, and additional work is suggested that would allow the extent and thickness of these saturated deposits to be mapped. This information could then be incorporated into a numerical model for simulating three-dimensional ground-water flow in the sedimentary deposits of the Reservation. The model should be adequately supported by data on water discharges and ground-water levels (hydraulic heads) distributed areally and at different depths in the geohydrologic system. Necessary information for this effort would require intensive review of existing information and the construction and sampling of additional test and observation wells in the area in order to obtain more information on lithology, water levels, and water quality for specific geohydrologic units. However, the number of new wells required would be far less than those needed to confirm or reject SEARCH's channel hypothesis. The total effort proposed would be wholly consistent with DOE's stated objectives for its ground-water-surveillance program.

Ground-water discharge to river--The mass-balance method employed by SEARCH, with improvements, is a practical and effective technique, and resultant estimates can greatly enhance the accuracy of ground-water models. Suggested improvements in the technique include:

1. Extending measurement sections farther into the river, definitely into the region of background river concentrations of the selected constituents, and reducing spacing between measuring/sampling stations along the sections.

2. Using established methods for determining depth-averaged river velocities and for determining discharge-weighted concentrations at measurement stations in the river.

3. Determining concentrations of the selected constituent with an instrument that is calibrated over the full range of concentrations encountered in the experiment, or by using approved laboratory methods capable of accurate determinations at low concentrations. Either or both methods need to include a quality-assurance program for concentration determinations.

4. Attempting to obtain the discharge-weighted concentration in the streambank discharge (springs and seeps) along the study reach.

5. Monitoring ground-water levels to identify changes in bank storage (temporary storage of river water in nearshore parts of the aquifers during periods of high river levels).

Traveltime estimates--The most practical approach to estimating radionuclide traveltimes in the ground-water is by means of a three-dimensional transport model--one that uses information produced by the three-dimensional ground-water-flow model and is adequately supported by water-chemistry data distributed areally and at different depths in the aquifer system. Such a three-dimensional ground-water transport model needs to be developed for the sedimentary deposits of the Hanford Reservation. The model should be used to examine the effect of high-permeability zones (or channels) on traveltimes. A more rigorous analysis of the ground-water chemistry coupled with better information on radionuclide discharges on the Reservation, could be used with the model to yield improved estimates of traveltimes. Future estimates of traveltimes need to include determinations of first-arrival, as well as average, traveltimes. Future estimates also need to include estimates of traveltimes in the unsaturated zone between the waste-disposal sites and the water table, and to take into consideration chemical interactions between the contaminants in the ground water, and between the contaminants and the aquifer materials.

Tritium discharges--To obtain tritium discharges from the Hanford area to the Columbia River by the method used by SEARCH, a different method for sampling the river at Richland or a different method for interpreting the data from this site is probably required. The need for improved methods could be confirmed by determining the lateral distribution of both tritium and water discharge across the entire width of the river at Richland. The distribution should be determined at least three times during different river stages. Similar data are also needed for the upstream sampling site at Priest Rapids Dam. If the concentrations along the west bank at the Richland sampling site are not good approximations of the tritium concentration in excess of that at Priest Rapids Dam, then a new method should be devised to sample the tritium in the river or to analyze the data. Two possible approaches, which would require repeated tritium sampling and concurrent streamflow measurements across the entire river cross section, are suggested.

Use of ground-water modeling--The use of a three-dimensional ground-water-flow model is the approach of choice for any study of natural or human-induced ground-water flow, and the movement of contaminants in the ground water, anywhere on the Reservation. It cannot be overemphasized, however, that reliable results from such a model can only be achieved if the model is based on reliable water-level and water-chemistry data throughout the area and depth of the aquifer system to be studied.

INTRODUCTION

Background

Waste containing many types of radioactive materials has been stored and disposed of at the Hanford Reservation since the production of plutonium began there during World War II. Reactor-cooling water is discharged into retention basins that drain through the ground into the Columbia River within a few days; and large quantities of wash and cooling water, derived from the chemical separation plants, are discharged at locations farther from the river (fig. 1).

In the chemical separations area, liquid waste has been disposed of chiefly at U-pond, B-pond, and Gable Mountain pond (fig. 1). According to Newcomb and others (1972) the cribs (trenches filled with permeable material) and tile fields are used mainly for disposal of water-borne contaminants carrying long-lived radioactive elements. Water discharged to the ponds, however, is generally either nonradioactive or carries low-level waste. Those authors pointed out that this wastewater may, at times, acquire a higher level of radioactivity. High- and low-level liquid waste was discharged below the ground through injection wells. Newcomb and others (1972) indicated that, because this practice resulted in the discharge of waste both above and below the water table, the use of injection wells was discontinued. Radionuclides in the liquid waste have reached the ground-water table and have been transported to the Columbia River. The rate of liquid-waste discharge has varied with time, and has been large enough to alter the natural (predevelopment) direction and rate of ground-water movement.

Since the Hanford Reservation was selected by the Department of Energy (DOE) as a possible site for the location of the nation's first commercial high-level nuclear waste repository, various groups have become increasingly interested in the possible effects on the environment of past and planned operations at the Reservation. There also has been public concern, particularly in the Pacific Northwest, that the radionuclide monitoring activities at the Reservation appear to be subject to limited or no review. Concerns have been raised regarding the rate of movement of radionuclides from the Reservation into the Columbia River and the impact of these radionuclides on the quality of the river itself. Since 1965, environmental monitoring at Hanford has been conducted for DOE and its predecessors by the Pacific Northwest Laboratory (PNL) of Battelle Memorial Institute.

One Washington-based consulting firm, SEARCH Technical Services, hereafter referred to as SEARCH, undertook in 1985-86 an independent study of the discharge of ground water and selected chemical constituents from the Hanford Reservation into the Columbia River adjacent to the Reservation. Following is a summary of SEARCH's four principal findings:

- SEARCH has hypothesized the existence of a narrow, buried, highly permeable channel filled with boulders that provides a pathway for the preferential movement of ground water from the 200-East Area to the Columbia River at about Hanford River Mile 28 (HRM 28) (see fig. 1).

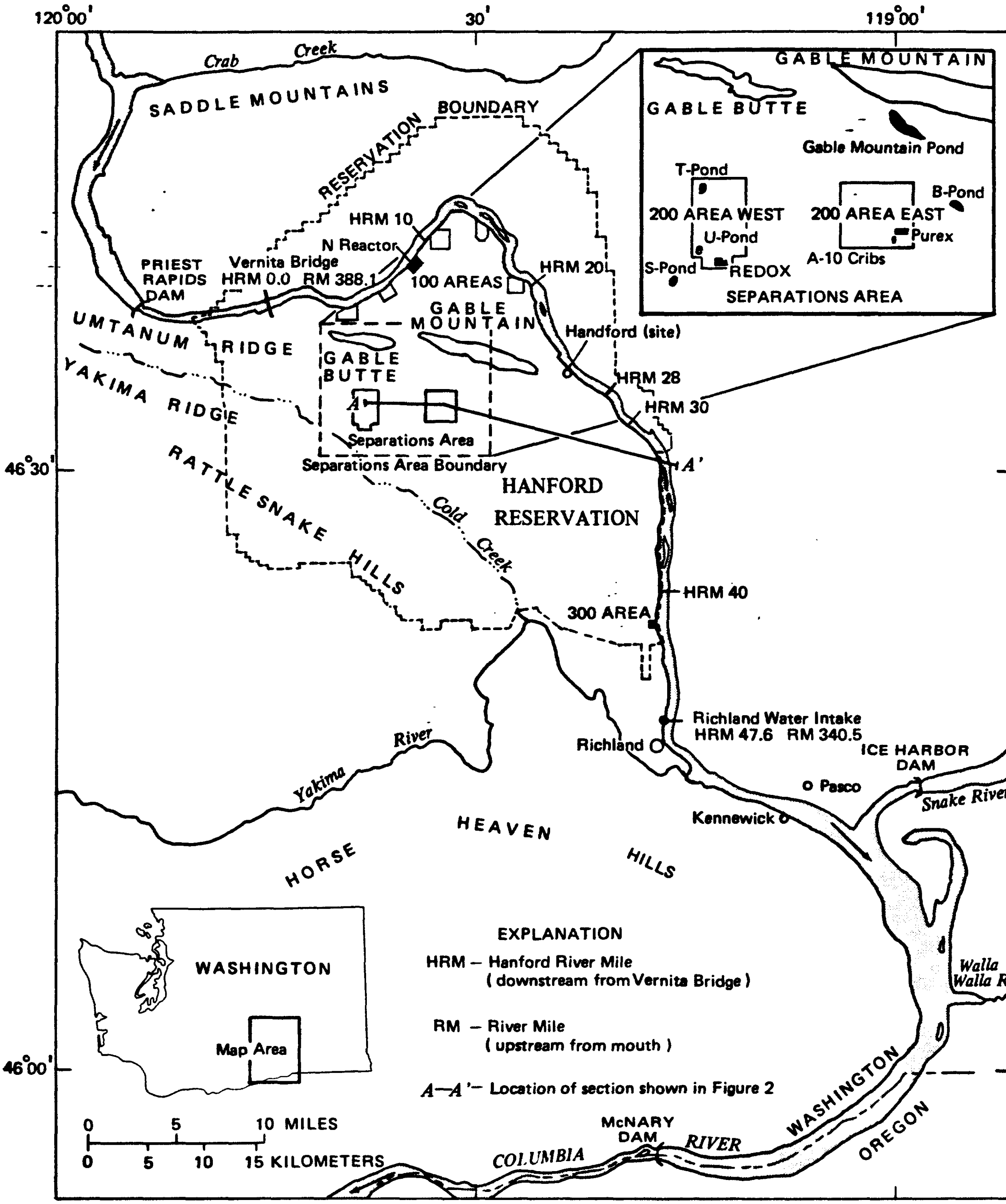


FIGURE 1.--Location and details of study area

- SEARCH claims to substantiate the existence of the hypothesized channel through a detailed study of streambank discharge to the Columbia River along an 852-foot reach of the river at about HRM 28.

- Using the streambank discharge estimated in their detailed study, SEARCH concludes that ground-water traveltimes from the 200-East Area to the Columbia River are on the order of 2.5 years, rather than the estimates of 30 to 50 years as estimated by PNL (Friedrichs and others, 1977) in a previous study.

- SEARCH further concludes that the short traveltimes and large ground-water discharge provided by the buried channel deposits are responsible for elevated tritium concentrations below HRM 28 in the Columbia River.

Largely because of disagreement as to the time required for radionuclides to be transported from disposal areas to the river, and because of the strong regional interest in possible effects of operations at the Reservation, the U.S. Geological Survey was asked to review and report on the SEARCH studies. In a letter of October 23, 1986, to the Director of the U.S. Geological Survey, U.S. Representative Les AuCoin of Oregon requested: "1. A written critique of SEARCH Technical Services' study of April 27, 1986; and, 2. Recommendations for work needed to enhance the credibility of the study, if necessary, and/or recommend the need for further study based on the results of the SEARCH study."

Purpose and Scope

The purpose of this report is to present the results of a review of SEARCH's methodology and interpretation of data, and to suggest beneficial future studies of the subjects in question. This review specifically evaluates (1) the approaches and techniques used by SEARCH to estimate the ground-water discharge into a short reach of the Columbia River near HRM 28; (2) the adequacy of the data SEARCH used to support the existence of a highly permeable ground-water channel connecting the 200-East Area to the short reach of the Columbia River; (3) the methodology used to calculate traveltime through the proposed channel; and (4) the method used by SEARCH to estimate the tritium discharged by ground water to the Columbia River.

The review was conducted using information supplied by SEARCH in its reports (Buske and Josephson, 1986a, 1986b, 1986c, 1986d), correspondence, and oral presentations in meetings; additional information was obtained from those DOE contractor reports that were readily available. No additional field measurements or other new data were collected by the Geological Survey.

GEOHYDROLOGIC SETTING

Geography and Geology

Most of the Hanford Reservation occupies extensive terrace lands along the last remaining free-flowing reach of the Columbia River in Washington State (fig. 1). The terrace plains increase gradually in altitude northward and westward, from about 340 feet at Richland to 700 to 800 feet in the northwestern part of the Reservation, then descend northward and northeastward to a general altitude of 450 feet in much of the northern part of the Reservation. The river level along the downstream third of the Reservation is controlled by the pool behind McNary Dam (normal pool altitude since 1953 is about 340 feet), and the discharge of the river is significantly controlled by upstream dams. The Reservation has a semiarid climate (about 6 inches annual precipitation) and sparse vegetation.

The bedrock of the area is basalt (fig. 2) that accumulated in a sequence of many flow layers to a thickness of at least several thousand feet. The basalt was warped and folded into a pattern of broad structural basins and prominent ridges that are generally tightly folded and commonly faulted. The Reservation lies mainly within one broad, saucer-like structural basin that is crossed by moderate-sized east-west-trending anticlinal ridges. The structure of the basalt was the major control on the extent of younger rock materials deposited in the Reservation area, and also is a major control on the entire ground-water system, especially the deeper parts.

The sedimentary deposits of the Hanford Reservation are composed primarily of two sedimentary units--the Ringold Formation and the overlying informally named Hanford Formation of Brown and Isaacson (1977) hereafter referred to simply as the Hanford Formation. These units are separated by an erosional unconformity. The Ringold Formation overlies the basaltic bedrock and is composed of fluvial and lacustrine beds of sand, silt, gravel, and clay, which are generally well sorted and semiconsolidated. The Hanford Formation is exposed at the surface as reworked aeolian sand dunes over much of the Reservation. In the western part of the Reservation, aeolian silt of the Pleistocene Palouse Formation is found between the Ringold and the Hanford Formations.

The Ringold Formation, which ranges in thickness up to 600 feet, may be subdivided into four units on the basis of texture, grain size and stratigraphic position (Brown, 1979). They are referred to as the basal, lower, middle and upper units of the Ringold Formation. The basal unit, consisting mostly of gravels, directly overlies the basalt over most of the Reservation. The lower unit, an extensive deposit of silt and clay, is present throughout most of the central part of the Reservation. The middle unit is an extensive conglomerate of well-rounded pebbles and gravel with a matrix of fine-to-medium sand. Sand beds and lenses are common in an otherwise uniform accumulation of gravel and sand. The upper unit consists predominantly of silt and fine sand. Within the Reservation, much of the upper unit has been removed by erosion, but significant remnant islands of this material remain.

These islands of fine-grained material can be very important to local patterns of ground-water flow. As part of PNL's ground-water monitoring and

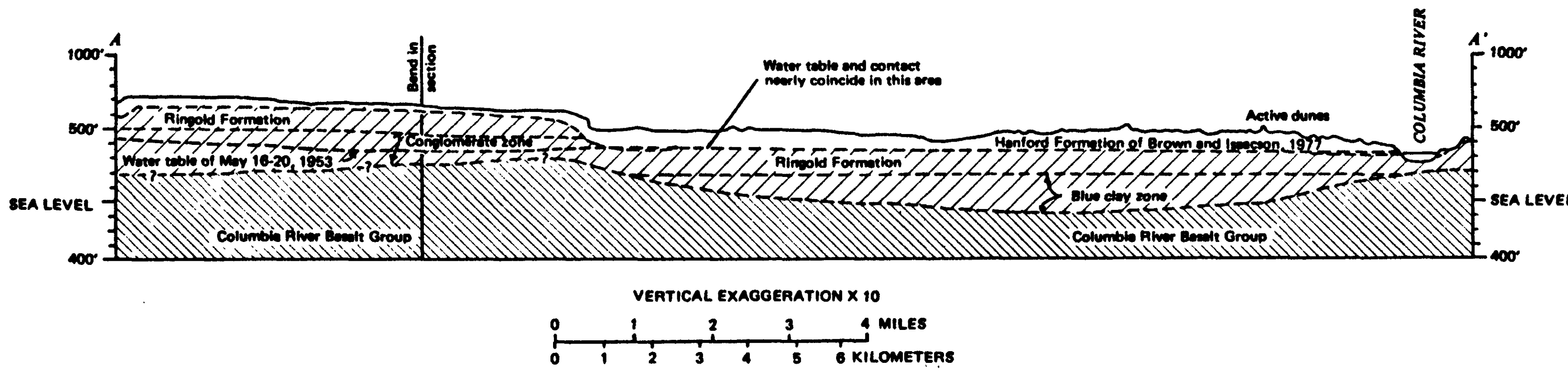


FIGURE 2.--Generalized geologic section at Hanford Reservation. (Modified from Newcomb, 1972, plate 1) See figure 1 for location.

well-drilling program, Eddy and others (1983) located a clay deposit, in four drill holes, that is believed to be an erosional remnant of the upper unit of the Ringold. The deposit is an elongated strip, at least 1 mile long, that parallels the west bank of the Columbia River south of SEARCH's study reach near HRM 28. The southern end of this strip has not been defined. Width of the clay deposit was not determined, nor was the continuity between drill holes; however, the clay deposit effectively reduced the hydraulic connection between the river and wells west of the deposit, as was demonstrated by significantly slower response time of water-level changes in the wells compared to changes in river stage.

Hydraulic properties of the Ringold Formation vary widely, depending on texture and grain size. Hydraulic conductivities of gravel-and-sand deposits range from 20 to 600 feet per day, while those of finer-grained deposits range from 0.1 to 10 feet per day (Graham, 1981). Newcomb and others (1972) estimated the average effective porosity of Ringold material at two locations beneath discharge ponds, both of which resulted in values of 11 percent. Biershenck's (1959) estimate of average effective porosity over a larger part of the Reservation, which included parts of the Hanford Formation, resulted in a value of 6.4 percent. In addition, Biershenck cited a similar estimate from U.S. Geological Survey personnel of 8.3 percent.

The Hanford Formation consists of beds of unconsolidated sand, gravel, boulders, and silt that were deposited from repeated inundations of the Pasco Basin by glacial floodwaters. This formation lies unconformably on the middle unit of the Ringold over most of the Reservation. Two textural subdivisions are commonly recognized within the Hanford Formation--the coarse-grained Pasco gravels and the fine-grained Touchet beds. The Pasco gravels predominate over the Reservation and immediately overlie the Ringold Formation, except in the western part, where the Palouse Formation is present. The Pasco gravels consist predominantly of gravel with some cobbles and boulders. Typically, the matrix of the unit is sand and, in places, contains silt. The lithologic composition of the unit is extremely heterogeneous and poorly mixed. Discontinuous lenses of all grain sizes are common. Total thickness of the Hanford Formation ranges up to 200 feet. Hydraulic conductivity for the Hanford Formation reportedly ranges from 500 to 20,300 feet per day (Graham 1981). The effective porosity of the Pasco gravels is unknown, but probably exceeds that of the Ringold Formation.

Hypothesized Channel

The narrow buried ground-water channel hypothesized by SEARCH is believed by them to be an erosional feature in the Ringold Formation that was backfilled with boulders and cobbles of the Pasco gravels with few or no smaller particles. The channel is hypothesized to be a continuous feature from the 200-East Area to the Columbia River near HRM 28. SEARCH hypothesized that the width of this channel is approximately equal to 852 feet, the length of Columbia River streambank along which an unusually large amount of ground-water discharge was observed.

Natural Ground-Water Flow System

Newcomb and others (1972) indicated that, prior to the introduction of liquid-waste-disposal practices on the Reservation, the water table was below the base of the Hanford Formation in all but a few parts of the terrace plain. Mapping of the extent of the saturated deposits of the Hanford Formation for the purposes of this study suggests that larger isolated but saturated areas of the Hanford Formation may have existed but were not recognized by Newcomb and his colleagues. The movement of water was from west to east, mainly through the Ringold Formation. The Columbia River served as the major discharge area for ground water (fig. 3). Maximum elevation of the water table was about 440 feet near the western boundary of the Reservation, and the minimum was just above the Columbia River, or about 340 feet.

Natural recharge to the ground-water system in the Reservation area occurs from (1) the infiltration of about 0.5 to 1 inch per year, or about 5 to 10 ft^3/s over the central part of the Reservation; (2) recharge by intermittent runoff from adjacent ridges; (3) ground-water inflow where the sediments extend off the Reservation and up Cold Creek and Dry Creek valleys (about 1 ft^3/s when combined with [2]; Newcomb and others, 1972); and (4) vertical flow from the underlying basalts (rate unknown). In addition, deposits near the river received seasonal recharge from the river during the high river stages (bank storage) and subsequently discharged this water to the river during periods of lower river stage.

Present Ground-Water Flow System

Wastewater discharges on the Hanford Reservation have altered the natural ground-water flow system. Wastewater discharge for the period 1943-1980 have been summarized by Zimmerman and others (1986; see table C1, Appendix C). The average annual rate of wastewater disposal in the 200-Areas over this time period was approximately 20 cubic feet per second. This rate is roughly 2 to 3 times the natural recharge rate to the central part of the Reservation. Since operation of the nuclear works began in 1943, large volumes of chemical-process and reactor-cooling waters have been discharged to ponds. In addition, smaller volumes of low- and intermediate-level radioactive liquid wastes have been discharged to the ground through condensation basins and subsurface disposal cribs. These disposal operations reportedly are confined to the 200-Areas in which are located the chemical- and fuel-processing operations, and the 100-Areas where nine plutonium reactors are located along the horn of the Columbia River (fig. 1).

The discharges from the 100-Areas have been much smaller than discharges from the 200-Areas. In the 100-Areas, only the N-Reactor (fig. 1) has been operational since 1971. Past or current operation of the facilities in the 100-Areas are believed not to have significant impact on the area where SEARCH conducted their investigations.

Major discharges, containing nitrate as well as radionuclides, have centered around the fuel-separation and reprocessing operations in the 200-East and 200-West Areas. In the 200-East Area, the B Plant has been operational from 1945 to 1952 and again from 1968 to at least 1980. The Plutonium Uranium Extraction Plant (known as PUREX) was operational from 1956

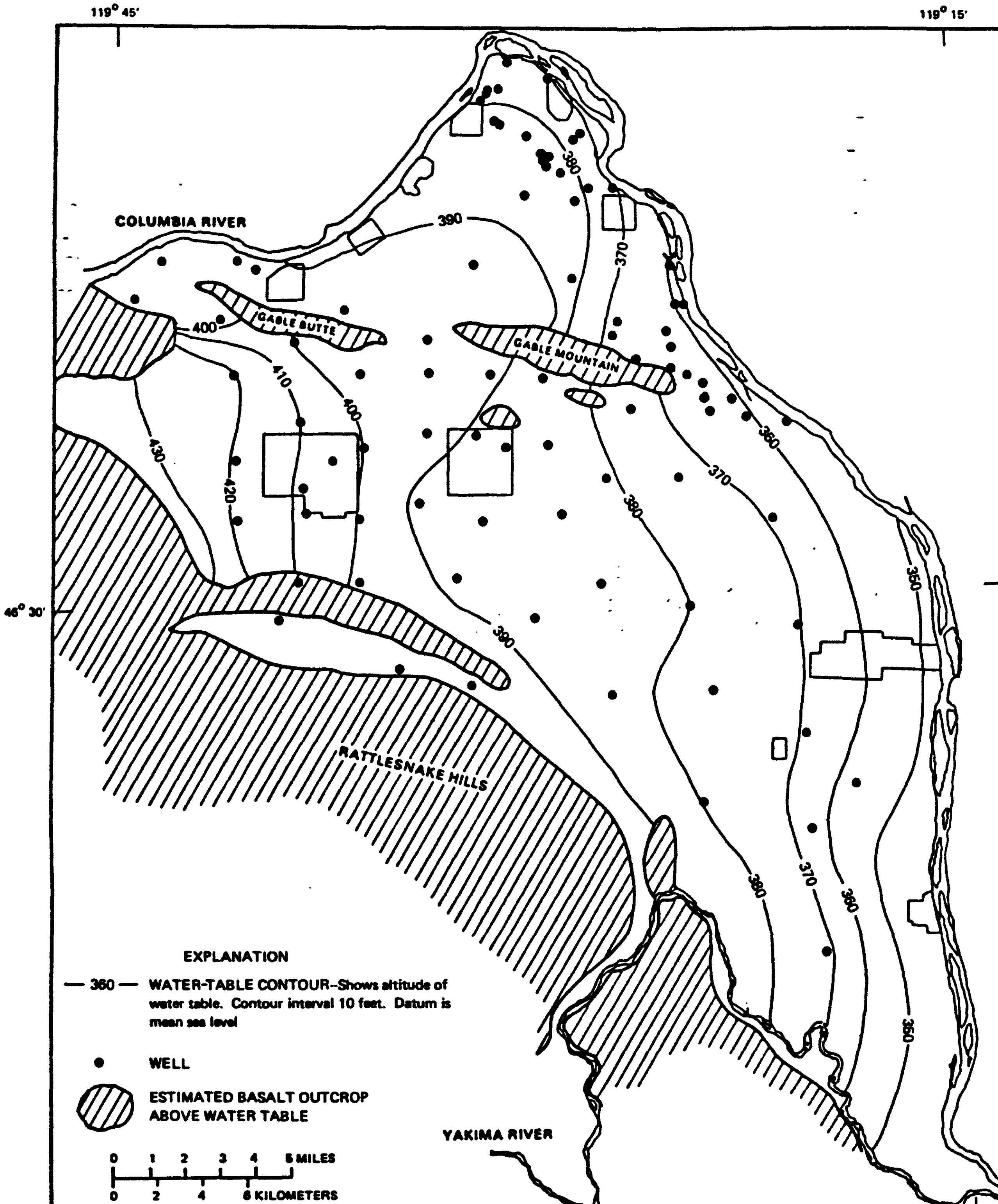


FIGURE 3.--Estimated water table altitude at the Hanford Reservation for 1944. (Modified from Energy Research and Development Administration, 1975, fig. 11, 3-14)

to 1972. The PUREX Plant was restarted in 1983 and has been operational since then. The startup and shutdown of operations at the PUREX Plant is reflected in the data for the PUREX crib in table C1 (see Appendix C). Chemical-process-cooling water from the 200-East Area is discharged to either B Pond or Gable Mountain Pond (fig. 1) and radioactive liquid waste is discharged to the cribs and tank farms. Fuel-separation activities are carried out at the Oxidation-Reduction (REDOX) plants and other sites within the 200-West Area where wastewater goes to ponds and associated cribs and tank farms.

The introduction of liquid-waste-disposal practices and the percolation of a part of these wastewaters downward to the water table induced substantial water-level rises under the main disposal areas (figs. 4 and 5). The rise of ground-water levels under the disposal ponds has resulted in the creation of ground-water mounds under the 200-Areas. Water-levels eventually rose about 90 feet under U Pond in the 200-West Area and about 30 feet under B Pond in the 200-East Area. Although the amount of wastewater discharged in the 200-West Area has been less than in the 200-East Area (see table C1, Appendix C), the water-level rises were greater in the 200-West Area. The reason is that the water table in the 200-West Area did not rise into the more highly permeable Hanford Formation, but did in the 200-East Area (Newcomb and others, 1972). Therefore, in the vicinity of B Pond, the added water has greater opportunity to drain laterally. The induced water-level rises extend over most of the study area. A comparison, made for this review, of the position of the water table and the base of the Hanford Formation, indicates that the water table is now largely above the base of this formation, resulting in broad interconnected areas of saturated deposits of the Hanford Formation between the 200-East Area and the Columbia River. However, in some places the continuity of the area of saturated highly permeable material is interrupted by less permeable material believed to be erosional remnants of the upper unit of the Ringold Formation. This is known to occur in a strip along the Columbia River south of HRM 28. (See the subsection "Geography and Geology.") One expected result of this geologic configuration is that ground-water discharge to the river should be greater along the river reaches where the broad expanses of the saturated deposits of the Hanford Formation are in direct hydraulic connection with the river.

Saturation of these highly permeable sediments probably has resulted in a large part of the wastewaters from the 200-East Area moving through the Hanford Formation to the river rather than through the less permeable Ringold Formation. The time of travel from the 200-East Area to the Columbia River undoubtedly is considerably less through the Hanford than through the Ringold Formation. The present-day movement of water is downward and lateral in the vicinity of the induced ground-water mounds and upward and lateral in the vicinity of the Columbia River. A comparison of water-table maps for 1981 (Eddy and others, 1982) and 1985 (see fig. 5) do not suggest any major changes in the ground-water-flow system of the sedimentary deposits for this period. However, changes can be expected to result from any changes in natural or wastewater recharge.

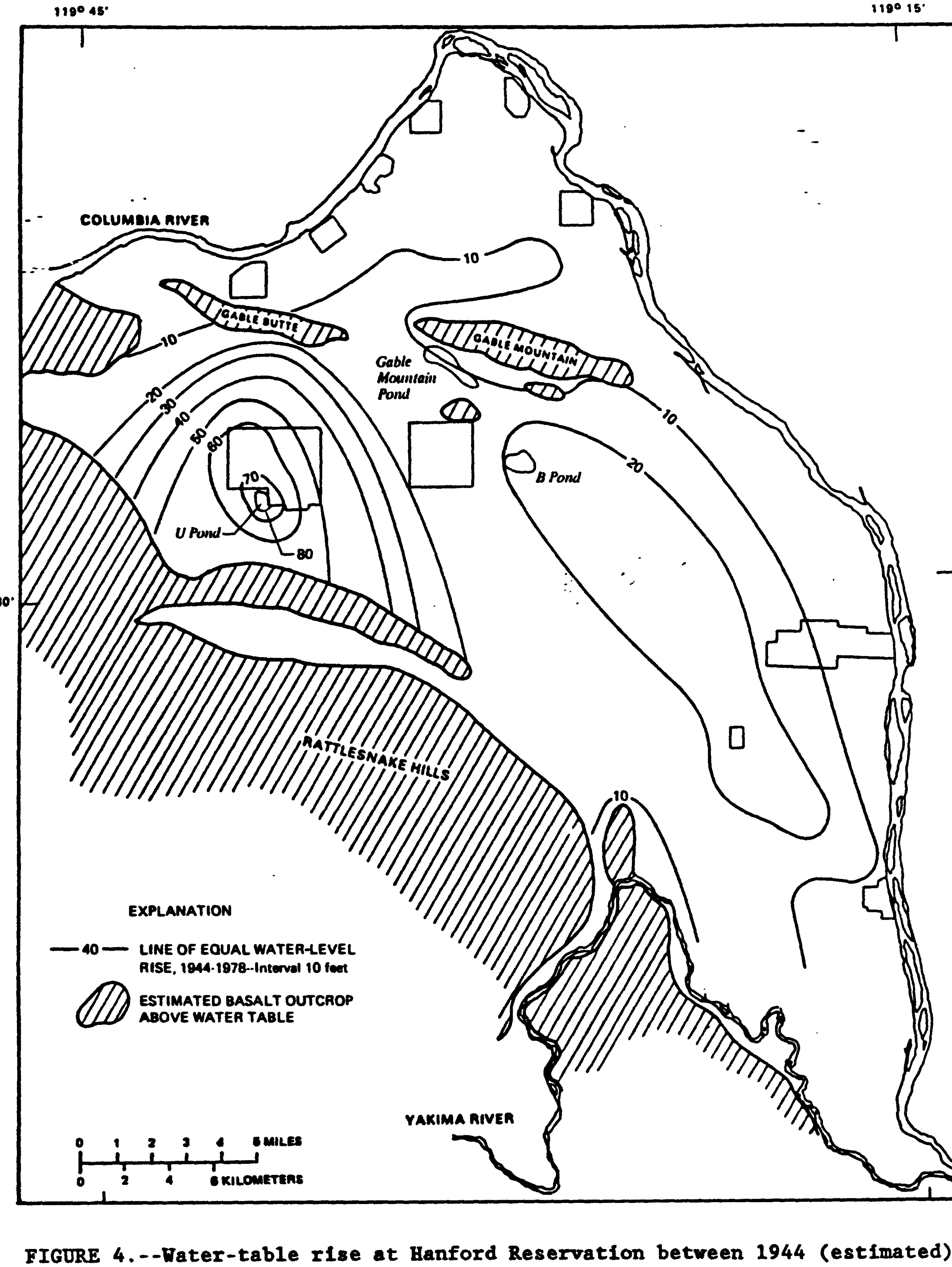


FIGURE 4.--Water-table rise at Hanford Reservation between 1944 (estimated) and 1978 (measured in wells). (Modified from Rockwell Hanford Operations, 1982)

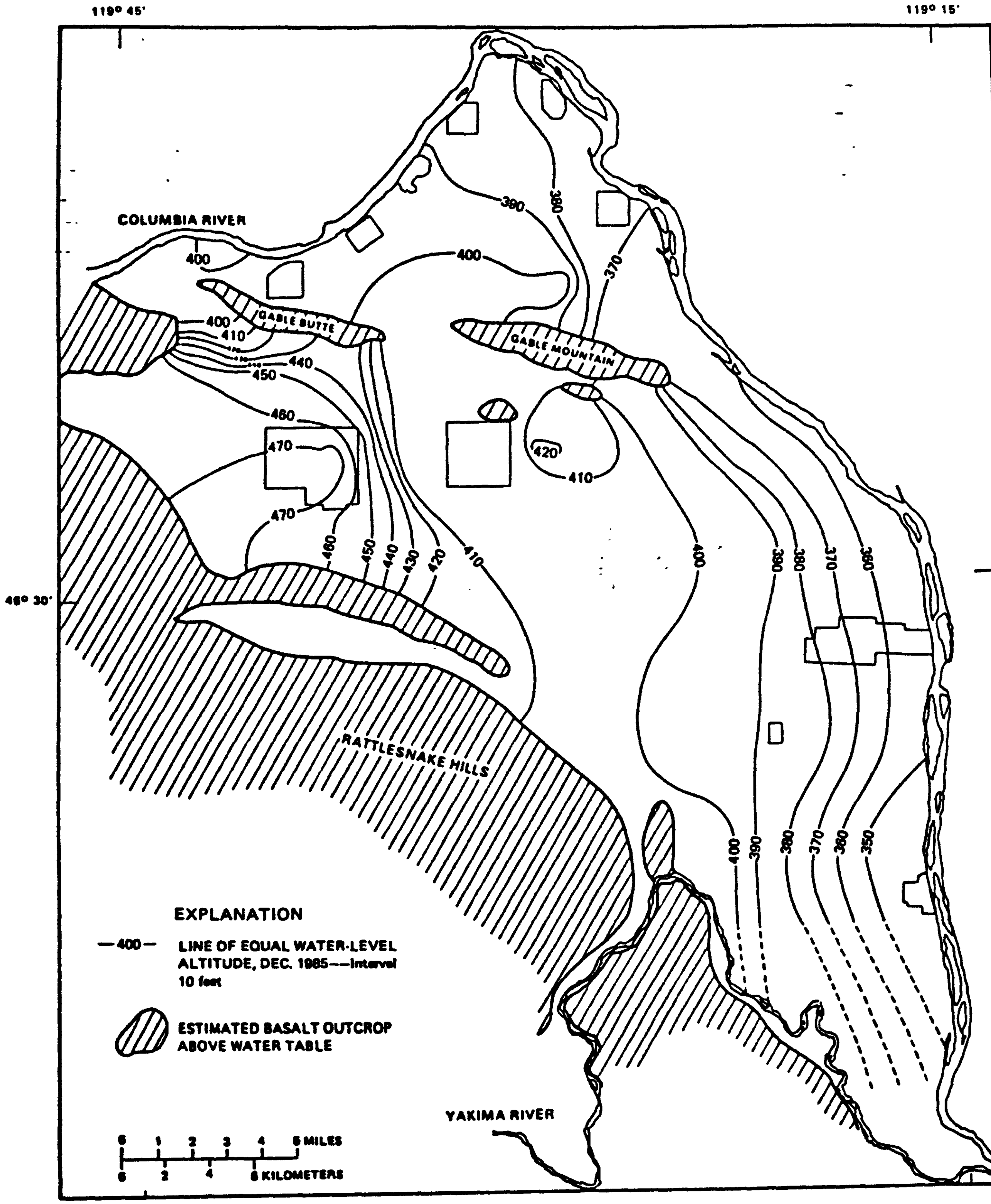


FIGURE 5.--Water-table altitude as measured in wells at Hanford Reservation, December 1985. (Modified from Price, 1986, fig. 3)

EVALUATION OF CHANNEL HYPOTHESIS

Summary of Findings

Geologic and hydrologic data were reviewed in an effort to find information that would either support or refute the existence of the buried ground-water channel hypothesized by SEARCH. None of the examined data directly refutes the concept of a relatively narrow channel of highly permeable material that connects the 200-East Area to the Columbia River at the location proposed by SEARCH. However, available data do suggest an alternative hypothesis that is believed to be more nearly consistent with known geohydrologic information and principles. This alternative hypothesis is that there is a broad expanse of saturated highly permeable material between the 200-East Area and the Columbia River that is in direct hydraulic connection with the Columbia River only along interspersed reaches.

Geologic and hydrologic information examined for this review, in addition to SEARCH's data, include: (1) reports on the geology and hydrology of the Hanford Reservation that discuss the existence of buried channels eroded into the Ringold Formation and the extent of saturated deposits of the Hanford Formation of Brown and Issacson (1977); (2) configuration of the water table; (3) temporal and area distribution of tritium; (4) the so-called "tritium notch"; and (5) a plot of time versus tritium concentration for well 40-1.

Saturated Deposits of the Hanford Formation

Several reports consider the question of highly permeable channels in the sedimentary deposits on the Hanford Reservation. Bierschenk (1957) identified areas of highly permeable sediments trending eastward along the flanks of Gable Mountain, and southeastward from the 200-East Area (fig. 1) toward the Columbia River. Brown (1960) described the Ringold Formation as having an extensively channeled, highly irregular erosional surface that was formed by the Columbia River prior to the deposition of the Pasco gravels of the Hanford Formation. He also observed that many of those channels were beneath the water table, allowing potentially rapid rates of ground-water flow southeastward toward the Columbia River. Brown and others (1962) concluded that ground-water contamination followed old Columbia River channels incised into the eroded surface of the low-permeability Ringold Formation; they estimated the permeabilities of the channel deposits were about 100 times that of the Ringold Formation. Fecht and others (1985) summarized knowledge of the paleo-drainage of the Columbia River and noted that the channel of the river had moved from its former position between Gable Mountain and Gable Butte to its present position at the eastern end of Gable Mountain. In aggregate, these reports provide evidence that channels of high-permeability sediments do exist at some places in the Reservation area, and that their general orientation is towards the southeast.

It is important to note that the high-permeability channels referred to by Bierschenk (1957), Brown (1960), and Brown and others (1962) are simply locations where deposits of the Hanford Formation occur in incised channels in the Ringold Formation and that at these locations the water table occurred above the base of the Hanford Formation. As was noted previously (see subsection, "Present Ground-Water Flow System"), present work indicates that the water table now is above the base of the Hanford Formation over a large part of the Reservation between the 200-East Area and the Columbia River. As a result, the importance of the incised channels as preferential paths of ground-water movement is lessened. Ground water would still travel along these subsurface channels, but not necessarily at rates faster than in the broad expanse of saturated Hanford deposits. This presumably would be true for the channel hypothesized by SEARCH.

An alternative to the channel hypothesis is that a significant part of the ground-water flow from the 200-East Area to the Columbia River occurs in a broad expanse of highly permeable deposits of Hanford Formation, and that these deposits are connected to the river only along interspersed reaches for reasons described in the subsections "Geography and Geology" and "Present Ground-Water Flow System." This alternate hypothesis can account for the observed localized high rate of ground-water discharge to the Columbia River near HRM 28, but would result in longer average ground-water traveltimes between the 200-East Area and the river than would result from the channel hypothesis.

Configuration of the Water Table

A narrow, continuous, highly-conductive channel such as the one postulated by SEARCH would tend to "short-circuit" the ground-water flow system and cause a significant convergence of flow paths toward it. If the channel geometry and hydraulic conductivity were nearly uniform, the channel would receive ground-water flow along its entire length, with the consequence of a steepening hydraulic gradient toward its discharge point. Both these effects should be observable in water-table contours.

The December 1985 water-table map (fig. 5) of the Hanford Reservation shows a generally east-to-northeast sloping water table with a hydraulic gradient of about 10 feet per mile. Although there is no indication on this map of ground-water flow converging towards a channel, it is possible that this convergence would not be apparent because the existing distribution and density of observation wells are inadequate for this purpose. Buske and Josephson (1986d) presented a water-level-contour map on which PNL's water-level contours were modified to show a possible effect of the hypothesized channel. The modified contours are intended to demonstrate that an "upstream" bend of the contours, which would occur if the channel were present, is not inconsistent with the water-level data. Although the SEARCH premise cannot be disproved, it should be emphasized that the contour modifications are speculative and that many other contour configurations could be drawn within the water-level-control points (observation wells). The PNL interpretation of the available water-level data (Price, 1986) is believed to be more consistent with the areal distribution of control points, and with hydrologic principles.

Any interpretation of the water-level data in the Hanford area will depend to a significant degree on an appreciation of the three-dimensional nature of the flow system and the resultant distribution of hydraulic heads. Some of the water entering the system flows downward from Hanford Formation to the Ringold Formation in recharge areas, and upwards from the Ringold in discharge areas. This vertical component of flow results in vertical differences in hydraulic head. Consequently, the water level in a well depends on the position and vertical extent of openings in the well. Some of the data used by PNL in preparing the water-level contours were from wells that were open to different or multiple geohydrologic units. Therefore, although these data may be useful for drawing generalized water-level contours for the regional flow system, they may be inadequate for defining small-scale local flow patterns such as individual preferential flow paths.

Temporal and Spatial Distribution of Tritium

Information on the distribution of tritium in the Hanford Reservation area offers another means to evaluate the channel hypothesis. Tritium (^3H) is an isotope of hydrogen with a half-life of 12 years that occurs as a substitute for normal hydrogen (^1H) in water molecules. Tritiated water molecules are almost chemically indistinguishable from normal water molecules and, therefore, are transported at a rate equal to that of normal water. Because they move with the water and can be detected in relatively small concentrations, they are ideal ground-water tracers (Fontes, 1980). Tritium is known to be present in the ground water discharging to the river from the Reservation.

The locations of major sources of tritium entering the ground-water system are generally acknowledged to be the 200-East and -West Areas, particularly the PUREX cribs and B Pond. Although these may not be the only sources, and while complete information on total tritium loading to the ground-water system is not readily available, the lack of such information does not preclude a qualitative appraisal of the dispersion of tritium in the flow system. An extensive network of observation wells is sampled regularly (Price, 1986), and water samples are analyzed for tritium and a variety of other constituents. On the basis of these data, maps of the distribution and concentration of tritium have been prepared by PNL on an annual basis. Figures 6 and 7, respectively, show the distribution of tritium concentration in 1975 and 1985.

Broadly viewed, these maps show an extensive plume of tritium extending from the 200-East Area towards the Columbia River in two lobes, one in a southeasterly direction, and the other in an easterly direction. These orientations appear to be wholly consistent with hydraulic gradients shown on the 1985 water-level-contour maps (fig. 5), and imply the dominance of the regional flow field on the dispersion of the plume. The patterns of tritium concentration do not reveal a preferential pathway that could be ascribed to a continuous high permeability channel. Such a pathway would be expected to show a narrow, elongate plume of high tritium concentrations extending from the zone of elevated tritium concentrations towards the river. On this basis, one can conclude that the available evidence on the areal distribution of tritium does not support the channel hypothesis.

That conclusion, however, does not necessarily contradict the channel hypothesis. As previously indicated, the distribution of the existing network of observation wells, from which the tritium samples were collected, is not dense enough to either confirm or refute the hypothesis.

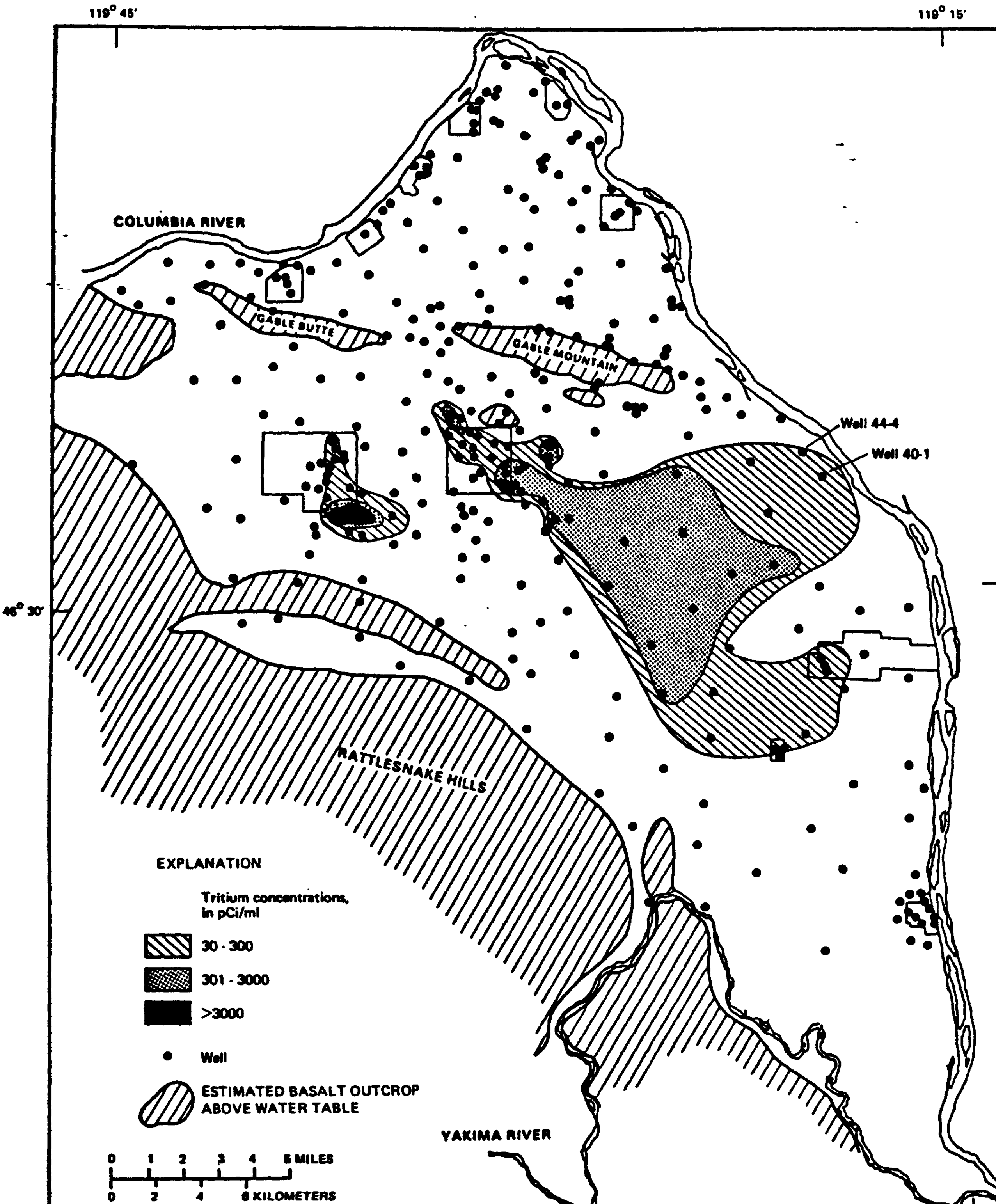


FIGURE 6.--Distribution of tritium concentrations as measured in water from wells at Hanford Reservation, December 1975. (Modified from Meyers and others, 1976, plate 3)

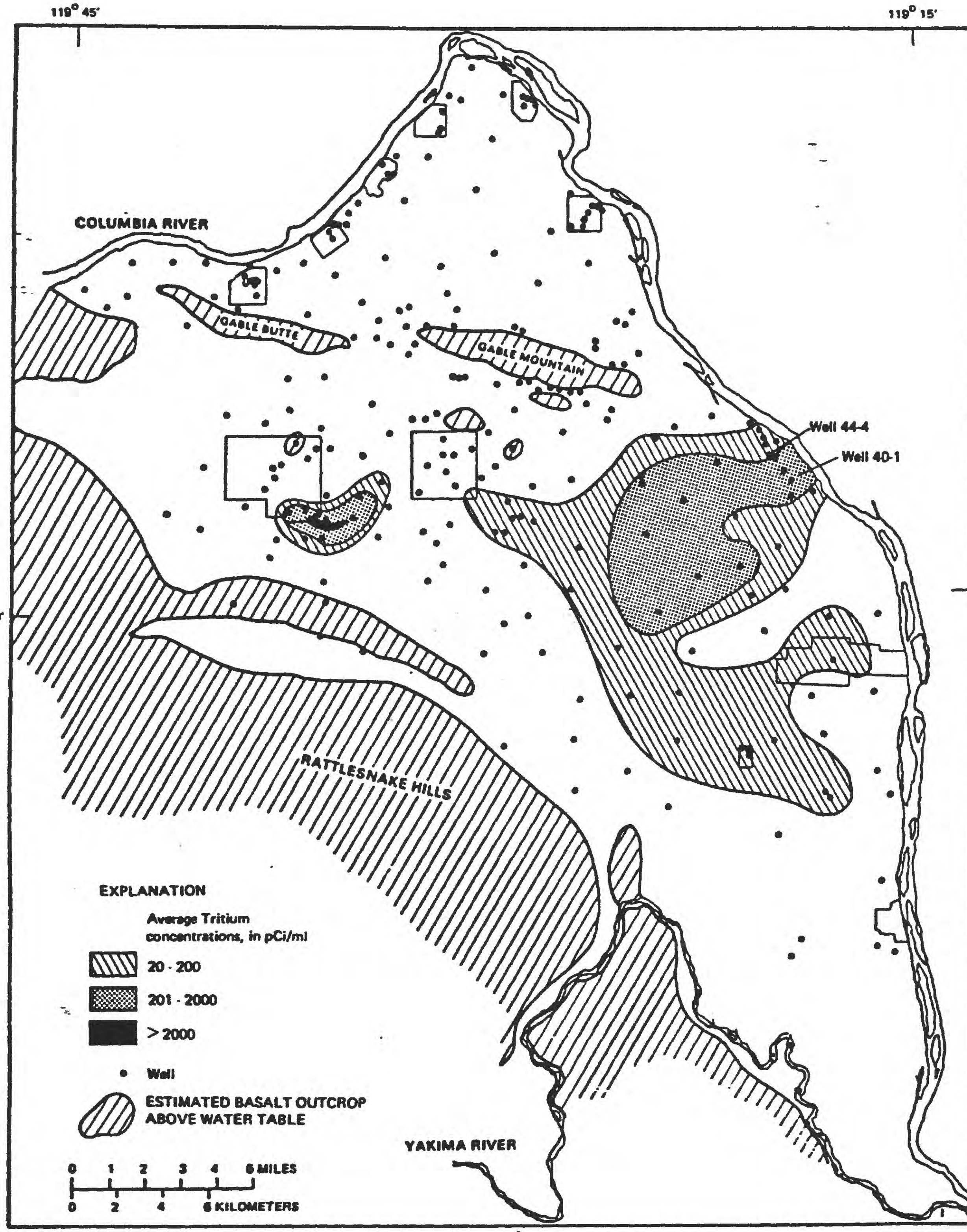


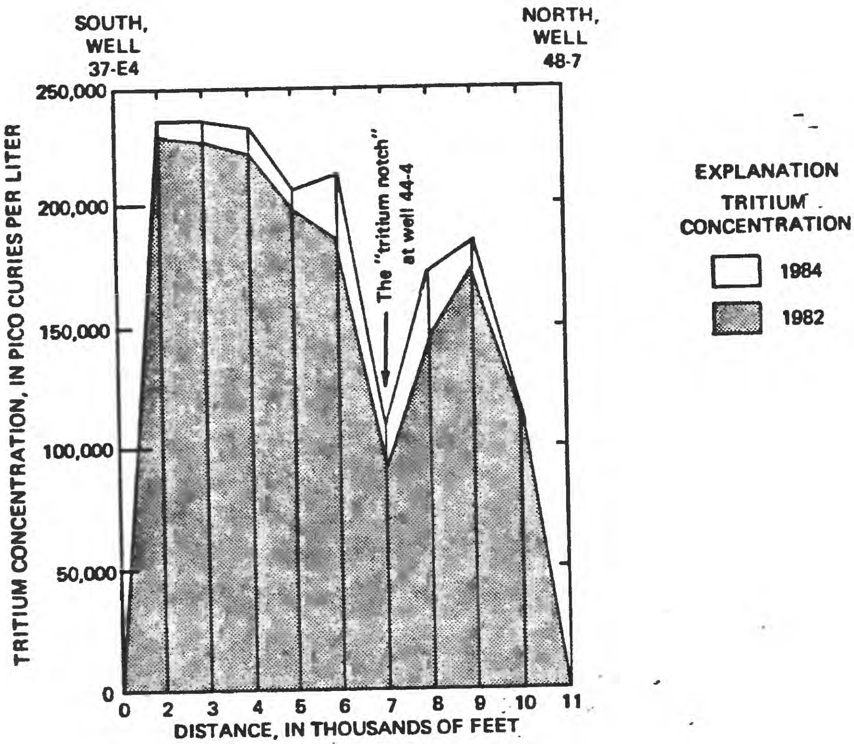
FIGURE 7.--Tritium concentrations as measured in water from wells at Hanford Reservation, average for calendar year 1985. (Modified from Price, 1986, fig. 18)

The Tritium Notch

Buske and Josephson (1986c) comment on an array of 11 wells along a 3-mile section that crosses the tritium plume within about one-half mile of the river. The location of these wells and a graph of the tritium concentrations are shown in figure 8. Geohydrologic data regarding these wells are contained in table 1. The "notch" in this profile is at well 44-4 (fig. 8), which yielded samples with tritium concentrations substantially less than are shown for adjacent wells. SEARCH postulates that the lower concentrations are the result of less-contaminated ground water flushing the channel of tritiated water after the PUREX Plant became inactive (1972-83). That is, tritium-poor water entering the system at the 200-East Area moved rapidly down the hypothesized highly conductive channel, displacing or diluting the tritium-rich water emplaced prior to 1972. According to that hypothesis, comparatively high concentrations of tritium in the adjacent sediments of lower permeability would be retained longer, thus producing the "notch" in the distribution of tritium concentrations along the line of wells.

The existence of the tritium "notch," however, does not necessarily support the channel hypothesis. Although the tritium analyses for 1982 and 1984 demonstrate the persistence of the "notch," there is a more plausible, but equally unproved, explanation for its existence. An examination of the geologic logs for the wells, summarized in table 1, shows that some of the wells penetrate both the Hanford and Ringold Formations. Comparison of the geohydrologic units and tritium concentrations in table 1 suggests that water from the less permeable Ringold Formation contains lower tritium concentrations than does water from the Hanford Formation. Therefore, water samples collected from wells that tap both units may reflect a dominant component of Ringold water. This is sustantiated by figure 9, which is a plot of tritium concentration versus percent of open interval in the Hanford Formation and the upper unit of the Ringold Formation. The graph indicates that, for most wells, the greater the percent of open interval in the Ringold Formation, the lower the tritium concentration. Given the proximity of these wells to the Columbia River, which is the regional ground-water drain, it is probable that hydraulic gradients in the Ringold are generally upward, towards the river. In this situation, a well tapping both the Ringold and Hanford Formations would be likely to convey water from the Ringold upward through the well into the more permeable Hanford Formation for eventual discharge to the river. Under some conditions of sampling from these wells, the resultant samples might consist mostly of water from the Ringold Formation.

Resolution of this issue would require an extensive drilling program to document local stratigraphic and hydraulic conditions and their control on ground-water-flow paths.



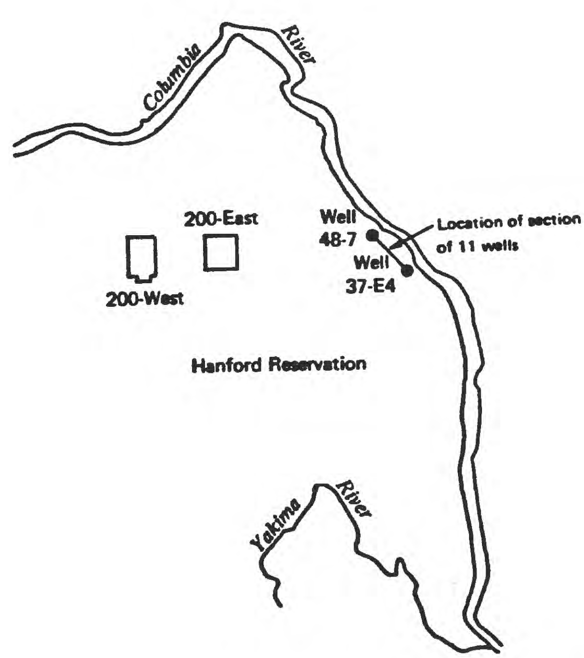


FIGURE 8.--Location of a line of 11 wells across the hypothesized channel, and graph showing tritium concentrations in samples from these wells. (Modified from Cline and others, 1985, fig. 7)

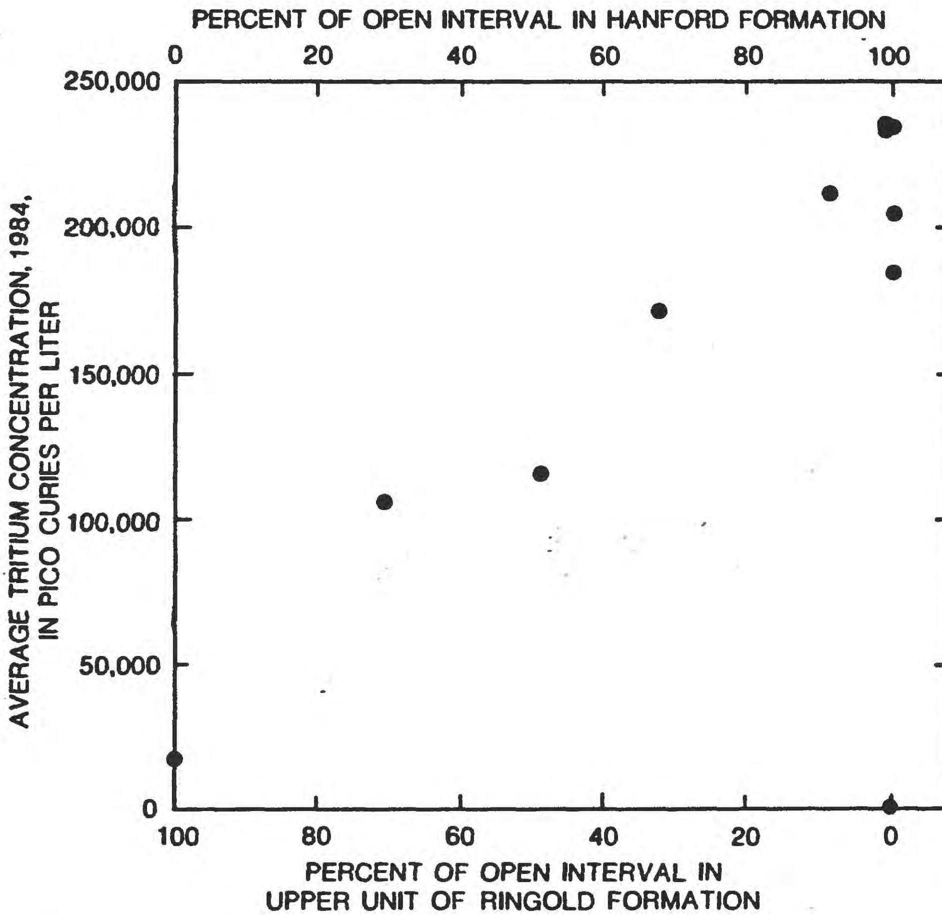


FIGURE 9.--Average Tritium concentration (1984) versus percentage of well open to Hanford Formation of Brown and Isaacson (1977) and the upper unit of Ringold Formation (Data from Cline and others, 1985).

TABLE 1.--Data for wells along line showing tritium "notch"

[Well numbers in brackets refer to former Hanford designation]

Well number	Land-surface datum[1,2] (feet)	Water-level altitude[3] (feet)	Hanford Formation, altitude of base[4] (feet)	Interval open below water table[5] (feet)	Geo-hydro-logic units tapped[5]	1984-average tritium concen-tration,[6] (pico curies per liter)
699-37-E4 [699-39-E3]	387	356	[7]337	51-67	Upper Ringold?	16,000
699-39-0 [699-39-1]	450	361	[8]286	0-6	Hanford?	237,000
699-40-1	438	362	328	0-24	Hanford	237,000
699-41-1	433	364	<345	0-17	Hanford	234,000
699-42-2	434	362	<339	2-18	Hanford	206,000
699-43-3	420	361	334	6-29	Hanford (21 ft)+ Upper Ringold (2 ft)	213,000
699-44-4 [699-45-4]	391	359	351	2-23	Hanford (6 ft)+ Upper Ringold (15 ft)	107,000
699-45-2 [699-44-4]	380	358	[9]346	4-16	Hanford? (8ft)+ Upper Ringold? (4ft)	172,000
699-46-4 [699-46-5]	382	357	<334	0-21	Hanford	185,000
699-47-5 [699-47-6]	382	357	347	0-19	Hanford (10 ft)+ Upper Ringold (9 ft)	115,000
699-48-7 [Han-6]	385	357	335	0-4	Hanford	-210

[1] Data from McGhan, V.L., and others, 1985
[2] Data from Fecht, K.R., and J.T. Lillie, 1982
[3] U.S. Geological Survey interpretation of Price, K.R., 1985, figure 3
[4] U.S. Geological Survey interpretation of well log from Fecht and Lillie, 1982
[5] U.S. Geological Survey interpretation of well construction details (McGhan, V.L., and others, 1985) and water-table map (Price, K.R., 1985)
[6] Data from Price, K.R. (1986) and well log by Fecht, K.R., and J.T. Lillie
[7] Based on log of well 699-36-E3
[8] Based on log of well 699-39-1
[9] Based on log of well 699-44-2

Prefix 699 of the Hanford well numbers is presented here for completeness, but omitted on maps and in text.

Tritium at Well 40-1

SEARCH also uses the history of tritium concentration in samples from well 40-1 (location in fig. 7) as an argument in support of the channel concept. Buske and Josephson (1986c) contended that the tritium concentration of 40,000 pc/L observed in 1963 marks the appearance of the large amounts of tritiated water released by PUREX starting in 1957.

Over the period of record starting in 1962, tritium concentrations at that well apparently have ranged from less than 1,000 pc/L, to about 250,000 pc/L, as shown in figure 10. From 1965 through 1974, tritium concentrations varied widely (about 400 to 60,000 pc/L). Starting in 1975, however, the observed tritium concentrations neatly define a gradual increase from about 60,000 pc/L to about 250,000 pc/L, in 1982. From 1982 to 1985, most concentrations were nearly the same, approximately 250,000 pc/L.

It seems clear that a rigorous analysis of these data from this single well is not possible, and that speculation as to cause-and-effect relations that link the release of tritium at PUREX with arrival times in observation wells must be evaluated in the context of flow dynamics of the entire ground-water system. Some of the variation of the tritium data from 1962 to 1965 perhaps can be attributed to analytical error or contaminated samples--however, there is no way to check. Additional variation perhaps can be attributed to the same mechanisms that produced the aforementioned tritium "notch;" that is, water samples derived from different depths in the geohydrologic system. Eddy and others (1978) remark "A concentration history of well 40-1 shows a marked increase in tritium concentration following remedial work, which included the removal of a set of piezometers and the shortening of the water column. Upward vertical flow of uncontaminated ground water may have diluted the concentration of contaminants, which may have caused the low readings obtained prior to rehabilitation."

Thus, the reduced scatter in tritium data after 1974 probably is attributable to an improved observation well, thereafter open only to the Hanford Formation. This strongly suggests that tritium concentrations occurred in the shallow part of the Ringold prior to 1975, when that geohydrologic unit presumably was supplying part of the water sampled at well 40-1.

Suggestions for Additional Study

Direct confirmation of the existence of the proposed channel and its function as a conveyor of tritiated water on the basis of direct physical evidence (geology, water levels, water chemistry) would require an extensive array of test wells that penetrate the channel along its postulated 10 to 17 miles length. Given the narrow width of the hypothesized channel and the presumed tortuosity of its path, possibly hundreds of test wells might be required to ultimately confirm or reject the channel hypothesis. Such an approach is not recommended.

Broad interconnected areas of saturated Hanford deposits are believed to exist between the 200-Areas and the Columbia River. However, in some places where erosional remnants of the Ringold Formation protrude above the water table, deposits of Hanford Formation are unsaturated. Additonal work is

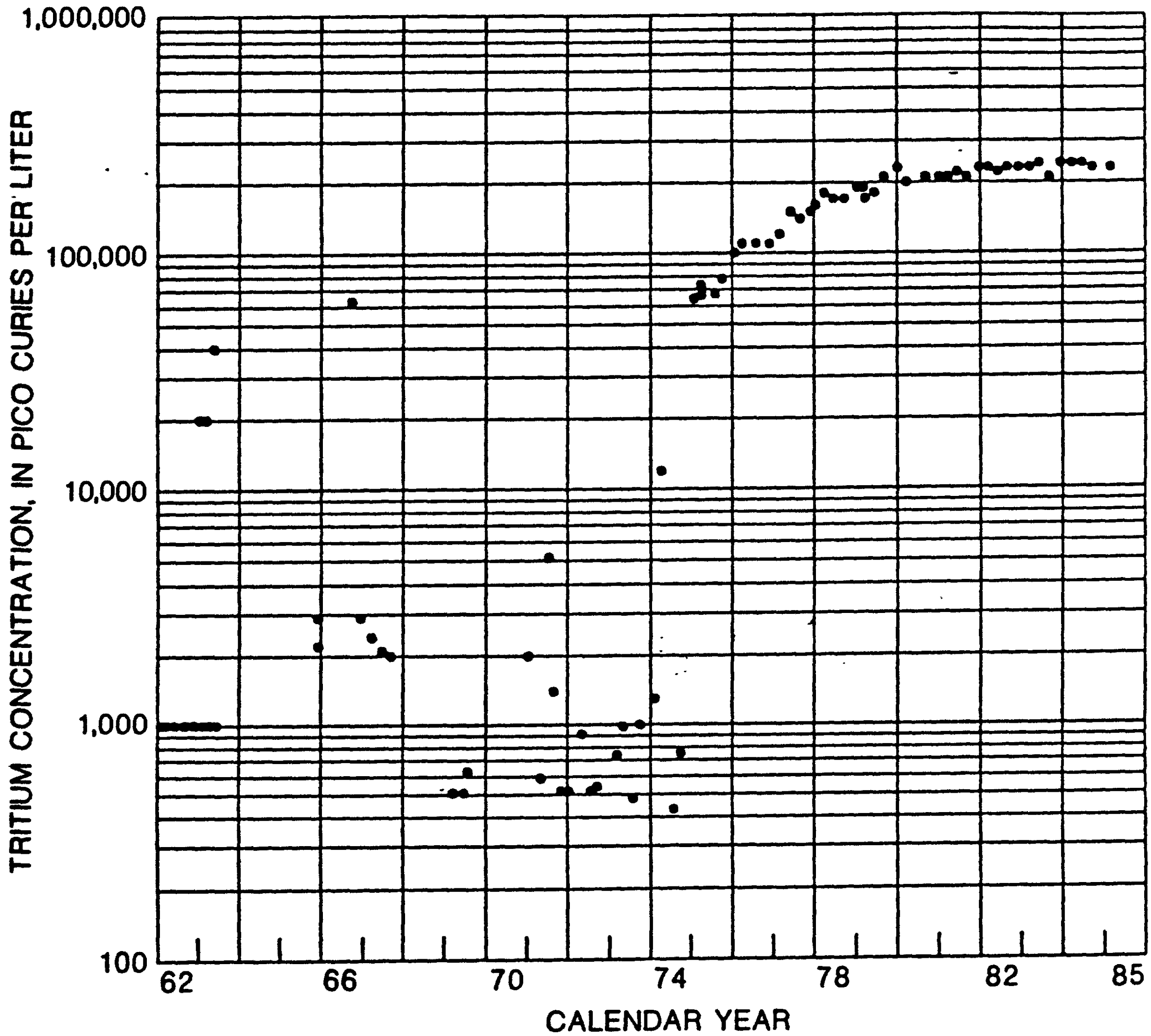


FIGURE 10.--Tritium concentrations in samples from well 40-1, 1962-1985. (Modified from Prater and others, 1984, fig. 10)

suggested that would allow the extent and thickness of the saturated deposits of the Hanford Formation to be mapped, and this information could be incorporated into a numerical model for simulating three-dimensional ground-water flow in the sedimentary deposits of the Reservation. Necessary information for this effort would require intensive review of existing data, and construction and sampling of additional test and observation wells, in order to obtain more information on lithology, water levels, and water chemistry for specific geohydrologic units. However, the number of wells required would be far less than those needed to confirm or reject SEARCH's channel hypothesis. The total effort would be wholly consistent with DOE's stated objectives for their ground-water surveillance program.

VALIDITY OF GROUND-WATER-DISCHARGE ESTIMATE

Summary of Findings

Buske and Josephson (1986a) determined that the discharge of nitrate-contaminated water to the Columbia River from 852 feet of Hanford streambank was 6.3 cubic feet per second in April 1986. They concluded that the discharge represented the mean annual ground-water discharge.

SEARCH used a nitrate-mass-balance method (described subsequently) which was appropriate for computation of the streambank discharge. Review of SEARCH's analysis confirms that a substantial discharge issued from the streambank, but the computed value may have appreciable error. Mathematical analyses indicate that the SEARCH result contains components of random error with a standard deviation of 27 percent, some systematic errors of up to ±30 percent, and additional systematic errors that could not be evaluated. SEARCH's conclusion that the discharge was ground water is reasonable, but an alternative line of reasoning suggests that the discharge contained a bank-storage component of indeterminate amount. Data are inadequate to support the selection of one conclusion over the other.

Analysis of Procedures and Results

Measurement and Computation Procedures

Buske and Josephson (1986a) described the methods and instruments they employed to measure the local discharge of nitrate-contamined water issuing from the streambank (riverbank and nearshore bed) along an 852-foot length of the Hanford Reservation shoreline of the Columbia River. This short reach of shoreline, located approximately at HRM 28 (fig. 1), is one of several sites along the Hanford shore where localized discharge issues from springs and where local concentrations of tritium and nitrate were noted by PNL to be high (McCormack and Carlile, 1984). Of all the sites identified in the 1984 PNL survey, the reach selected by SEARCH had the greatest concentrations of tritium and nitrate in the water discharging from the springs. This site is near the terminus of the central part of a tritium-nitrate-contaminated ground-water plume originating at the 200-Areas (figs. 6 and 7).

During April 19-21, 1986, SEARCH conducted an experiment in which they determined, at five different times, the streambank discharge into the 852-foot reach of the river. Streambank discharge was determined by mass-balance calculation for nitrate using observed nitrate concentrations in springs and observed velocities, depths, and nitrate concentrations along partial transects (cross sections) in the river.

Between 5:00 p.m. on April 18 and about 8:00 a.m. on April 19, river stage decreased about 2 1/2 feet. After that time, the stage remained relatively steady until about 6:00 p.m. April 21 (Buske and Josephson, 1986b). At five different times they collected water samples for nitrate-concentration at fixed stations along two transects that extended part way into the river, perpendicular to the Hanford shore. The transect at the upstream end of the 852-foot reach extended 50-feet from shore and had four measurement stations. The other transect, at the downstream end of the reach, extended 100-feet into the river and had six measurement stations. They also measured water velocities twice and water depths at least once at each station.

Most of the samples of river water collected to determine nitrate concentration were taken from near the water surface, although a few were taken at measured depths beneath the surface. Water velocities were usually measured 1 foot beneath the water surface, but at some locations in deeper water the velocities were measured at two or three depths (1, 2, 3, or 4 feet below the water surface).

Nitrate concentrations were measured in six springs, one of which was a submerged spring. The springs were located 20 feet, 109 feet (submerged), 260 feet, 426 feet, 792 feet, and 912 feet upstream of the downstream river transect. Nitrate concentrations in all the springs increased progressively during the experiment. Data for spring S-1, the most downstream spring, are shown in figure 11. Water discharge was not directly measured at any of the springs, but Buske and Josephson (1986a) note that the flow of shoreline springs decreased markedly after noon on April 20, and that no discharge was observable from submerged springs between the 0.3-foot and 5.0-foot depths toward the end of the experiment.

SEARCH used the principle of conservation of mass to calculate streambank discharges. In this experiment, the conserved mass is the nitrate discharging from the streambank. Fundamental assumptions for application of this principle are that (1) none of the nitrate transported in flowing water is lost by chemical change or sorption, and (2) if the mass of nitrate stored within the reach does not change with time, the mass of nitrate entering the reach from all sources during a discrete time must balance (equal) the mass of nitrate leaving the reach through all outlets during the same time. In applying the principle, it was assumed that the mass of nitrate entering the reach per unit of time was equal to the sum of the nitrate passing through the upstream transect plus the nitrate emanating from the springs and streambank; and the mass of nitrate leaving the reach per unit of time equals the nitrate discharge passing through the downstream transect. The discharge of water from the streambank to the river is calculated as the difference in nitrate discharges at the two transects divided by the nitrate concentration of the water from the springs (see equation A2, Appendix A).

The values of streambank discharge calculated for the reach are shown by the heavy dots in figure 12. In the calculations, nitrate concentrations in spring S-1 were used to represent the concentrations in streambank discharge (Buske and Josephson, 1986b). Nitrate discharges through each transect were calculated using water depths and distances between measurement stations along each transect, averages of river-water velocities measured at two different times at each station (SEARCH, oral commun., January 21, 1987), and concentrations in water samples collected at each of the measurement stations during each of the five measurements.

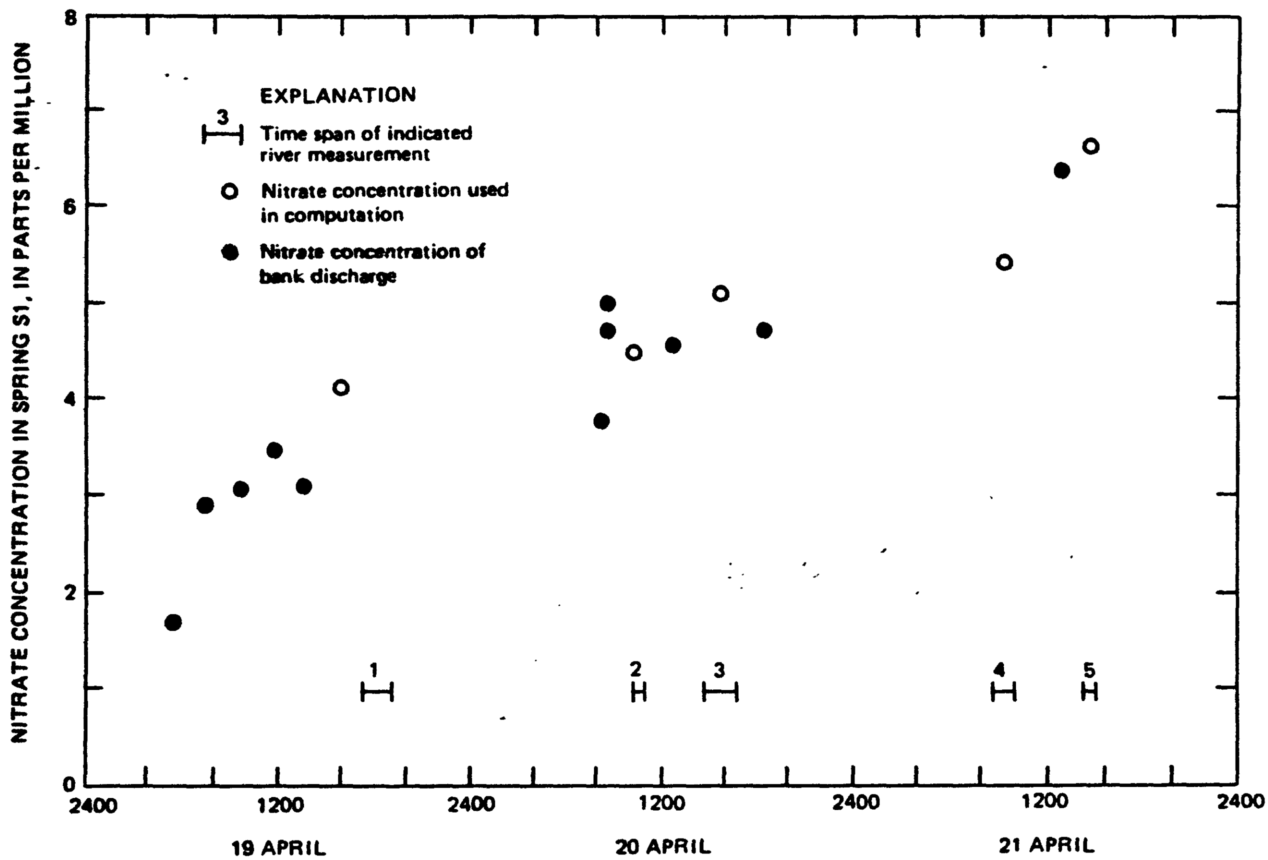


FIGURE 11.--Nitrate concentrations in water samples from spring S-1, April 19-21, 1986 (From Buske and Josephson, 1986a, table 1).

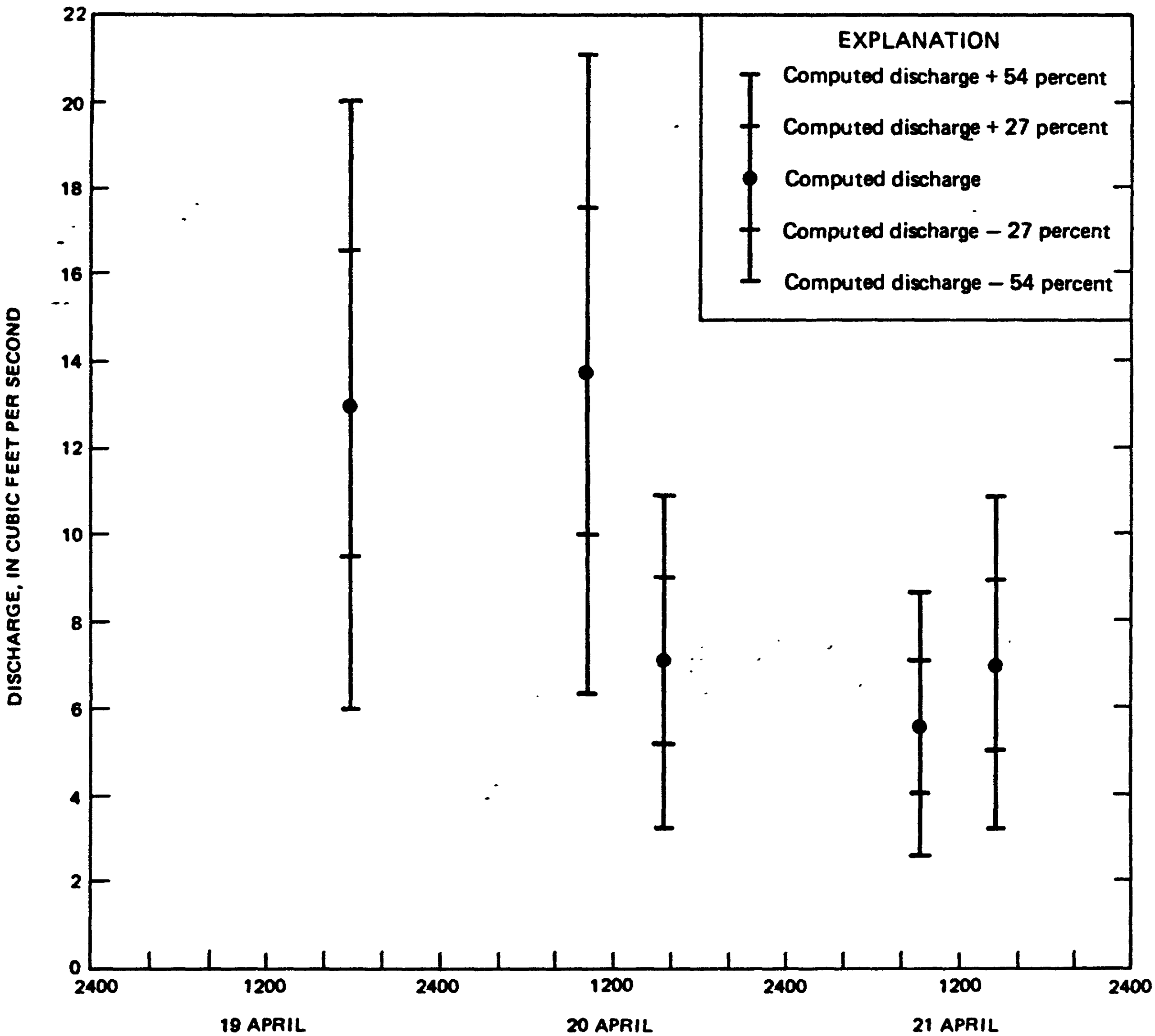


FIGURE 12.--Computed streambank discharge with error bars near Hanford River Mile 28, Hanford Reservation, April 19-21, 1986. (Computed discharge values taken from Buske and Josephson, 1986a.)

Observations of an apparent marked decrease in spring discharge after noon on April 20, led SEARCH to conclude that the streambank discharges calculated from the last two measurements of the experiment represented an equilibrium condition, and that the average of the two discharges (6.3 cubic feet per second) was an estiate of the mean annual ground-water discharge into the Columbia River from this 852-foot reach.

Accuracy of Mass-Balance Calculations

Nitrate as a tracer and SEARCH's determination of nitrate

Nitrate (NO_3^-) is generally accepted to be appropriate for tracing the movement of water under conditions similar to those during the SEARCH experiment. Nitrate is known to be present in the ground water discharging to the river at the experiment site with concentrations substantially greater than that of the river water.

Salts of nitrate, such as sodium nitrate and potassium nitrate, are highly water-soluble and nitrate is not readily sorbed by sediments. However, nitrate can undergo chemical change in a reducing (oxygen-poor) environment. No oxygen-concentration data for the river are given, but the relatively shallow water where measurements were made (0.5 to 8 feet) is not likely to have a sufficiently reducing environment to change nitrate to a lower oxidation state, particularly in the short time of its travel in the reach.

SEARCH used a portable electronic meter with an ion-specific electrode for determining nitrate concentrations. The nitrate-ion specific-electrode method is not adequate for determining actual nitrate concentrations in the river and ground waters at low concentrations, but probably is acceptable for determining differences between nitrate concentrations at the sampling stations and river background concentrations. The SEARCH report (Buske and Josephson, 1986a) indicated that the limitations of the instrument are acceptable and that resulting determinations are conservative; that is, use of concentrations determined with this instrument results in underestimated streambank discharges. A review of the manufacturer's specifications and of the experimental procedures support SEARCH's conclusion about the suitability of the method used for nitrate determinations. Therefore, nitrate concentrations measured by SEARCH can be used in the mass-balance calculations to determine streambank discharge in the river reach.

The instrument used by SEARCH consists of an Orion nitrate electrode and a portable electronic meter, the Orion SA270.* This instrument can be read with the resolution of 0.01 ppm as nitrogen. However, concentrations determined with this instrument probably have an error that is greater than the resolution of the instrument. For concentrations less than about 0.5 ppm, the electrode response is nonlinear. If calibration is assumed to be linear over

* Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U. S. Geological Survey.

the entire range, as was done by SEARCH, then low-level concentrations determined with the instrument are greater than actual concentrations and errors increase with decreasing concentrations. Consequently, differences between river background concentrations and concentrations at measurement stations are underestimated. As a result, the mass-balance calculations underestimate the streambank discharges, as SEARCH stated.

Accuracy of computed streambank discharges

From the evidence given by Buske and Josephson (1986a), it seems reasonable to accept that during each set of river measurements (1) conditions in the river adequately represented the assumed steady-state conditions and (2) all important avenues of nitrate transport into and out of the reach could be accounted for. Therefore, the mass-balance method is valid in this application. However, the accuracy of a streambank discharge calculated by the mass-balance equation (discussed in appendix A) is dependent on the accuracy with which each of the independent variables are measured, and on the procedures for calculating nitrate transport. Some of the measurement and calculation procedures resulted in systematic errors in the computed streambank discharges. These are in addition to random errors that are normally expected.

Random errors inherent in the determination of river depths and flow velocities, and of nitrate concentrations in the river and springs during the measurements, can be expected to produce random errors, having a standard deviation of about 27 percent, in each of the computed streambank discharges. The computation of these random errors is discussed in Appendix B.

The computation of streambank discharge also is subject to systematic errors that resulted from (1) not measuring water velocities at proper depths to define the mean velocities at stations in the measurement transects; (2) not extending the measurement transects far enough out from the streambank to account for all of the nitrate in excess of background concentration; (3) not including enough measurement stations in the transects to fully account for the variability of velocities and nitrate concentrations across the transects; (4) not taking discharge-weighted water samples for determining nitrate concentrations at the measurement stations. In addition, it is possible that the true nitrate background concentration in the river was not determined because of instrument limitations, and that the nitrate concentration in spring S-1 did not accurately represent the discharge-weighted average concentration of all sources of flow from the streambank.

Adjusting observed velocities from Buske and Josephson (1986a, table 2) to estimate depth-averaged values (error 1), and extending the measurement transects to 200 feet from shore (error 2) results in a 20-percent increase in the computed streambank discharge for measurement 1 and a 30-percent reduction in the discharge for measurement 3.

Rough calculations also are possible for effects of inaccurate measurements of background nitrate concentrations in the river. Trial computations indicate that a 0.01 ppm increase in background nitrate concentration would result in about a 15-percent decrease in calculated streambank discharge; similarly, a 0.01 ppm decrease in background concentrations would cause a 15-percent increase in computed streambank discharge.

The effect on the calculation of streambank discharge of an insufficient number of measurement stations in the transects cannot be evaluated without additional data. Also, only sparse and inconclusive data are available for estimating the influence of nonuniform vertical distributions of nitrate concentrations at the river measurement stations. However, for springs that lie between the upstream and downstream transects, especially those in deeper water or those near the downstream transects, vertical mixing of the nitrate may be incomplete. Thus, concentrations in the single-point samples, especially those from near the water surface, may not be equivalent to discharge-weighted average nitrate concentrations at the measurement stations, which are required to compute accurate nitrate discharges through the transects. Flow distances required for complete vertical mixing are estimated in appendix B.

The nitrate concentration in water from spring S-1 was used to represent the average nitrate concentration in streambank discharges, but the measured nitrate concentrations in this spring were higher than in any other sampled spring. The use of high nitrate concentration causes the computed streambank discharge to be lower than that computed using a mean concentration for all springs.

The net effect of all systematic errors is indeterminate; however, it directly biases the value of any computed streambank discharge, and causes the standard deviation of the error to be greater than that caused by random errors alone. This implies that there is a 67-percent probability, or less, that the "actual" discharge at the time of each measurement was within approximately 27 percent of the computed value, and that there is a 95-percent probability, or less, that the actual discharge is within approximately 54 percent of the computed value. Error bars based on these probabilities are included with the computed discharges (heavy dots) in figure 12.

Ground-water and bank-storage components of discharge

SEARCH estimated that, at the end of their experiments, about 6.3 cubic feet per second of water was being discharged from the 852-foot long streambank into the Columbia River. The opinion of SEARCH investigators, which is based on a reasonable and consistent interpretation of their data and other information, is that this discharge represents a long-term average ground-water discharge. An alternate interpretation, which also is reasonable and consistent, is that the computed streambank discharge contains a component of discharge that represents a draining of water from bank storage. However, the data are insufficient for computation of this component, or for selection of one interpretation over the other.

Whenever the river stage rises, ground-water levels adjacent to the river also rise, resulting in a temporary increase in the amount of water being stored in the aquifer and streambank. One source of the increase in storage can be ground water that formerly was discharging to the river but that is retarded by the high river stage. Another source is river water that enters the streambank and aquifer during high river stage. When the river stage lowers, the excess water stored in the streambank and aquifer drains to the river at a progressively decreasing rate. During this time, the relative proportion of ground water to river water in the discharge to the river gradually increases until the discharge consists totally of ground water.

The SEARCH data show that nitrate concentrations in all springs trended upward from beginning to end of the experiment (see trend for spring S-1 in fig. 11). This trend is consistent with the concept that, after a lowering of river stage, the streambank discharge is a mixture of nitrate-contaminated ground water plus river water with a low nitrate concentration. Nitrate concentrations in samples from inland wells near the study reach typically have nitrate concentrations of 5 to 10 ppm (Prater and others, 1984), while concentrations in river water are only about 0.2 ppm. The maximum concentration in spring S-1 at the end of the experiment was 6.6 ppm, while maximum concentrations in the other springs were lower, ranging from 3.3 to 5.6 ppm.

The concept of a progressively decreasing streambank discharge throughout the experiment is not inconsistent with the discharges calculated by SEARCH if the confidence limits on the data are considered (see error bars in figure 12). Also, the time from the stabilization of the river stage to the end of the experiment (about 55 hours) probably was too short for bank storage to be released completely. A mathematical analysis (Cooper and Rorabaugh, 1963) and field evidence (Newcomb and Brown, 1961) suggest that a large part of the bank storage (30 to 40 percent) is released in the first day or two after the river stage is lowered, and thereafter, the rate of release progressively diminishes.

Suggestions for Additional Studies

If estimates of localized ground water discharge to the river are desired, the mass-balance method employed by SEARCH, with improvements, is a practical and effective technique. Use of reliable estimates of such discharge can greatly enhance the accuracy of ground water models. Well-calibrated models provide practical means for estimating flow paths, traveltimes, and discharge locations. Suggested improvements in the technique include:

1. Extending measurement transects farther into the river, to the region of assured background river concentrations, and reducing spacing between stations along the transects.

2. Using established methods for determining depth-averaged velocities and discharge-weighted concentrations at measurement stations in the river.

3. Determining concentrations with an instrument that is calibrated over the full range of concentrations encountered in the experiment, or by using approved laboratory methods capable of accurate determinations at low concentrations. Either or both approaches need to include a quality-assurance program for concentration determinations.

4. Attempting to obtain discharge-weighted constituent concentrations in the streambank discharge along the study reach.

5. Monitoring ground-water levels near the river to identify changes in bank storage.

GROUND-WATER TRAVELTIME

Summary of Findings

SEARCH estimated that the average ground-water traveltime through the postulated channel from the 200-East Area to the Columbia River is about 2.5 years. This review suggests that a more reasonable estimate of traveltime between these points is probably on the order of 10 to 20 years, but could be as low as 6 years. The results of this review also indicate that the available data, including those of SEARCH, do not allow reliable determination of the average traveltime.

Evaluation of the assumptions inherent in calculations by the SEARCH investigators indicate that their estimate of traveltime cannot be supported. Some of the possible errors associated with their calculated values are large and can cause the resulting traveltime to be significantly longer or shorter. It is also highly probable that the conceptual model they assumed in determining traveltime is not realistic.

Definition of Traveltime

Some confusion has arisen concerning the terms arrival time and traveltime as they are used in regard to the movement of contaminants in a ground-water system. In addition, estimating these times in natural systems is subject to much uncertainty because of the inherent velocity variations in ground-water systems due to heterogenous hydraulic properties of geologic materials. Contamination does not arrive all at once, but rather arrives in a continuous manner as different streamlets of ground water arrive at different times due to variations in their different paths. Accordingly, the traveltime for a contaminant to move from one place to another can vary widely as a result of a wide range of pathways. Within this time range two time periods are of particular importance--the first-arrival traveltime and the average traveltime (often referred to as breakthrough time). For a system with continuous tracer input at the source the time of first arrival at any particular point would be marked by the first appearance of a tracer at that point. This would represent, for example, the fastest pathway from the PUREX plant to that point, such as the river or a sampling well. The average traveltime is considered to be the time when the concentration of the pollutant first reaches one-half of its steady-state value, and is representative of the average pathway.

Traveltimes of ground water and contaminants depend on several factors. Some of these include: the flow path; the presence and character of any unsaturated parts of the flow path; the hydraulic gradients in the ground-water system; the physical and chemical properties of the geologic material; and the chemical properties of the contaminant. The latter two factors can be important because the movement of some contaminants can be retarded by sorbtion onto soil and rock materials. Consequently, making reliable interpretations that use values of traveltimes requires careful consideration of all factors on which they are based.

Estimate by SEARCH

The method used by SEARCH to estimate an average traveltime along the hypothesized buried channel pathway involved the computation of the ratio of the average traveltime for the channel to the average traveltime for a "seepage" (widely distributed flow) pathway that is,

$$\frac{\text{channel traveltime}}{\text{seepage traveltime}} = \frac{\text{(relative path length)(relative porosity)}}{\text{(relative flow rate)}} , \quad (1)$$

where the quantities in parentheses are ratios of SEARCH estimates to those of PNL.

This equation is derived from:

$$t = \frac{d}{v} \quad ; \qquad (2)$$

where t = average traveltime,
d = path length,
v = flow velocity;

and

$$v = \frac{Q}{A\theta} \quad ; \qquad (3)$$

where Q = water discharge
A = cross-sectional area, and
θ = effective porosity;

which results in $t = \frac{d\theta}{(Q/A)}$. (4)

The "seepage" flow used in the SEARCH computations is the flow simulated by PNL's Variable Thickness Transport (VTT) model. This model numerically simulates ground-water flow in two dimensions, and assumes a uniform vertical distribution of ground-water flow over a large thickness of the sedimentary deposits. In their use of equation (1) SEARCH investigators used a seepage traveltime of 50 years, a relative path length of 1.5, a relative porosity of 2.5, and a relative flow rate of 77. The resulting computed traveltime for the channel, about 2.5 years, differs from the "seepage" traveltime, 50 years, principally because of the relative-flow-rate factor.

In developing that traveltime estimate, SEARCH used a seepage flow rate of 0.5 ft^3/s/mile, which was obtained from the VTT model and is an average ground-water discharge to the river along a 6-mile reach in the vicinity of HRM 28. Prater and others (1984), however, indicate that the seepage discharge to the river is not uniform over the 6-mile reach, and that discharge over a one-mile segment of the reach that includes the postulated channel is 1.5 ft^3/s/mile. The use of this larger discharge in equation (1) would result in a threefold increase in the calculated channel traveltime to about 7.5 years.

SEARCH defined the relative flow rate as the ratio of discharge per unit width of the postulated channel (852 feet) to the discharge per unit width of the 6-mile river reach (Buske and Josephson, 1986a). As can be seen in equation (4), however, the term in the denominator is the ratio of discharge to the area, rather than a ratio of discharge to width. Accordingly, the use of width rather than area in the SEARCH calculation implicitly requires the assumption that the thickness of the postulated channel is the same as the thickness of the entire alluvial section that is simulated in the VTT model. That assumption appears to be at odds with SEARCH's channel concept. Because of the large uncertainty in the values of the parameters in equation (1), and because of the unknown depth of the postulated channel in relation to the total saturated thickness of the ground-water flow system, the traveltimes calculated by the SEARCH method should be considered speculative.

In addition, any errors in SEARCH's estimate of ground-water discharge to the river would cause corresponding errors in the computed relative-flow rate and channel traveltime. As discussed in the section "Validity of Ground-Water-Discharge Estimate," the estimated discharge contains errors caused by random and systematic errors in measurements made during the experiment, and because the estimated discharge may contain a component of bank-storage discharge.

Estimates from Radionuclide Concentrations in Wells

Ground-water and radionuclide rates of movement and traveltimes to the Columbia River have been estimated using radionuclide concentrations in wells. Newcomb and others (1972) recognized the importance of saturated conditions in the Hanford Formation of Brown and Isaacson (1977) when addressing the relatively rapid rate of ground-water movement from the 200-East Area that was documented by Brown and Haney (1964). Newcomb and his colleagues state:

> "A most significant development in subsurface disposal involves the movement of ground water carrying tritium and ruthenium-106 southeastward and eastward from the area of the eastern large recharge mound through the highly permeable glaciofluviatile and fluviatile materials for 14 miles to the zone of bank storage along the Columbia River (Brown and Haney, 1964). This movement in general followed the direction of highest permeability, as indicated by the relatively flat hydraulic gradients and the bulging of contour lines on the ground-water contour maps of 1953 (Newcomb and Strand, 1953) and of 1951, 1955, and 1957 (Bierschenk and McConiga, 1957). Movement of the tritium and ruthenium at the rate of about 2 miles per year (Brown and Haney, 1964) through the glaciofluviatile and fluviatile deposits over a 6- to 8-year period illustrates the acceleration that occurs in the ground-water flow once the water table has risen above the base of the highly permeable deposits, ..."

The glaciofluviatile and fluviatile deposits of Newcomb and others correlate directly with the Hanford Formation of this report.

Brown and Haney (1964) extrapolated their data to estimate traveltimes as low as 7 to 8 years for the movement of ruthenium, and 6 to 7 years for the movement of tritium from the 200-East Area to the river. It is unclear whether the traveltimes represent first-arrival or average traveltimes. On the basis of their discussion, however, the traveltime values probably represent the first arrivals. Brown and Haney (1964) also estimate a traveltime for the movement of radionuclides from the 200-West Area to the Columbia River at about 20 years owing to the greater distance and lower hydraulic conductivity of the materials in the 200-West Area.

Average traveltime for radionuclide transport from the 200-East Area to the Columbia River was estimated as part of the work for this review. The estimate is based primarily on an analysis of variations in tritium and nitrogen concentrations in wells, combined with the historical information about wastewater disposal at the PUREX cribs. The estimated traveltime was slightly longer than 13 years; however, because of uncertainties in interpreting some of the data, it would be more appropriate to state that the average traveltime is in the range 10 to 20 years. Methods of computing traveltime are given in appendix C, and summary data are shown in figure 13 and table C2. Additional support for a traveltime in the range 10 to 20 years was obtained from an analysis of the decreases in tritium concentrations in wells following the shutdown of the PUREX plant from 1972 to 1982.

The data on figure 13 show a consistent increase in traveltime with increasing distance from the 200-East Area. At well 40-1, which is near the river at HRM 28, average traveltime is about 13 years. In the southeasterly flowing segment of the plume shown in figure 7, at two wells about 3 1/2 miles from the river, estimated average traveltimes are in the range of 10 to 13 years, indicating somewhat longer traveltimes to the river along this flow path.

Suggestions for Additional Studies

Ground-water modeling is the most practical approach for estimating traveltimes. It is suggested that a three-dimensional-transport model be developed in conjunction with the three-dimensional-ground-water-flow model for the sedimentary deposits of the Hanford Reservation. The model should be used to examine the effect of high-permeability zones (or channels) on flow directions and on traveltimes. A more rigorous analysis of the water-chemistry data than was done for this review, coupled with better information on radionuclide discharges on the Reservation, would yield improved estimates of traveltimes and provide necessary information for construction and calibration of the model. All future estimates of traveltimes should include determinations of first-arrival, as well as average, traveltimes. Future estimates, should also include estimates of traveltimes in the unsaturated zone at the beginning of flow paths, and take into consideration chemical interactions between the constituents in the ground water, and between the constituents and the rock materials.

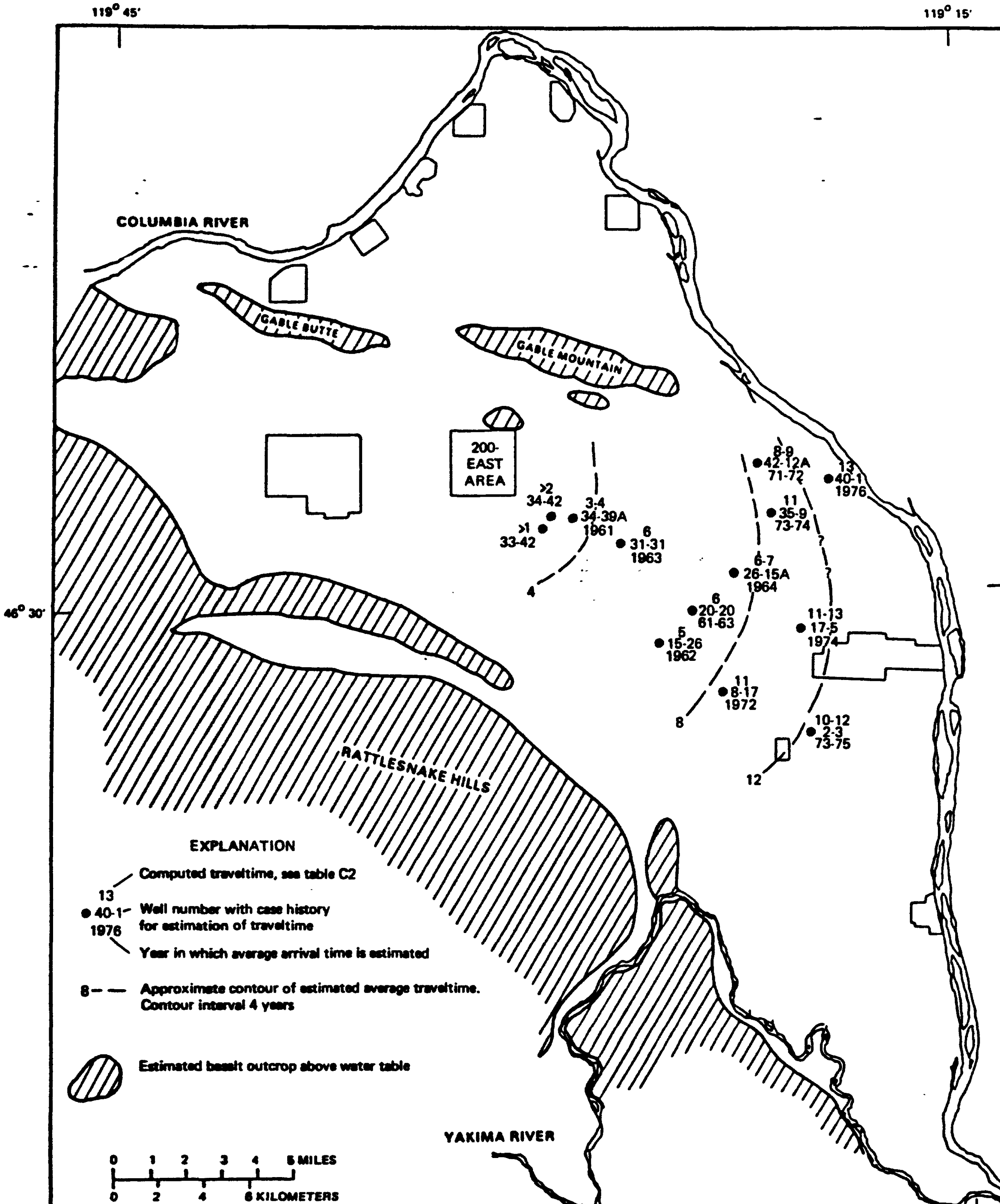


FIGURE 13.--Estimated average traveltimes for contaminants moving from the 200-East Area towards the Columbia River.

TRITIUM DISCHARGE TO THE COLUMBIA RIVER

Summary of Findings

SEARCH estimated that 2,500 ± 400 curies per year of tritium, were being discharged by ground water from the Hanford area to the Columbia River (letter to Mr. K. L. Price, of Pacific Northwest Laboratory, December 24, 1985). The letter states that the PNL ground-water model (Price and others, 1985) accounts for only 450 curies per year, or 18 percent of the foregoing estimate. A review of the SEARCH method suggests that the resultant estimate of tritium discharged by ground water to the river is high by a factor of approximately three. Hence, the PNL ground-water model more likely accounts for about 54 percent of the annual tritium discharge. The overestimate by SEARCH is the result of erroneously assuming that tritium-contaminated ground water entering the river from the Hanford area was nearly uniformily mixed within the river cross section at the Richland sampling site.

Calculations suggest that any tritium that is discharged near the river's west bank in the vicinity of HRM 28 would not be well-mixed across the river at Richland, but would tend to remain more concentrated in the western part of the river. At the Richland sampling site, which is also near the river's west bank, concentrations of tritium that originates near the west bank at HRM 28 would be approximately three times the cross-sectional average.

Method of Estimating Tritium Discharge

SEARCH estimated the discharge of tritium in ground water from the Hanford area to the Columbia River by using a mass-balance equation for tritium in the reach of the river between Priest Rapids Dam and Richland, as follows:

$$Q_u C_u + Q_g C_g + Q_N C_N = Q_d C_d \qquad (5)$$

Each Q in the equation is a water discharge, each C is the tritium concentration in that water, and the product QC is a tritium discharge. The subscripts u and d refer to cross sections of the Columbia River upstream (Priest Rapids Dam) and downstream (Richland) of the Hanford area, respectively; the subscript g refers to the tritium-contaminated ground water discharging to the river; and N refers to N-reactor, which is the only additional appreciable source of tritium to the river in the study reach.

Solving equation 5 for $Q_g C_g$, and replacing Q_d and Q_u by the average river discharge in the reach, Q_r , gives

$$Q_g C_g = Q_r (C_d - C_u) - Q_N C_N \qquad (6)$$

An assumption that is implicit in equations 5 and 6 is that the concentrations C_u and C_d are discharge-weighted average concentrations for the river cross sections.

Annual mean values of Q_gC_g for 1980 through 1984 were computed by SEARCH using annual mean tritium concentrations in samples collected by PNL at Priest Rapids Dam and at the Richland water intake for C_u and C_d, and annual mean river discharges for Q_r. The reported values of tritium discharge from N-reactor, Q_NC_N used by SEARCH were 6 percent or less of the tritium discharge ascribable to ground water, Q_gC_g. Annual mean values of Q_gC_g for all years except 1982, for which SEARCH thought the data were suspect, were then averaged. That value was reduced by about 25 percent to account for suspected correlations between instantaneous river discharge and tritium concentration, and by another 5 percent to account for lack of complete mixing of tritium discharges from the 300-Area, which is about 3 miles upstream from the Richland sampling site. It was assumed that tritium discharged near HRM 28, about 19 miles upstream from the Richland sampling site, was well-mixed across the river at Richland. This latter assumption is evaluated in the following section and in Appendix D.

Lateral Mixing in River

Although the rate of lateral mixing in a river cannot be accurately determined without field tests on the specific river at the reach of interest, tests on many rivers have established some procedures for estimating lateral mixing rates without field tests. These established procedures are accurate to within about 50 percent. At the Richland sampling site, the lateral distribution of tritium that is discharged near the west bank at HRM 28 was estimated for this review using procedures outlined by Fischer and others (1979). The procedures used are outlined in the following paragraphs, and the computational details are given in Appendix D.

An equation that describes the lateral mixing of tritium discharged at the shoreline is

$$s_b^2 = s_a^2 + 2 E_z (x_b - x_a)/v \quad , \qquad (7)$$

where s_b^2 and s_a^2 are the variances of the lateral concentration distribution about the shoreline in two cross sections with streamwise coordinates x_b and x_a, and v is the river velocity. The term, E_z, is the lateral diffusion coefficient and can be approximated by

$$E_z = \alpha u_* d, \qquad (8)$$

where d is the river depth, and α is a dimensionless coefficient. The variable u_* is the shear velocity and is equal to $\sqrt{gdS}$, where g is the gravitational acceleration and S is the river slope.

Given the variance, s^2, relative values of concentrations at points in the cross sections can be computed by assuming the distribution to be Gaussian

$$c(z)/c(0) = \exp(-z^2/2 s^2), \tag{9}$$

where c(z) is the concentration at a distance z from the bank, and c(0) is the concentration at the west bank.

For making the lateral mixing computations in the river between HRM 28 and the Richland sampling site (HRM 47.6), the river was theoretically divided into two reaches with different geometric and hydraulic characteristics. The boundary between the two reaches is at HRM 32. In the downstream reach, the river is about twice as wide as in the upstream reach, and the velocities, depths, and slopes are less. Data for the upstream reach were estimated from measurements made at Vernita Bridge, and for the downstream reach, from measurements at Richland (see Appendix D).

The computation of the variance, s^2, at the Richland sampling site was performed in three steps. First, equation (7) was used for the reach between HRM 28 and 32. Second, the computed value of s_b^2 at HRM 32 was then quadrupled ($2^2 = 4$) to account for lateral advective spreading of a constituent that would be expected to occur when the river width doubles. This quadrupled value was used for s_a^2 in the third step where equation (7) was used for the reach between HRM 32 and 47.6. The computed value of s_b^2 at the Richland sampling site, together with equation (9) and an estimated river width of 2,000 feet, were used to compute the ratio of the concentration at the west bank to the cross-sectional average concentration. This computation resulted in a ratio of approximately three. The consequence of SEARCH's using the concentrations at the west bank for c_d in equation (6) is an overestimation of the ground-water tritium discharge, $Q_g C_g$, by a factor of approximately three.

Suggestions for Additional Studies

The computation of the lateral distribution of tritium in the Columbia River at the Richland sampling site was based on numerous estimates and assumptions, and the results should be considered tentative. If accurate knowledge of tritium discharges from the Hanford area to the Columbia River is desired, the results should be confirmed by determining the lateral distribution of both tritium and water discharge across the river at Richland. The distributions should be determined at least three times during different river conditions and also should be determined at the upstream sampling site at Priest Rapids Dam. If the concentrations at the west bank at the Richland sampling site do not yield good approximations of the tritium concentration in excess of that at Priest Rapids Dam, then a new method should be devised to sample the river or to analyze the data. One method would be to take samples at a sufficient number of stations in the river cross sections to allow direct computations of tritium discharges. A second method would be to sample a large number of stations across the river a sufficient number of times to establish relationships between the concentration of tritium at the west bank and the discharge-weighted average concentration. If suitably accurate relations can be found, then they can be used in conjunction with data collected by present means to estimate tritium discharges.

CONCLUSIONS

SEARCH Technical Services has hypothesized that a highly permeable ground-water channel incised into the Ringold Formation connects the 200-East Area on the Hanford Reservation to the Columbia River. SEARCH claimed that the channel hypothesis is supported by a large localized streambank discharge to the Columbia River that they measured along an 852-foot reach of the river near Hanford River Mile 28, and by their interpretation of geologic, hydrologic, and water-chemistry data. On the basis of the channel hypothesis, they estimated that the average ground-water traveltime between the 200-East Area and the river is 2.5 years. Using published data on tritium concentrations in the Columbia River, they also concluded that about 2,500 curies per year are discharged to the river by ground water.

A review of geologic, hydrologic and water-chemistry data, undertaken to evaluate the possibility of a narrow high-permeability channel, does not confirm or refute the channel's existence. To a very large degree, the available data suggest that the channel, even if it should exist, is not the principal pathway of the relatively high streambank discharge that occurs in the vicinity of SEARCH's study reach. This relatively high discharge is most likely the result of liquid waste disposal on the Reservation, which has caused a significant rise in ground-water levels, thus saturating highly permeable deposits of the Hanford Formation of Brown and Isaacson (1977) over a broad area between the 200-East Area and the river. Saturation of these deposits has resulted in a widespread movement of water from the 200-East Area to the river. An area of low-permeability deposits extends for some distance along the west bank of the Columbia River just south of SEARCH's study reach. This low-permeability material probably causes convergence of water flowing to the Columbia River to the north (into SEARCH's study reach), thereby contributing to the high localized streambank discharge. Rising water levels in the Hanford Formation over a large area would tend to reduce the importance of a single narrow buried channel filled with Hanford Formation deposits in the same area.

Examination of the temporal and spatial configuration of ground-water levels and tritium concentrations directly reinforces this alternative interpretation. The evaluation of the temporal changes in tritium concentration at well 40-1 and of SEARCH's tritium "notch" concept, both of which were used by SEARCH as supporting evidence for the existence of a narrow channel, indicates that SEARCH's interpretation of these data is subject to considerable question; these data certainly do not directly confirm the existence of the proposed channel.

A review of the assumptions inherent in SEARCH's calculation of a 2.5-year average traveltime from the 200-East Area to the Columbia River through their proposed channel indicates that their value of traveltime cannot be supported. Some of the possible errors associated with their method of calculating traveltime are large and can cause the resulting traveltime to be significantly longer or shorter. To calculate traveltime, SEARCH used an equation containing ratios between parameters for the hypothesized channel and parameters derived from the PNL VTT model. Because of the large uncertainty in the values of the parameters used, and because of the unknown depth of the postulated channel in relation to the total saturated thickness of the ground-water flow system, the traveltimes calculated by the SEARCH method should be considered speculative. An analyses of data on radionuclide and nitrate concentrations in ground water, which was done as part of this review, resulted in an estimated average traveltime between the 200-East Area and the Columbia River near HRM 28 of 10 to 20 years. Brown and Haney (1964), using similar-type data, estimated traveltimes (probably first-arrival traveltimes) as low as 6 years. It is believed that the best estimate of average traveltime is 10 to 20 years.

SEARCH's estimate of the discharge of tritium in ground water from the Hanford Reservation to the Columbia River (2,500 curies per year) is probably high by a factor of approximately three. The discharge is believed to be overestimated because of incomplete lateral mixing of tritium across the river (instead of complete mixing as assumed by SEARCH) in the reach between the location of the major ground-water discharge of tritium and a sampling site near the riverbank at Richland.

A field experiment conducted by SEARCH adequately demonstrated that the streambank discharge from the Hanford Reservation to an 852-ft reach of the Columbia River was relatively large, 6.3 cubic feet per second. However, this value contains components of random error with a standard deviation of 27 percent, some systematic errors of up to +30 percent, and additional systematic errors that could not be evaluated. SEARCH's conclusion that this discharge is representative of an average ground-water discharge is reasonable, but an alternative line of reasoning suggests that this discharge contained a bank-storage component of indeterminate amount. Errors in estimated ground-water discharge would lead to consequent errors in SEARCH's estimated traveltime.

SUMMARY OF SUGGESTIONS FOR ADDITIONAL STUDIES

Confirmation of the presence of the hypothesized channel on the basis of direct physical evidence (geology, water levels, water chemistry) cannot be accomplished without an extensive array of closely spaced test wells that would penetrate the proposed channel along its hypothesized 10 to 17 miles length. It is possible that hundreds of test wells would be required to ultimately confirm or reject the channel hypothesis. An indirect approach using a three-dimensional numerical model simulating ground-water flow in the sedimentary deposits would be more appropriate. The model could be used to test the effect of high-permeability areas (or channels) on the overall flow system. Emphasis needs to be placed on determining the relative contribution of discharges from high-permeability pathways to the Columbia River. This effort would require intensive review of existing information and possibly constructing additional test and observation wells to obtain information on lithology, water levels, and water chemistry for specific geohydrologic units. The number of new wells required would be far less than those required to confirm or reject directly SEARCH's channel hypothesis.

A transport model, based on the three-dimensional ground-water flow model would be an effective approach for estimating traveltimes. As an alternative, a more rigorous analysis of the water-chemistry data than was done for this review, coupled with better information on radionuclide discharges on the Reservation could yield good estimates of traveltimes. In addition, these data would be useful and necessary for the construction and calibration of the three-dimensional model. All estimates should consider first-arrival as well as average traveltimes. Estimates should also include the effects of flow in the unsaturated part of the flow path and the effects of chemical interactions.

The mass-balance method employed by SEARCH, with improvements, is a practical and effective technique for estimating localized streambank discharge to the river. Suggested improvements include: 1) extending measurement transects into the river to the region of background river concentrations, and reducing spacing between stations along the transects; 2) using established methods for determining depth-averaged velocities and discharge-weighted concentrations at measurement stations in the river; 3) determining concentrations with an instrument that is calibrated over the full range of concentrations encountered in the experiment, or by using approved laboratory methods capable of accurate determinations at low concentrations (inclusion of a quality-assurance program for the laboratory determinations would also be desirable); and 4) attempting to obtain the discharge-weighted concentration in streambank discharge within the study reach. Streambank discharge in the Hanford reach of the Columbia River would almost always be affected by changes in bank storage. Consequently, changes in ground-water levels should be monitored and the data used to estimate the bank-storage component.

To obtain tritium discharges from the Hanford area to the Columbia River by the mass-balance method used by SEARCH, better estimates of the discharge-weighted average tritium concentrations in the cross section at the downstream sampling site at Richland are required. Lateral distributions of tritium concentrations should be determined during a number of flow conditions at the Richland sampling site. If the concentrations on the west bank at the Richland sampling site do not yield good approximations of the tritium concentration in excess of that at the upstream sampling site at Priest Rapids Dam, then a new method should be devised to sample the river or to analyze the data. The method used to determine average concentrations at Priest Rapids Dam should also be checked.

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APPENDIX A - RANDOM ERRORS IN COMPUTED STREAMBANK DISCHARGES

Method of Random-Error Computation

Uncertainty in measured values causes uncertainty in values computed from them. For the purpose of this analysis, random errors in values measured in the experiment to compute streambank discharge are considered to be independent. For any value A that is computed from values B and C,

$$\sigma_A^2 = \sigma_B^2 + \sigma_C^2 , \qquad \text{(A1)}$$

where σ_X^2 is the variance of error in variable X, and is equivalent to the square of the standard deviation of the error. If A results from multiplication or division of B and C, the units of σ in equation A1 are in percent. If A results from addition or subtraction of B and C, σ is in the same units as A, B, and C.

To estimate random error in the computed streambank discharges resulting from random errors in measured values involved in the computation, variances of errors in the measured values were estimated and then added in units appropriate to the computation.

The streambank discharge is computed from the following equation:

$$Q_s = \frac{(\Sigma w_i d_i v_i (c_i - c_b))_{ds} - (\Sigma w_i d_i v_i (c_i - c_b))_{us}}{C_s} , \qquad \text{(A2)}$$

where Q_s = streambank discharge, in cubic feet per second,
w_i = width of i th section in the transect being measured, in feet,
d_i = average depth of i th section, in feet,
v_i = average velocity in i th section, in feet per second,
c_i = average nitrate concentration in i th section, in parts per million (ppm),
c_b = background nitrate concentration in river water, in ppm,
C_s = nitrate concentration in streambank discharge to river, in ppm,
ds = subscript referring to downstream transect, and
us = subscript referring to upstream transect.

By assuming that the errors in measured variables and, subsequently, the error in computed streambank discharge are normally distributed, confidence limits on the computed bank discharges may be estimated. If the only error in the computed discharge is caused by random errors in measured values, then there is a 0.67 probability that the true discharge is within ±1 standard deviation of the computed discharge, and there is a 0.95 probability that the true discharge is within ±2 standard deviations.

Error Estimates

Standard deviations of the errors in each of the variables in equation A2 were estimated using data in Buske and Josephson (1986a). These errors and the methods used in obtaining them are given in the following paragraphs.

The error in the widths, w_i, was assumed to be zero.

Depths were measured to the nearest 0.1 foot. Therefore, the error in depth is approximately uniformly distributed between -0.05 and +0.05 foot, so consequently the standard deviation of the error in depth is $0.05/\sqrt{3} = 0.029$ foot.

By statistical analyses of the differences in velocities measured at the same stations at two different times (Measurement 1 and Measurement 3), the standard deviation of the error in the average velocity at each station was computed to be 0.035 foot per second.

The error in nitrate concentration in spring S-1 and at each station in the river was estimated by computing the variance in the concentration about a linear regression line of concentration as a function of time for each location. The standard deviations of the random concentration errors are listed in table A1.

TABLE A1--Random errors in nitrate concentrations

[Stations: US, upstream; DS, downstream]

Station	Standard deviation of random error in concentration, in ppm
0/US	0.068
0.5/US	.044
1/US	.010
2/US	.015
0/DS	.689
0.5/DS	.047
1/DS	.010
2/DS	.028
3/DS	.026
4/DS	.015
midstream	.005
Spring S-1	.46

The standard deviations of the errors in the variables were then used to estimate the standard deviations of the errors in computed streambank discharges for measurements 1 and 3. The standard deviations of the errors in the discharges were found to be 27 and 31 percent, respectively. The error in each discharge was caused mostly by errors in nitrate concentrations at station 3/DS; errors in concentrations at stations 2/DS and 4/DS, and spring S-1 also contributed heavily. This resulted because concentrations at these river stations were close to the background concentration, and the relatively large velocities and depths at these stations resulted in a large fraction of the nitrate discharge being computed with data collected at these stations. The standard deviations of errors in streambank discharges that were computed using only errors in concentrations (zero error in velocity and depth) are nearly the same as when velocity and depth errors are included.

APPENDIX B.--VERTICAL MIXING

An estimate of the vertical mixing of solute discharged from a point source on the bottom of a river may be made from a combination of theoretical and empirical equations (Fischer and others, 1979). The variance, s^2, of the vertical distribution about a point on the river bed increases in the downstream direction as described by equation B1 if the increase is not limited by the water surface.

$$s^2 = 2\, E_y x/v \quad , \qquad \text{(B1)}$$

where E_y = vertical diffusion coefficient in square feet per second,
x = distance downstream from source, in feet, and
v = stream velocity, in feet per second.

Nearly complete vertical mixing would occur when the variance equals the depth squared.

The vertical diffusion coefficient E_y can be approximated by

$$E_y = 0.067\, u_* d \quad , \qquad \text{(B2)}$$

where d = water depth, in feet, and
$u_* = \sqrt{gdS}$ = shear velocity, in feet per second,

in which g = acceleration due to gravity, in feet per second squared, and
S = energy slope, in feet per foot.

Substituting the above expressions into equation (B1) with $s^2 = d^2$ and solving for x gives the distance required for nearly complete vertical mixing:

$$x = \frac{vd^{1/2}}{0.134\, \sqrt{gS}} \qquad \text{(B3)}$$

Using a slope of 2.34×10^{-4} (table D1) together with depths and velocities from Buske and Josephson (1986a) the following are estimates for distances downstream from a source necessary to obtain nearly complete vertical mixing:

Depth of water, in feet	Distance required for vertical mixing, in feet
1	25
2	85
4	200
8	480

In summary, it can be concluded that the nitrate concentrations at the sampling stations may not be uniformly distributed in the vertical. This statement is supported by the above calculations. Several hundreds of feet of stream distance are necessary for complete mixing, and the SEARCH reports indicate that some of the springs are only a short distance upstream from the upstream or downstream transects (20 and 60 feet).

APPENDIX C.--ESTIMATE OF AVERAGE TRAVELTIMES

Ground-water traveltimes were estimated using tritium and nitrate concentrations in wells downgradient from the PUREX Plant. The major source of these pollutants in the ground-water system is attributed to wastewater discharged from the PUREX Plant operation to the PUREX crib area. The PUREX Plant operated from 1957-1972 and again from 1983 to present (1986). Total wastewater discharge from the 200-East and -West Areas and wastewater discharged to the PUREX crib area for the period 1944-1980 are shown in table C1. Wastewater discharge to the PUREX crib area includes some wastewater in addition to that from PUREX operation, as indicated by discharge to the PUREX crib area while the PUREX Plant was inactive. Tritium discharge was not uniform during the period of operation from 1957 to 1972. Peaks in tritium discharge occurred in 1957 and 1963, with the peak in 1963 being five times as large as the peak in 1957 (Brown and Haney, 1964). Data were not available for identifying peaks in tritium discharge after 1964.

Ground-water traveltimes were estimated using three methods and the results are summarized in table C2 and figure 13. The first method, used for wells with concentration peaks that could be correlated to peaks in tritium discharge from the PUREX Plant, the average traveltime was taken to be the time between peak discharge of tritium from PUREX to the time when peak concentration was observed in the well. The second method was used for wells that showed sustained concentration levels that approximated steady-state conditions. In this method the average traveltime was taken to be the time between the peak in tritium discharge and the time when the concentration observed at the well reached one-half of its maximum sustained level. The third method, used only for two wells close to the source area, estimated first-arrival rather than average traveltime. This traveltime was taken to be the time between PUREX restart in 1983, and the time when the tritium concentration in wells began to increase. The selection of the year (1957 or 1963) to use for a start time for methods one and two is based on the areal distribution of average arrival occurring in the different wells. The 1957 start time was used for wells close to the source area and the estimated average arrival time was prior to 1963. Farther away from the source area, the 1963 date was used. The rationale for using the 1963 date for wells farther from the source area is that dispersion of the larger 1963 peak would be expected to mask evidence of the lower 1957 peak. It should be noted that using this procedure resulted in a shorter estimate of the traveltime than would result if 1957 had been used as the starting time. Uncertainties in the interpretation of the concentration history for each well resulted in a different degree of confidence for the traveltime estimated for each well. Relative confidences are included in table C2.

TABLE C1.--Wastewater discharges from Hanford 200 Areas
[Data from Zimmerman and others, 1986, tables 1 and 3]

Time period	Volume, in 10^9 liters			
	200-East Area			Total, 200-East plus 200-West Areas
	PUREX Crib	Total	200-West Area	
1943 - 1950	0.0000	10.06	22.41	32.47
1951 - 1955	.0526	9.214	67.73	76.94
1956 - 1960	4.372	63.33	57.79	121.1
1961 - 1965	3.973	78.15	43.72	121.9
1966 - 1970	2.600	75.31	25.32	100.6
1971 - 1975	.671	61.37	23.08	84.45
1976 - 1980	.676	68.36	27.37	95.73
1981 - 1986	(not available)			

TABLE C2.--Data for determination of average ground-water traveltime from PUREX to indicated wells

Well number, Hanford designation	Constituent	Method[1] of estimate	Relative quality of estimate	Estimated average arrival year	Source-input year	Average travel-time, in years
2-3	Tritium	1/2 SL	Good	1975	1963	12
2-3	Nitrate	1/2 SL	Fair	1973	1963	10
8-17	Tritium	1/2 SL	Good	1972	1963	9
15-26	Tritium	1/2 SL	Poor	1961-63	1957	5
17-5	Tritium	1/2 SL	Poor	1974	1963	11
17-5	Nitrate	Peak	Poor	1976	1963	13
20-20	Tritium	Peak	Good	1963-64	1957	6-7
26-15	Tritium	1/2 SL	Fair	1963-64	1957	6-7
31-31	Tritium	Peak	Poor	1963	1957	6
33-42	Tritium	Initial	Good	[2]1983	1983	>1
34-42	Tritium	Initial	Good	[2]1985	1983	>2
34-39	Tritium	Peak	Fair	1960-61	1957	3-4
35-9	Tritium	1/2 SL	Good	1974	1963	11
35-9	Nitrate	1/2 SL	Fair	1973-74	1963	10-11
40-1	Tritium	1/2 SL	Good	1976	1963	13
41-23	Tritium	1/2 SL	Good	1964	1957	7
42-12	Nitrate	1/2 SL	Fair	1971-72	1963	8-9

[1]Method of estimate:

1/2 SL--average arrival time estimated as time of 1/2 maximum sustained concentration

Peak--Average arrival time estimated as time of maximum concentration

Initial--Time to initial response and trend reversal after restart of PUREX plant in 1983

[2]First-arrival traveltime

APPENDIX D - LATERAL MIXING IN COLUMBIA RIVER

The Manning equation for flow velocity in a river is

$$v = \frac{1.49}{n} S^{1/2} d^{2/3} \quad , \tag{D1}$$

where v = average water velocity, in feet per second (ft/s),
n = a roughness coefficient,
S = energy slope, in feet per foot, and
d = average river depth, in feet.

The river discharge ,Q_r, in cubic feet per second (ft^3/s), is approximated by

$$Q_r = v\,d\,w \quad ,$$
$$= \frac{1.49}{n} S^{1/2} d^{5/3} w \quad . \tag{D2}$$

where w is the stream width.

If w, S, and n are assumed not to vary with river discharge, the ratios of depths and velocities for different discharges can be derived from equation D2,

$$d_1/d_2 = (Q_1/Q_2)^{3/5} \quad , \tag{D3}$$

and

$$v_1/v_2 = (d_1/d_2)^{2/3} = (Q_1/Q_2)^{2/5} \quad . \tag{D4}$$

Hydraulic data used in the lateral mixing calculations for the Columbia River during the mean annual river discharge (110,000 ft^3/s) were estimated from the historical data. Observations at Vernita Bridge were assumed to be representative of the river upstream of HRM 32, and data from observations at Richland were assumed representative of the reach downstream of HRM 32.

Values of the coefficient α in the expression for the lateral diffusion coefficient (see equation 8, p.43) were chosen on the basis of information given by Fischer and others (1979). They state that in natural streams with slow meanders and moderate sidewall irregularities α is usually in the range 0.4 to 0.8. Although the study reach of the Columbia River is believed to be of this type, the values of α were selected as 0.6 to 1.0 to slightly overestimate the mixing so as not to overestimate the error in SEARCH's reported tritium discharge. This was done in spite of the fact that numerous islands in the reach downstream of HRM 32 would inhibit lateral mixing.

Table D1 summarizes the calculations of lateral mixing between HRM 28 and the sampling site at Richland (HRM 47.6).

TABLE D1.--Component values for calculating lateral mixing in Columbia River between Hanford River Mile 28 and the Richland sampling site

	Upstream, Hanford River Miles 28-32	Downstream, Hanford River Miles 32-47.6
River discharge (Q_r), in cubic feet per second	145,800 (measured on 12/31/74)	113,000 (measured on 4/8/75)
Observed average flow velocity (v), in feet per second, for above river discharge	5.95	3.48
Observed average water depth (d), in feet, for above river discharge	19.8	15.3
Estimate of flow velocity (v), in feet per second, at Q=110,000 cubic feet per second by equation D4	5.32	3.45
Estimate of average water depth (d), in feet, at Q=110,000 cubic feet per second, by equation D3	16.7	15.1
Estimate of energy slope (S) at Q=110,000 cubic feet per second, by equation D2, with n=0.028	2.34×10^{-4}	1.13×10^{-4}
$u_* d = (gS)^{1/2} d^{3/2}$, in square feet per second	5.92	3.54
Lateral diffusion coefficient (E_z), in square feet per second, by equation 8	3.55 for α=0.6 5.92 for α=1.0	2.12 for α=0.6 3.54 for α=1.0
Variance about shoreline (s^2), in square feet, at HRM 28, estimated from Buske and Josephson (1986a)	$(40)^2$	--
Variance about shoreline (s^2) in square feet, at HRM 32 (by equation 7 for upstream, multiplied by 4 for downstream)	$(172)^2$ for α=0.6 $(220)^2$ for α=1.0	$(345)^2$ for α=0.6 $(440)^2$ for α=1.0
Variance about shoreline (s^2), in square feet, at Richland, HRM 47.6 (by equation 7)	-- --	$(472)^2$ for α=0.6 $(606)^2$ for α=1.0

Equations (7) and (8) are given on page 43.

Table D2 gives details of the calculation of the cross-sectional average concentration $\bar{C}$ at the Richland sampling site by the equation

$$\bar{C} = \frac{\Sigma \Delta z_i [(c(z)/c(0))_i + (c(z)/c(0)_{i+1}]/2}{\Sigma \Delta z_i} \qquad \text{(D5)}$$

The lateral distribution of concentration was assumed to be Gaussian (see equation (9), p.) and the reach width was assumed to be 2,000 feet. The conclusion from the theoretical results in table D2 is that concentrations near the west bank at the Richland sampling site of discharged tritium are 2.6 to 3.3 (1/.38 to 1/.30) times the cross-sectional average concentration. Taking into consideration the assumptions and estimates used in obtaining these results a statement consistent with the accuracy of the results is that the concentrations of the west bank are approximately three times the cross-sectional average concentrations.

TABLE D2.--Estimation of cross-sectional average relative concentration at Richland sampling site

z, distance from right bank (feet)	Δz (feet)	Relative concentration (for α=0.6) c(z)/c(0)	Relative concentration (for α=1.0) c(z)/c(0)
0		1.00	1.00
	200		
200		.91	.95
	200		
400		.70	.80
	200		
600		.45	.61
	200		
800		.24	.42
	200		
1,000		.11	.26
	200		
1,200		.04	.14
	400		
1,600		.00	.03
	400		
2,000		.00	.00
$\bar{C}$, Average relative concentration		.30	.38