SIMULATION OF THE IMPACTS OF SNAKE RIVER PLAIN AQUIFER WATER USE ON FLOW IN THE SNAKE RIVER

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ABSTRACT

Ground-water pumping on the eastern Snake River Plain and water use in tributary valleys will ultimately affect flow in the Snake River. Spring flows to the Snake River have declined during the past two decades. The decline in spring and river discharge may be attributed to water-level declines in the Snake River Plain aquifer resulting from the combined effects of changes in aquifer recharge and increases in ground-water pumping.

The effects of increased water use at selected locations in the Snake River Plain were estimated by simulating aquifer water use, spring flows, and river leakage using a ground-water flow model. The model was based on superposition concepts and designed to estimate only the changes in river flow resulting from ground-water use at specific locations in the aquifer. The model was constructed with an initially flat water table with four river reaches interconnected with the aquifer (e.g. fixed head nodes), but with no hydraulic gradient between the river and aquifer. Ground-water pumping was simulated at discrete locations and the response of river recharge and discharge was determined from computer modelling. Changes in flow are graphed in terms of a percentage of the rate of water use.

Simulation results demonstrate how the river recharge and discharge in each of the four hydraulically connected reaches varies in response to ground-water use at different locations. Eighteen water use sites were simulated throughout the Snake River Plain. In general, sites located east of Arco had greatest impact on the Snake River reach extending from the Above Blackfoot to Near Blackfoot river gages. Water use sites west of Arco primarily impacted spring discharge in the Kimberly to King Hill reach of the river. Simulations indicate that ground-water use within 10 miles of a hydraulically connected reach will result in river flow depletion greater than 80 percent of the rate of water use within 10 years of continuous usage. Water use locations about 45 miles from the river reaches result in river depletion at a rate of about 75 percent of the average water use rate after 100 years of water use. Additionally, ground-water use will impact spring discharge and Snake River flow for several decades after ground-water use is discontinued. Seasonal water use produces approximately the same results as a continuous water use at the same long-term average use rate, provided the point of water use is not near the river.

The accuracy of the model predictions are affected by several factors. The degree of interconnection of the Snake River and Snake River Plain aquifer is not known with complete certainty in all areas. Local aquifer systems and additional surface water sources may be hydraulically connected with the Snake River Plain aquifer which are not included in the present simulation. Prediction accuracy is also compromised by errors in estimation of aquifer properties and numerical and descretization errors inherent with numerical simulation.

The applied procedure and resulting graphs will further the general understanding of surface water and ground water interaction

in the eastern Snake River Plain. The method allows evaluation of individual ground-water use impacts on several reaches of the Snake River.

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STATEMENT OF THE PROBLEM

Idaho water law is based upon the Appropriation Doctrine which provides that the "first in time is the first in right". That is, a water right priority is based upon the date in which a water user first began to apply the water to a beneficial use. Beneficial use may include irrigation, hydropower, aquaculture, or other applications. In the past, the State of Idaho has not found it necessary to regulate ground-water uses with surface waters.

The times are changing. In 1977, hydropower concerns on the Snake River raised the issue that upstream water users, including those using ground-water were depleting Snake River flow and the revenues generated by Idaho Power Company. In 1982 the Idaho Supreme Court ruled the hydropower water rights of Idaho Power Company at Swan Falls Dam were not subordinate to upstream development. Idaho Power Company subsequently filed suit against thousands of upstream water users. The suit was ultimately settled by a compromise which included conditions which reduced Idaho Power's water right at Swan Falls and established a "Trust Area" in the upper Snake River Plain. New water development in the Trust Area was restricted due to potential impacts on flows of the Snake River. The Swan Falls decision resulted in the ongoing adjudication of all water rights in the Snake River basin.

The drought of the late 1980's and early 1990's has revived and amplified the competition for water resources in the Big Lost River basin, tributary to, and on the north side of, the Snake River Plain. Surface-water irrigators experienced diminished flows in the Lost River and accused ground-water users of depleting the river by lowering the water table and increasing seepage losses. A judicial decision provided the Idaho Department of Water Resources with the authority to implement an interim Director's Report that recognized the interaction of surface water and ground water and required compensation from ground-water users for depletion of surface water flows.

Changes in water use from the Snake River and the Snake River Plain aquifer have also generated the concern of irrigation districts relying on river flow for water supply. Surface-water irrigators are aware that the supply of water in the river is diminishing, partly as a result of water use by ground-water pumpers. The Twin Falls and Northside canal companies filed suit against the Idaho Department of Water Resources (IDWR), seeking an injuction against issuance of additional permits for ground-water development in the area tributary to the Snake River upstream from Milner Dam. Settlement between the irrigation companies and IDWR included the commitment to conduct investigations of the interaction between the Snake River and the Snake River Plain aquifer. The investigative efforts of IDWR will be focused on simulating the impacts of ground-water pumping on spring flows recharging the river and on seepage from the river to the Snake River Plain aquifer.

The investigation described in this report was conducted to provide preliminary insight into river-aquifer interaction in the Snake River Plain, and to demonstrate a technique that may prove useful in subsequent studies.

SCOPE OF THE INVESTIGATION

This investigation is intended to be an initial step in the process of simulating pumping impacts on flow in the Snake River. It should be a valuable aid to the Idaho Department of Water Resources in planning and implementing further investigations. This study should also be of use in furthering the understanding of water users regarding ground-water and surface-water interactions in the Snake River Plain. It is anticipated that three major benefits will be derived from this report:

1) A simplified technique for simulating and presenting the time-varied impacts of ground-water pumping on river flows will be accepted.
2) Results of the study provide a base from which concepts of river-aquifer interaction can be improved.
3) Results of the study provide preliminary estimates of the time-varied impacts of ground-water pumping on river flow for specific locations.

This study was based on Snake River Plain aquifer data obtained from modelling efforts of the Idaho Department of Water Resources. Aquifer boundaries and properties used in this study were taken directly from the IDWR model of the eastern Snake River Plain. The data represent the inputs of IDWR model as of April 1, 1993. Predictive simulations of this study were conducted using MODFLOW (McDonald and Harbaugh, 1986) in order to utilize a more widely accepted model code. The MODFLOW model was created with the same grid dimensions, aquifer properties, and boundaries as the IDWR model.

The study was conducted as part of a graduate Hydrology course at the University of Idaho with technical cooperation from Idaho Department of Water Resources, and the U.S. Geological Survey. Funding for publication of this report was contributed by the Idaho Water Resources Research Institute.

STUDY OBJECTIVES

The study has two general objectives:

1) To provide an efficient technique for evaluating the effects of Snake River Plain aquifer water use on flow in the Snake River, and
2) To apply the technique at various locations in the plain to provide estimates of time-varied river impacts.

The specific objectives of the study include:

1) To develop a ground-water flow model which simply and accurately predicts impacts of water use in the Snake River Plain on flow in the Snake River.
2) To verify and demonstrate the utility of the approach to others interested in similar applications.
3) To predict time-varied effects of water use at strategic locations within the plain on the flow in the Snake River.
4) To make predictions easily understandable and sufficiently generic that they may be applied to many situations, independent of the magnitude of the pumping or change in water use.
5) To identify and describe the deficiencies and assumptions that underlie this and similar modelling efforts.
6) To recommend future investigations to further the understanding of water-use interactions in the Snake River basin.

HYDROGEOLOGIC FEATURES

Flow System Description

Regional ground water flow is primarily from the northeast to southwest throughout most of the Plain. Near the margins, tributary underflow contributes substantial recharge to the Snake River Plain aquifer and flow has a direction more toward the center of the plain (Figure 1). Water-table gradients vary from 3 to 100 feet per mile, averaging 12 feet per mile (Lindholm, 1986). The Snake River channel is a topographic low and is the major control on depth to ground water along its reach with exception of the reach north of Blackfoot and from Lake Walcott to Milner (Lindholm, 1986). In general, the depth to ground water increases with distance from the Snake River. The depth varies from less than 50 feet near Egin Bench, Mud Lake and northeast of American Falls Reservoir, to over 1000 ft near Craters of the Moon National Monument.

Recharge to the Snake River Plain aquifer results from irrigation losses (about 60%), losses from the Snake River (10%), tributary ground-water underflow (14%), precipitation (8%), and seepage from streams and canals (6%) (Garabedian, 1986). Ground water flow is primarily horizontal in the center of the Plain, but has a downward component near recharge areas and tributary aquifers and an upward component of flow at discharge sites. Aquifer discharge to the Snake River from Milner to King Hill has increased from 4100 cfs in the 1920's to a high of 6800 cfs in the 1950s, and has subsequently decreased to about 6000 cfs in 1980 (Kjelstrom, 1986). The increased discharge prior to 1950 was due to increased recharge from surface irrigation losses to the aquifer. The decrease in flow since the 1950's has resulted from increased ground-water pumpage, climatic variations, and decreases in recharge from irrigation resulting from more efficient irrigation practices.

Aquifer Characteristics

The Snake River Plain exists in a structural downwarp 30 to 60 miles wide, arcing 370 miles through southern and eastern Idaho. Geologically, the Plain is composed of 2,000 to 10,000 feet of Quaternary basalt overlying extensive rhyolitic deposits. The Snake River Plain aquifer flows through numerous, relatively thin, interfingering basalt flows, typically with an areal extent of 50 to 100 square miles. Some of the basalt flows were historically exposed at the surface long enough to collect sediment deposited by streams, floods, and wind. These sediment deposits are referred to as sedimentary interbeds.

Structural characteristics of individual basalt flows generally control the movement of ground water. Vesicular, highly-fractured flow tops and fractured flow bases form the most permeable zones of the aquifer, while the dense, massive central portion of the basalt flows may have very low permeability.

Sedimentary interbeds also have a significant impact on aquifer properties. In general, they have lower hydraulic conductivities than the surrounding basalts, and on a large scale, sedimentary layering results in predominantly horizontal water flow. On the local scale, water movement is affected by fractures which can introduce significant vertical flow components.

Transmissivity of the Snake River Plain aquifer is highly variable, typically ranging from 1,000 to 100,000 ft^2/day (Whitehead, 1986). In areas of thick, fractured basalt, transmissivity of the aquifer can be extremely high. However, in areas where sediments predominate, the transmissivity may be much lower.

Storage coefficients determined from aquifer tests vary from 10^{-5} to 10^{-1}, indicating that aquifer conditions range from confined to unconfined (Whitehead 1992). As a whole, the aquifer behaves as an unconfined system, but clay layers and dense, unfractured basalt are locally confining. Because it behaves as an unconfined aquifer over large scales, modeling the aquifer as an unconfined is appropriate.

The Snake River Plain Aquifer is very complex due to the heterogeneous characteristics, although these features tend to average out at large scales, creating the image of a nearly homogeneous flow system.

Aquifer Boundaries

The highly permeable Quaternary basalt flows that comprise most of the Snake River Plain aquifer are bounded sedimentary and Tertiary rocks forming mountains to the north and east (Figure 1). The southwest margin of the plain, as interpreted by Whitehead (1986) extends south of the Snake River in the area between Lake Walcot and King Hill. The eastern Snake River Plain is separated from the western Plain by a drainage divide from the northern boundary of the Plain to the Snake River at King Hill.

The mountainous boundaries on all sides are dissected by streams. Streams on the north side of the plain (except Big Wood and Little Wood Rivers) are generally not directly tributary to the Snake River. Streamflows are either consumptively used for irrigation or seep into the alluvial materials of the tributary valleys and the basalts of the Snake River Plain. Streams on the east and south sides of the plain are directly tributary to the Snake River. Local aquifer systems in the tributary alluvial valleys discharge into the Snake River Plain aquifer. At the base of the valleys, alluvial sediments interfinger with the Snake River Plain basalt and ground-water from the alluvium merges with the regional Snake River Plain aquifer.

MODEL DESCRIPTION AND DATA DEVELOPMENT

Model Codes and Conceptual Description

The Idaho Department of Water Resources (IDWR) model of the Eastern Snake River Plain aquifer has been used for planning purposes for many years. The finite-difference model was originally developed and documented by De Sonneville (1974). Since conception, the model has undergone several modifications and recalibrations. The most recent model documentation is provided by Johnson and Brockway (1983). Some changes in model code have been implemented, but not documented since the publication by Johnson and Brockway (1983).

The conceptual model employed by the State in the IDWR model has changed little since the development by DeSonneville (1974). Even though concepts have changed little, the input values representing aquifer properties have been changed several times as improved data becomes available. The current calibration of aquifer properties is based largely on information collected during the U.S. Geological Survey's Regional Aquifer Systems Analysis Program in the early 1980's.

The aquifer properties, boundary configuration, and recharge and discharge inputs to the IDWR model served as basis of this investigation. Model inputs were reformatted to use the more widely accepted, U.S. Geological Survey's, MODFLOW code (documented in McDonald and Harbaugh, 1988). The MODFLOW simulations used identical simulation conditions as those of the IDWR model in use on April 1, 1993. No changes were made to grid locations, aquifer transmissivity and storativity, river interconnection, and aquifer boundaries.

The model boundaries and grid system employed in both models are illustrated in Figure 2. The entire block-centered grid employs 55 columns in ascending order from west to east, and 40 rows in ascending order from south to north. Each grid cell is square, with side dimensions of 16,404 feet. The origin of the grid is located at 42°14'48" latitude and 115°04'21" longitude. The ordinate is oriented parallel to the central meridian of Universal Transverse Mercator zone 12 (111° longitude) (Johnson, Brockway, and Lindgren; 1985).

The Snake River interaction with the ground water is simulated identically in both models. Reaches of the river are either classified as perched above the aquifer, or hydraulically connected with the Snake River Plain aquifer. In areas where the river is perched above the aquifer, no interaction with the aquifer exists. Hydraulically connected reaches of the Snake River (Figure 2) are considered to be a direct reflection of the elevation of the water table (e.g. fixed head nodes). In reaches around American Falls, and in the Kimberly to King Hill reach, the elevation of springs are considered the surface expression of water table. Four hydraulically connected reaches of the Snake River are simulated:

1) From the "Above Blackfoot" river gage to the gage identified as "Near Blackfoot",
2) from the "Near Blackfoot" gage to Neeley,
3) from Neeley to Minidoka, and
4) from Kimberly to King Hill.

Model boundaries are consistent between the IDWR and MODFLOW models. In some areas the boundary is formed by the hydraulically connected Snake River (Figure 2). In all other locations a no flow boundary is assumed. The validity of the boundary assumptions are discussed in the chapter on "Validity of Results".

Data Validation

Identical input conditions were run in the IDWR model and MODFLOW to verify that correct data reformatting was achieved and that both model codes produce comparable results.

A transient, base-study data set, currently used by IDWR, served as the basis for comparison of the two models. Input data for the IDWR model were provided by Mr. John Lindgren of IDWR in the following computer files:

Basic Simulation Conditions	BASE_1.DAT
Storage and Hydraulic Conductivity	FINAL.PAR
Recharge and Discharge	SPC_FLUX.DAT

A comparison simulation was run using the IDWR ground-water model with the following changes incorporated:

Number of timesteps:	Changed from 24 to 10. Stress periods were used in MODFLOW corresponding to timesteps in the IDWR model.
Total simulation time:	Changed from 365 to 152 days.
River stage:	Time variant conditions of the IDWR model changed to constant for all reaches.
Recharge and discharge:	Cumulative value for each node and timestep input as "Well term" in MODFLOW. Signs were reversed to accommodate model conventions.

The resulting MODFLOW input files and altered IDWR model input files are available on request. The MODFLOW input files included input for the *BASIC* package, the *BLOCK CENTERED FILE*, the *WELL* package, and *OUTPUT CONTROL FILE*.

Simulation results from equivalent model inputs were compared for the IDWR and MODFLOW model codes. Differences in head values resulting from simulation of 10 time periods, representing 152 days, were determined. Simulated heads from the two model codes, with equivalent input conditions, differed by as much as 39 feet. Input values of recharge and discharge, hydraulic conductivity, aquifer thickness, and boundary conditions were checked and found to be the same in both model data sets. The differences in simulated head are, therefore, likely the result of different model conventions for averaging transmissivity between model node points.

The IDWR model and MODFLOW employ different concepts in distributing and averaging transmissivity between adjacent node points. MODFLOW applies the concept that hydraulic conductivity is constant within grid cells which extend halfway between node points. The IDWR model assumes that hydraulic conductivity varies linearly between the input values for specific node points. The resulting equations for calculating average transmissivity between nodes points are as follows:

for the IDWR Model:

$$T_{avg} = (T1-T2) / \mathrm{Ln}(T1/T2) \quad ,$$

and for MODFLOW (assuming uniform, square grid):

$$T_{avg} = 2 / (1/T1+1/T2) \quad ,$$

where T1 and T2 represent transmissivity at any two adjacent grid points, and T_{avg} represents the model computed transmissivity between grid points.

The different assumptions result in lower average transmissivities between node points in the MODFLOW model, where transmissivity greatly varies between adjacent node points or cells. For example, average transmissivities for several degrees of transmissivity variation between adjacent nodes are calculated as shown in Table 1.

Table 1. Comparison of Node-Averaged Transmissivities

		Average Transmissivity	
T1	T2	IDWR Model	MODFLOW
10	10	10	10
10	20	14	13
10	100	39	18
10	1000	215	20

It cannot be concluded with complete certainty that transmissivity averaging accounts for the differences in IDWR and MODFLOW simulations, unless the code of one of the two models is changed and the simulated head values are again compared. Differences in model convergence criteria may also result in small simulation differences between the two models.

The differing transmissivity averaging technique affects the predictions of well pumping on Snake River losses. MODFLOW, which was used to develop the predictions of this study, will consistently over-estimate (increase) the time required for river impacts, when compared to the IDWR model. The difference between the two models, however, is not expected to be significant with respect to errors induced by other factors discussed in a following chapter on "Validity of Results."

Description of Predictive Simulations

This study is designed to predict changes in flow of the Snake River over long time periods in response to changes in water use on the Snake River Plain. A model which is simulating only the effects of changes in water use is termed a superposition model by Reilly and others (1987). The results are applicable to any water use change that results in changes in the rate water is recharging to or discharging from the aquifer. The results are generic in the sense that they do not address impacts of specific water users, but may be applied to any individual or group of users.

Simulations were conducted under conditions of an initially flat water table, with no aquifer recharge or discharge and with the Snake River at the same elevation as the water table. Under this condition, there is no gradient between the river and the aquifer, and therefore no water movement between the aquifer and river. Individual water use effects were evaluated by simulating withdrawal of water from selected locations in the aquifer. Simulated drawdown propagates outward from the source of withdrawal until the cone of depression reaches the Snake River. Water is then removed from the Snake River in proportion to the amount of aquifer drawdown adjacent to the river. The impacts increase with time until nearly all of the aquifer withdrawals are being extracted from the river. This type of simulation (superposition) is effective for showing changes due to individual water use activities.

The simulation results from flat water table simulations are identical to those that would be achieved by simulating the actual slope of the water table and the numerous recharge and discharge events that are continually occurring. The flat water table simulation does not require the use of a "base simulation" to establish conditions without the existence of the activity under examination. The simulation results are simplified because only a single recharge or discharge event is occurring at all times.

Simulated effects of water use on flow of the Snake River are the same, regardless of whether the river is gaining water from, or losing water to the aquifer. Ground-water use results in a decline in the water table which may have either of two effects, depending on the specific conditions existing at any location. If the ground-water is recharging the river at the location of interest (such as at the Thousand Springs area), then a decline in the water table results in a decrease in the hydraulic gradient to the river or springs, and a decline in discharge. If the river is normally losing ground-water to the aquifer through seepage, then the amount of seepage will increase as a result of a lower water table and increased hydraulic gradient away from the river. In either situation, the normal flow of the river is depleted by the same amount.

Input Changes to Simulate Effects Under Flat Water Table Conditions

The input data set to the MODFLOW model was altered to achieve the initially flat water table conditions required for prediction of ground-water pumping impacts on the Snake River. The following is a list of changes made in the MODFLOW verification data set to conduct predictive simulations:

1) Initial head at all model nodes was set equal to 4000 feet. This automatically establishes the head of Snake River fixed head nodes to same value.
2) All recharge to and discharge from the Snake River Plain aquifer was set to zero. This maintains the water-table in a level situation except for the effects of the single induced stress.
3) The simulation conditions were changed from unconfined to confined, without altering storativity. Additionally,

transmissivity of each node point was calculated as the product of hydraulic conductivity and the difference between the original water table elevations and estimated elevation of the bottom of the aquifer (included in original input data).

4) Two MODFLOW stress periods with 50 uniform timesteps of one year duration were used.
5) A single well discharging 10,000,000 cubic feet per day (115 cfs) was simulated at the selected water use site. The magnitude was established such that pumping impacts would be substantially greater than numerical errors. The location of the water use site was varied to examine impacts at different locations.

SIMULATION RESULTS

Presentation Concepts

Simulations were conducted to predict effects of water use on the Snake River Plain on the flow in four reaches of the Snake River (Figure 3). The four reaches were established to be consistent with reaches used in the IDWR Snake River Plain model. In both models, these four reaches are the only surface water sources simulated as interconnected with the Snake River Plain aquifer. The reaches are identified in the IDWR Model by the following numeric code:

Above Blackfoot to Near Blackfoot	Reach 1,
Near Blackfoot to Neeley	Reach 2,
Neeley to Minidoka	Reach 3,
Kimberly to King Hill	Reach 4.

The end points of each reach are established by the location of U.S. Geological Survey river gaging stations. Each river reach is represented in the model as a series of grid points, approximately corresponding to the geographic location of the reach. Results are presented as a series of graphs illustrating the effects of any individual water use simulation on flow in each of the four river reaches and a curve representing the cumulative effect on the river. The cumulative effect curve is the sum of the curves representing effects on the four individual river reaches.

Graphical results are presented which show how river flow is impacted by water use at different locations in the Snake River Plain. Eighteen water use sites were selected throughout the Plain (Figure 3). Eighteen figures are presented, each representing effects from water use at a specific location in the Snake River Plain (Figures 4 through 21). The location of the 18 selected sites was determined based on either a) the presence of significant water use in the area, b) significance to Trust and Non-Trust areas established in the Swan Falls Agreement, c) proximity to tributary basins to the Snake River Plain, or d) to fill in large gaps in the areal distribution presented by the previous conditions. The site

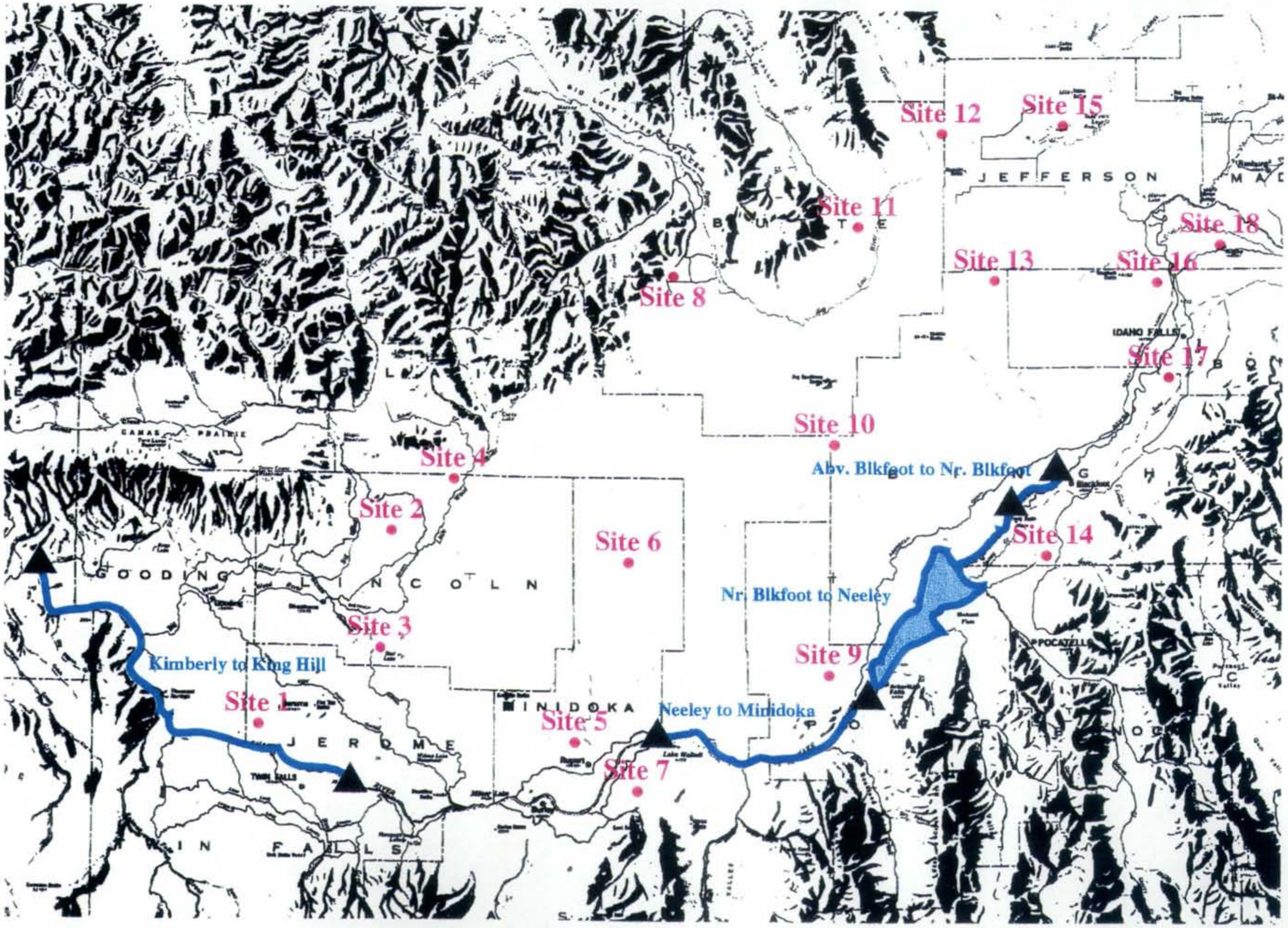

Figure 3. Location of Water Use Sites and River Reaches Used in Predictive Simulations.

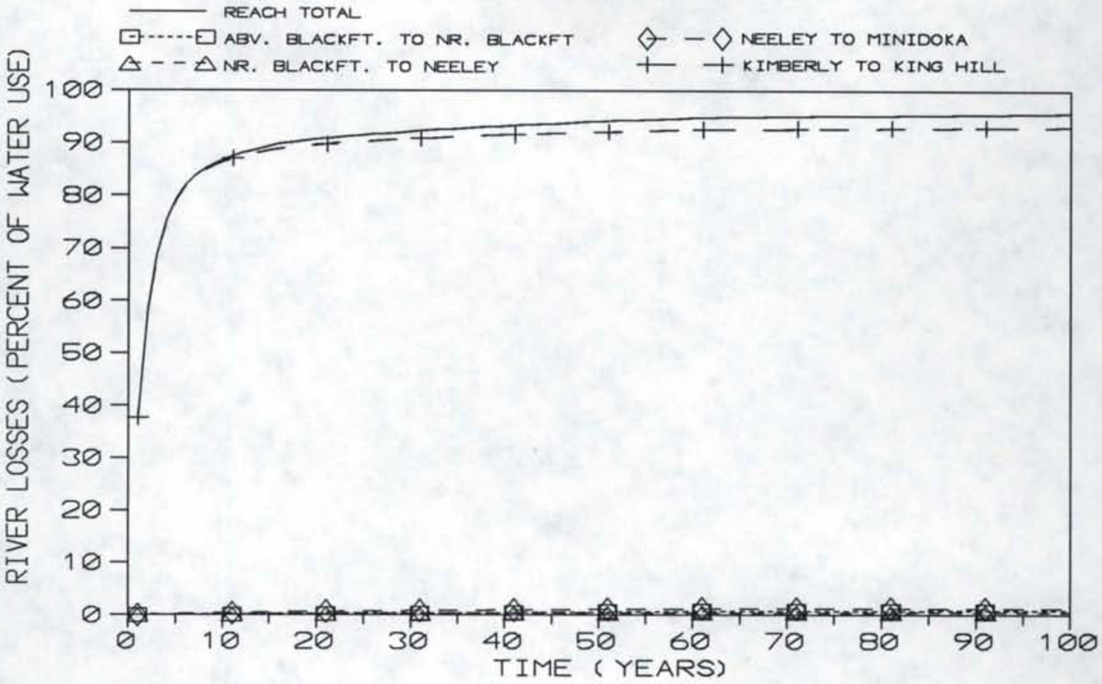

Figure 4. Snake River Losses Resulting From Water Use At Site 1.

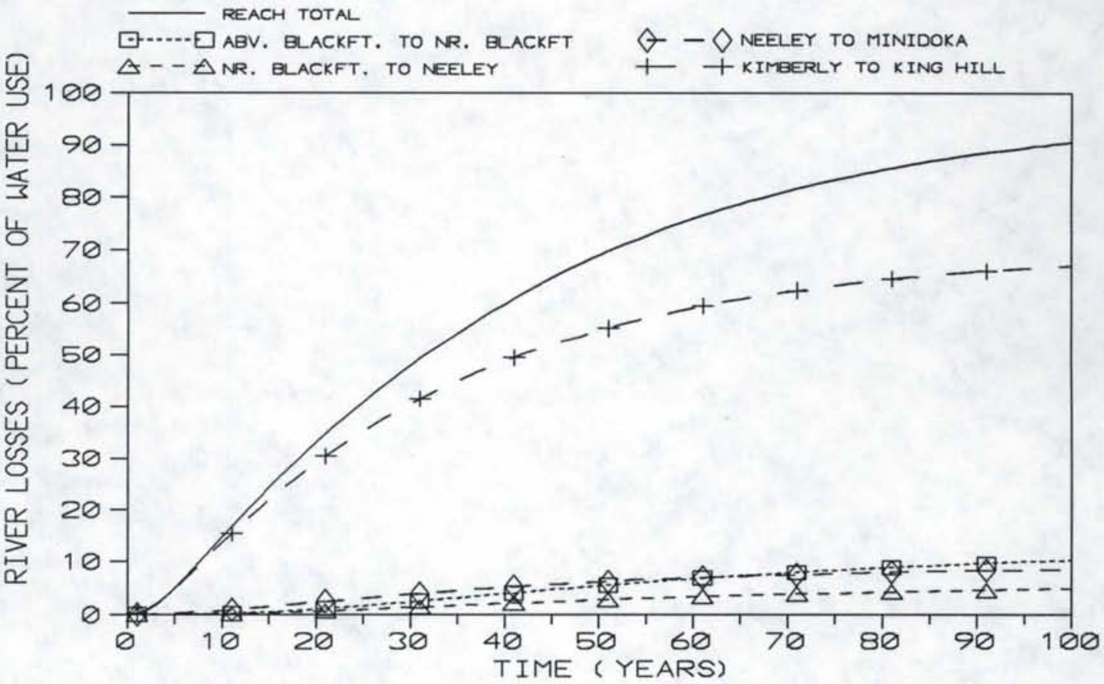

Figure 5. Snake River Losses Resulting From Water Use At Site 2.

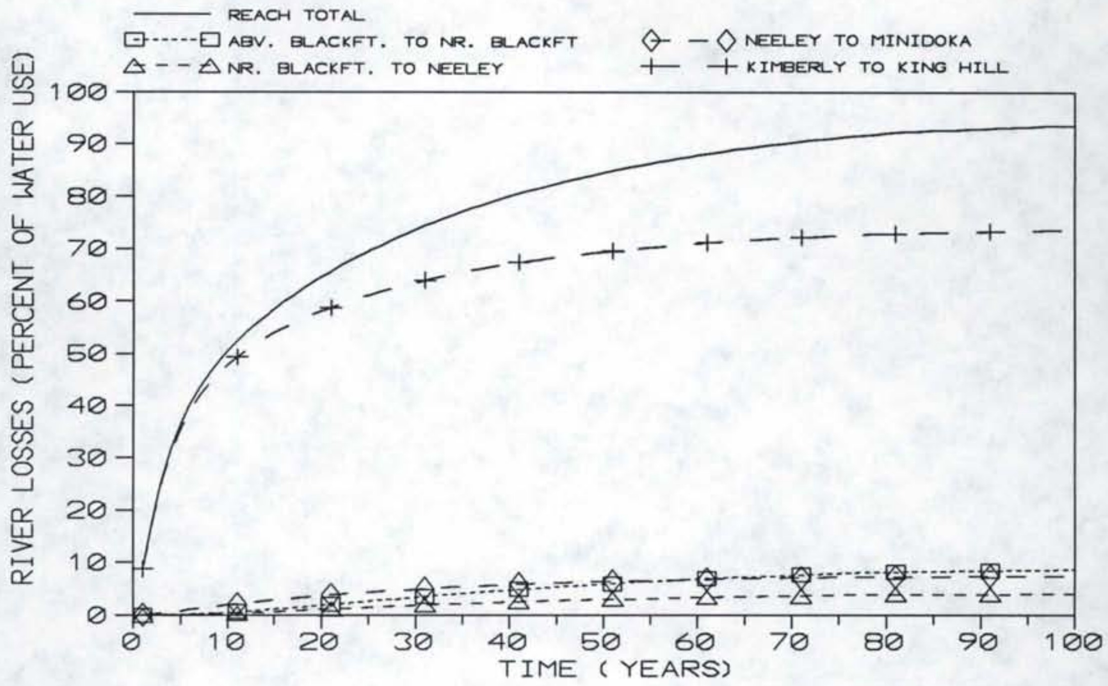

Figure 6. Snake River Losses Resulting From Water Use At Site 3.

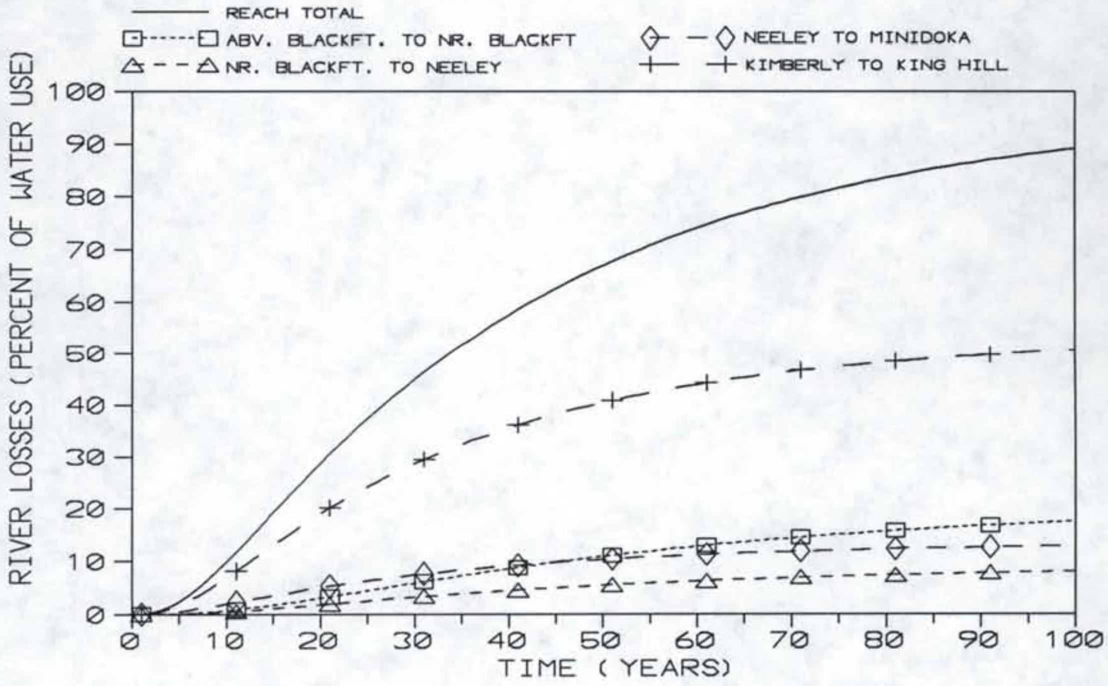

Figure 7. Snake River Losses Resulting From Water Use At Site 4.

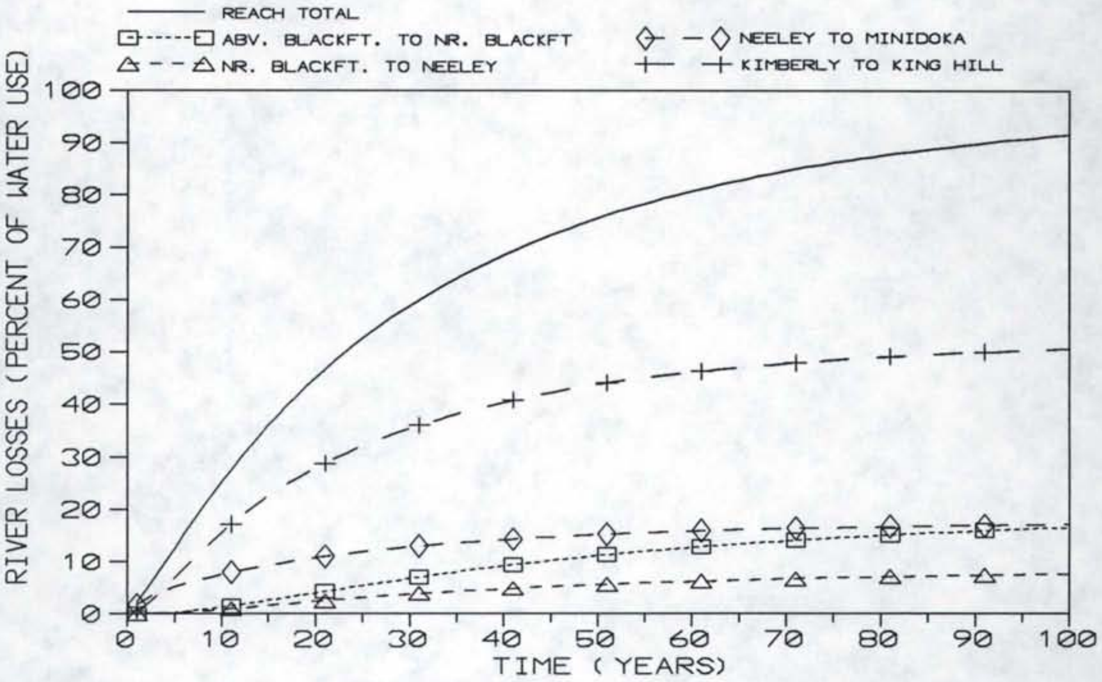

Figure 8. Snake River Losses Resulting From Water Use At Site 5.

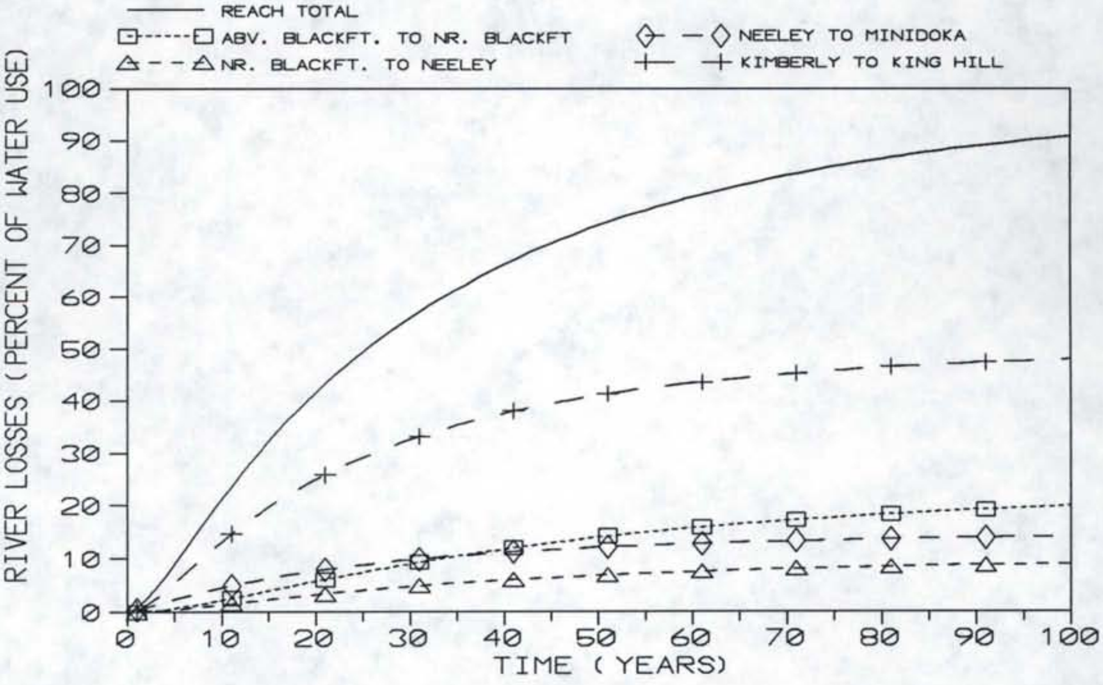

Figure 9. Snake River Losses Resulting From Water Use At Site 6.

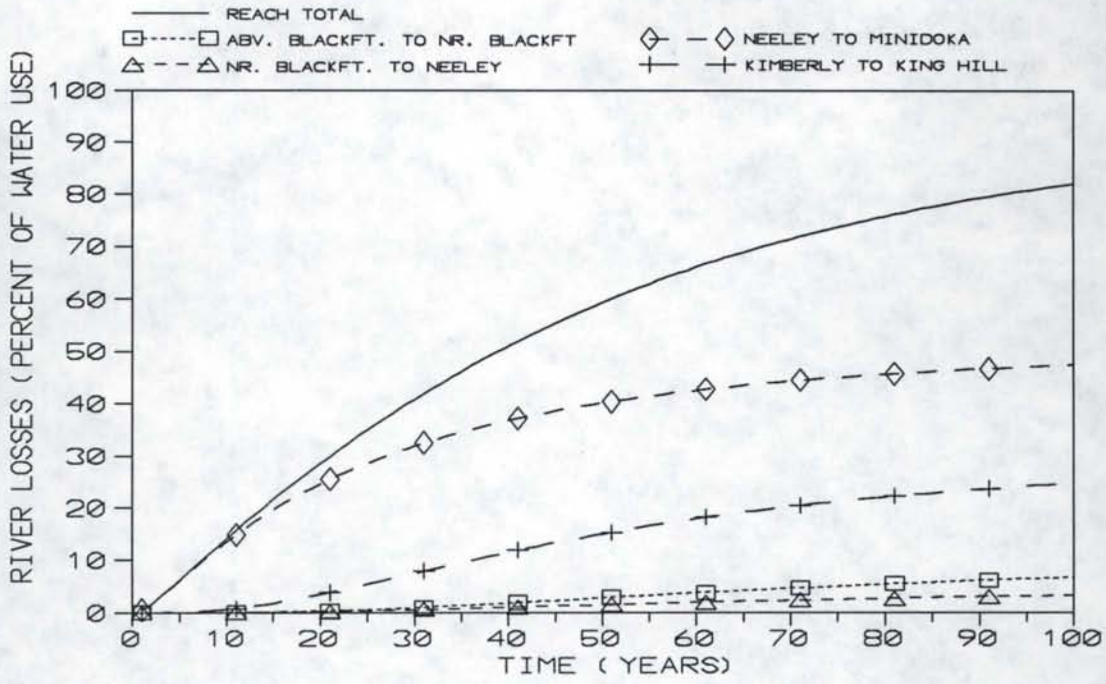

Figure 10. Snake River Losses Resulting From Water Use At Site 7.

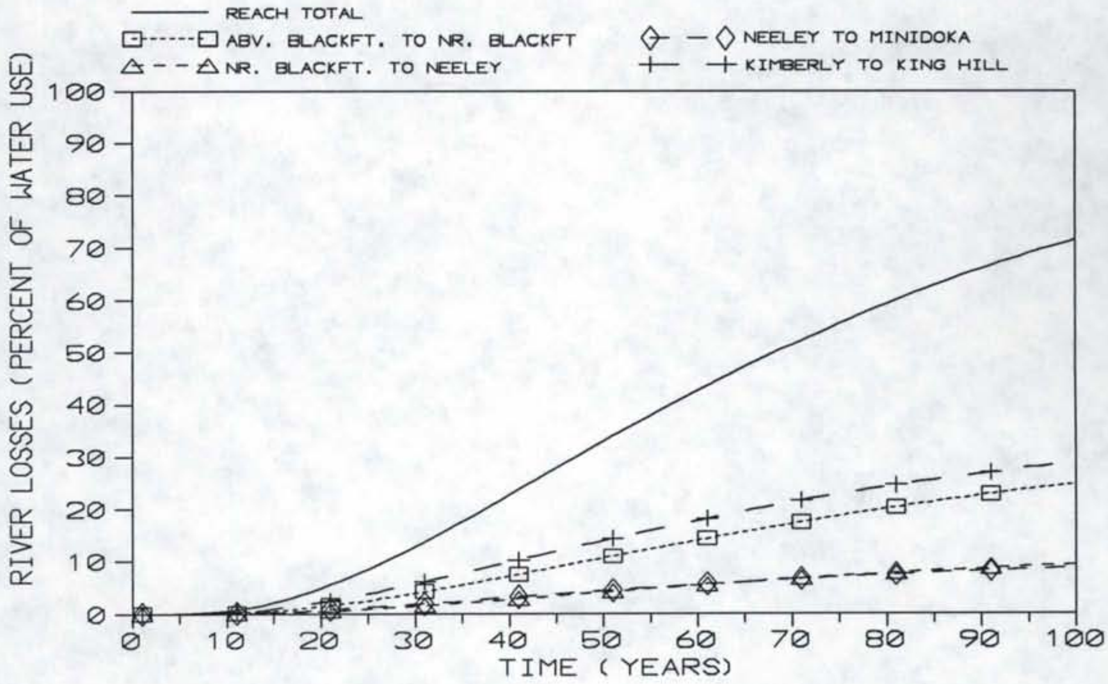

Figure 11. Snake River Losses Resulting From Water Use At Site 8.

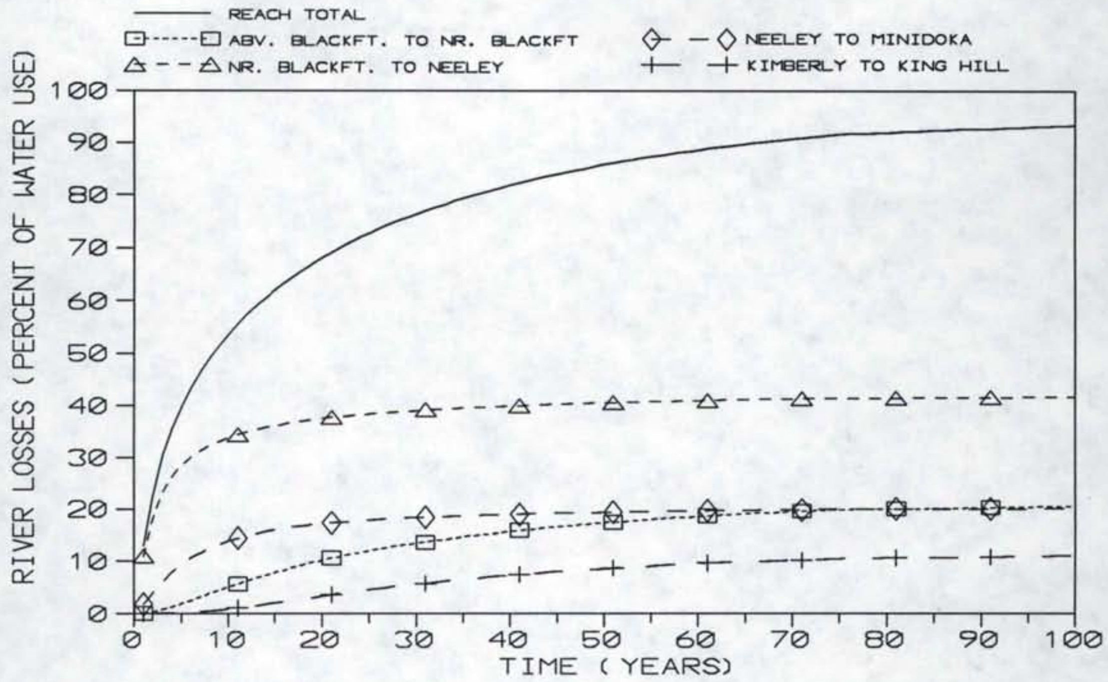

Figure 12. Snake River Losses Resulting From Water Use At Site 9.

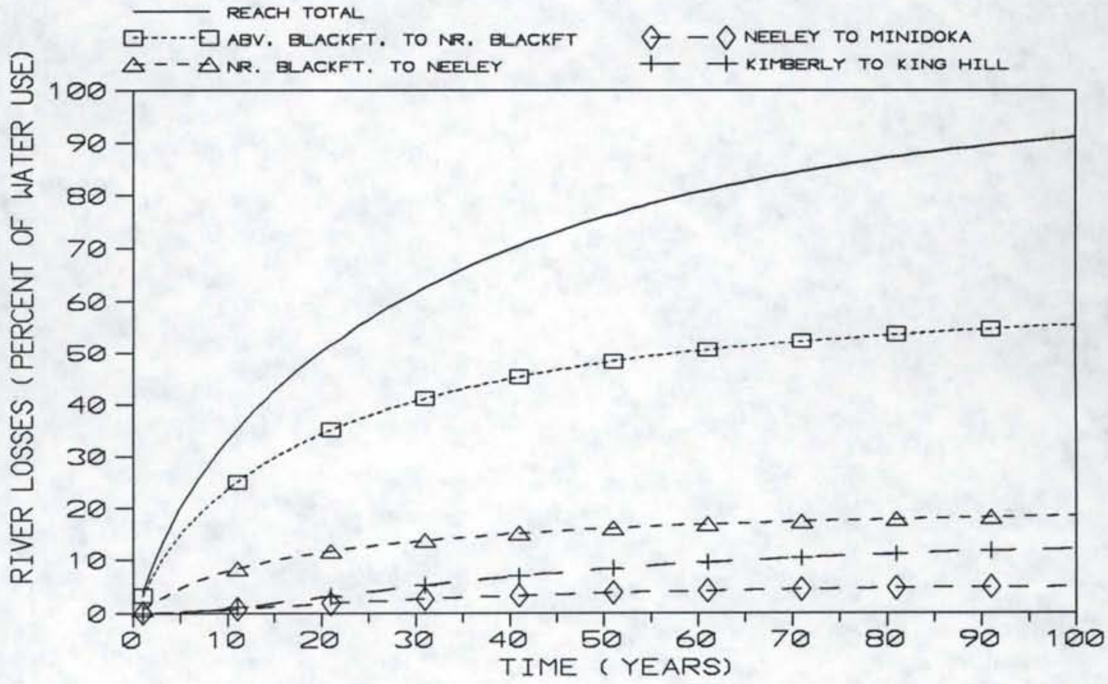

Figure 13. Snake River Losses Resulting From Water Use At Site 10.

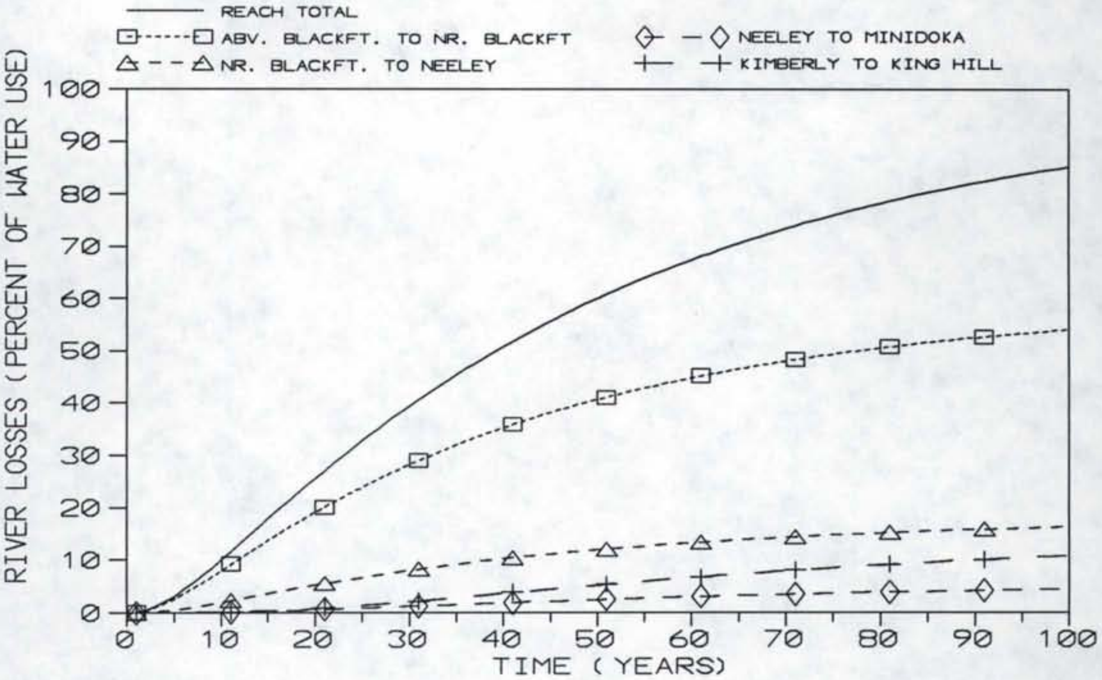

Figure 14. Snake River Losses Resulting From Water Use At Site 11.

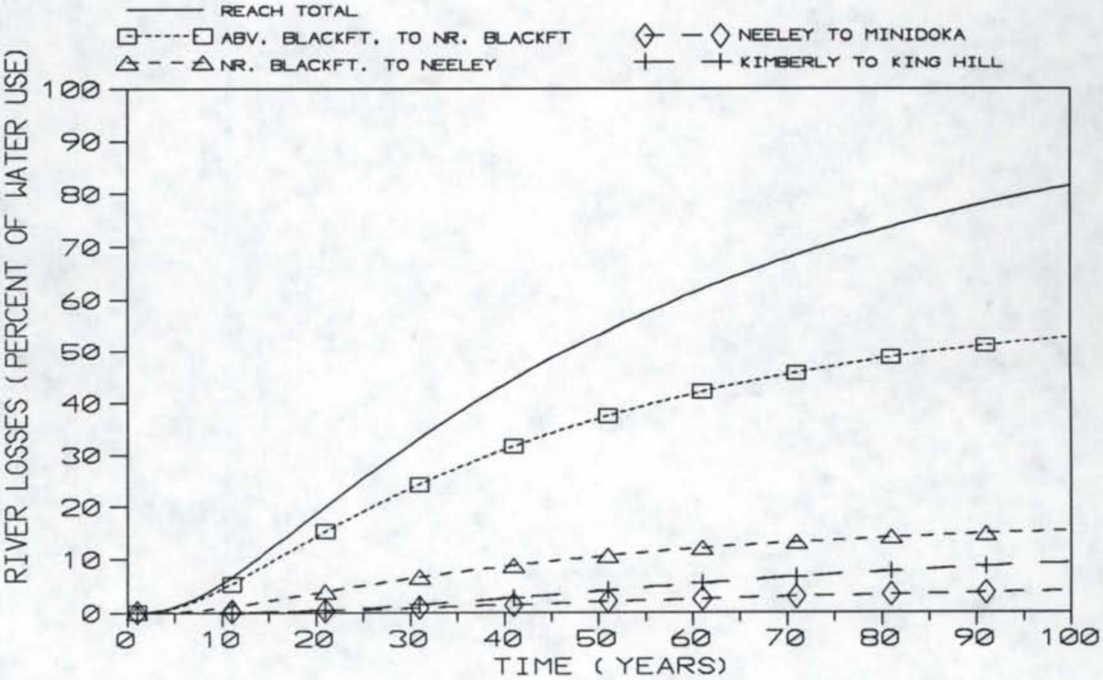

Figure 15. Snake River Losses Resulting From Water Use At Site 12.

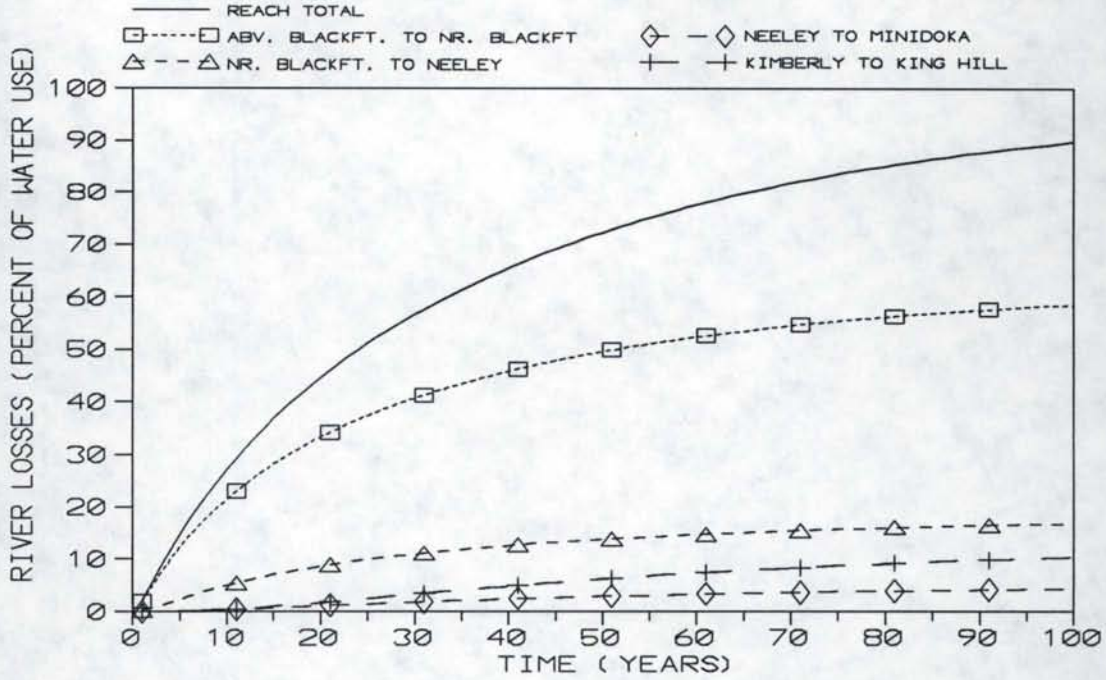

Figure 16. Snake River Losses Resulting From Water Use At Site 13.

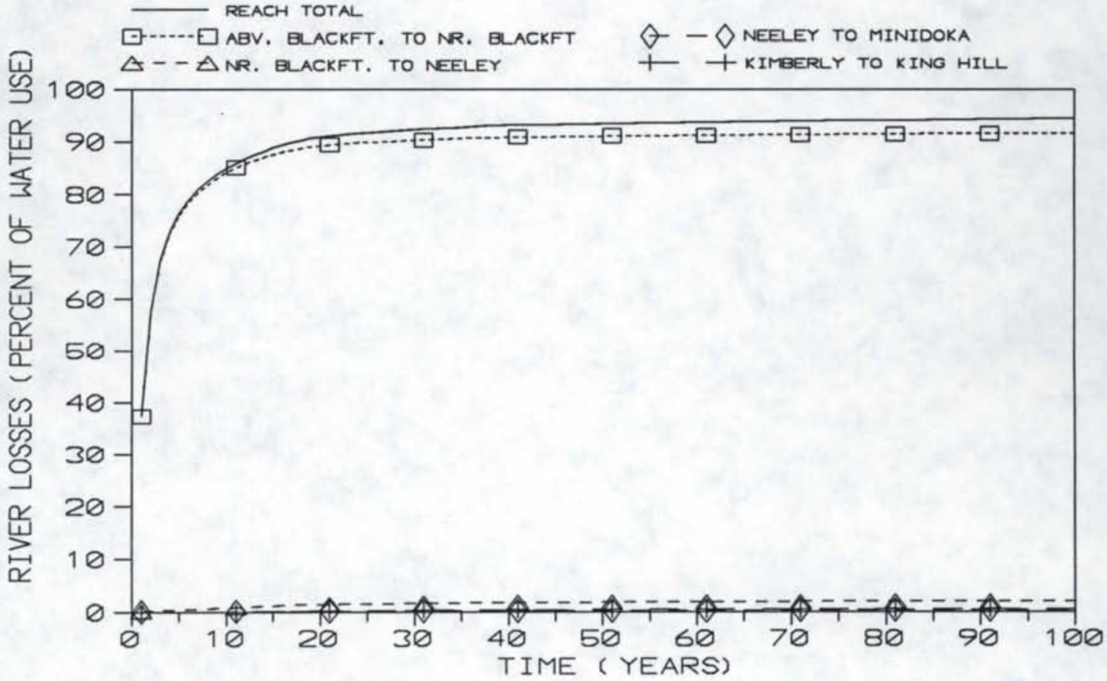

Figure 17. Snake River Losses Resulting From Water Use At Site 14.

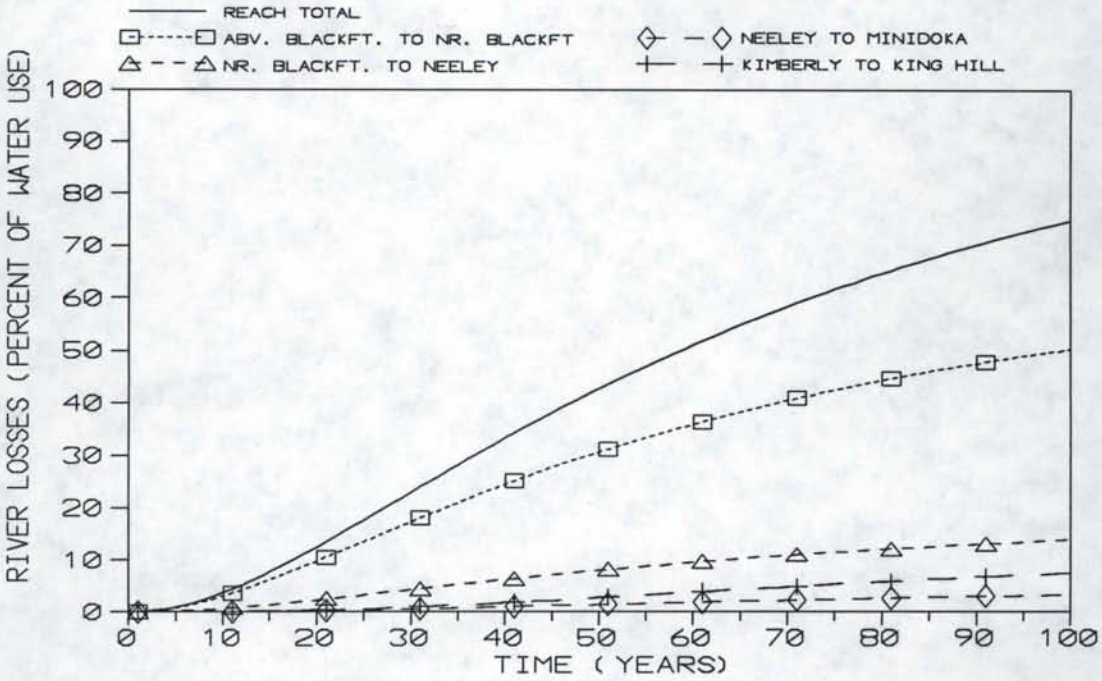

Figure 18. Snake River Losses Resulting From Water Use At Site 15.

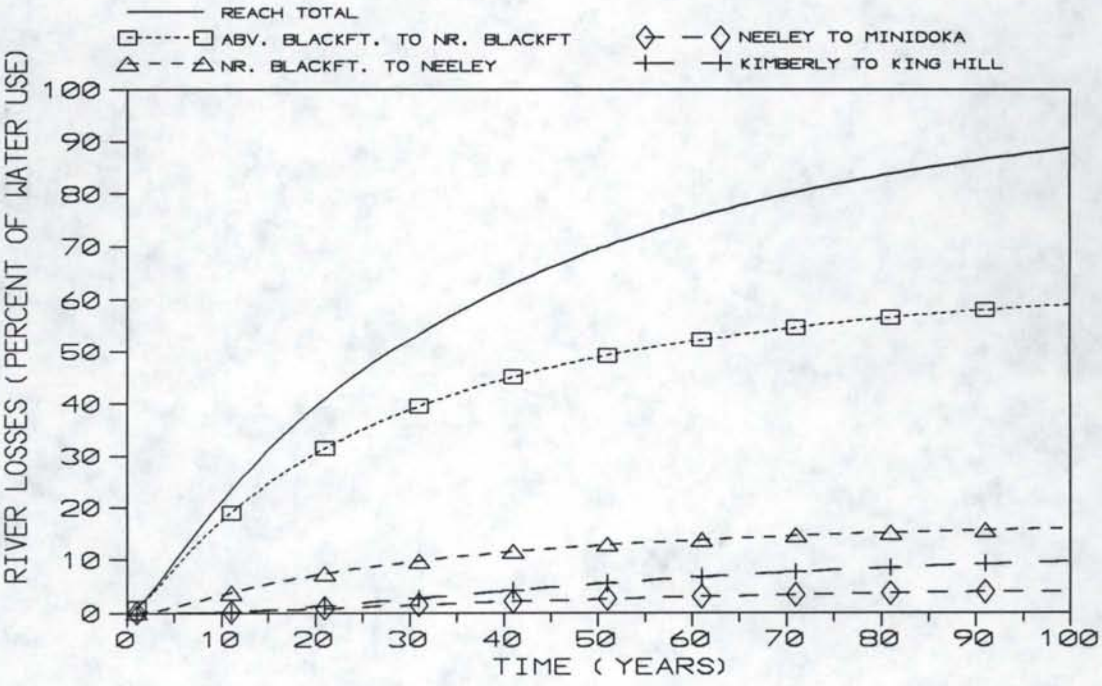

Figure 19. River Losses Resulting From Water Use At Site 16.

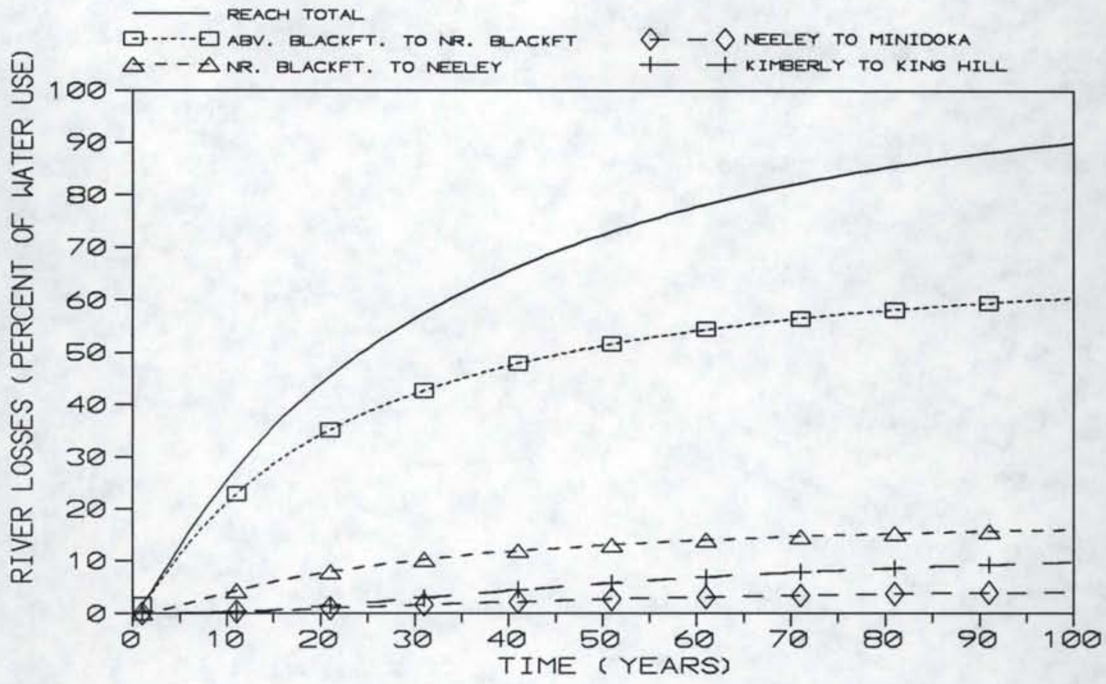

Figure 20. Snake River Losses Resulting From Water Use At Site 17.

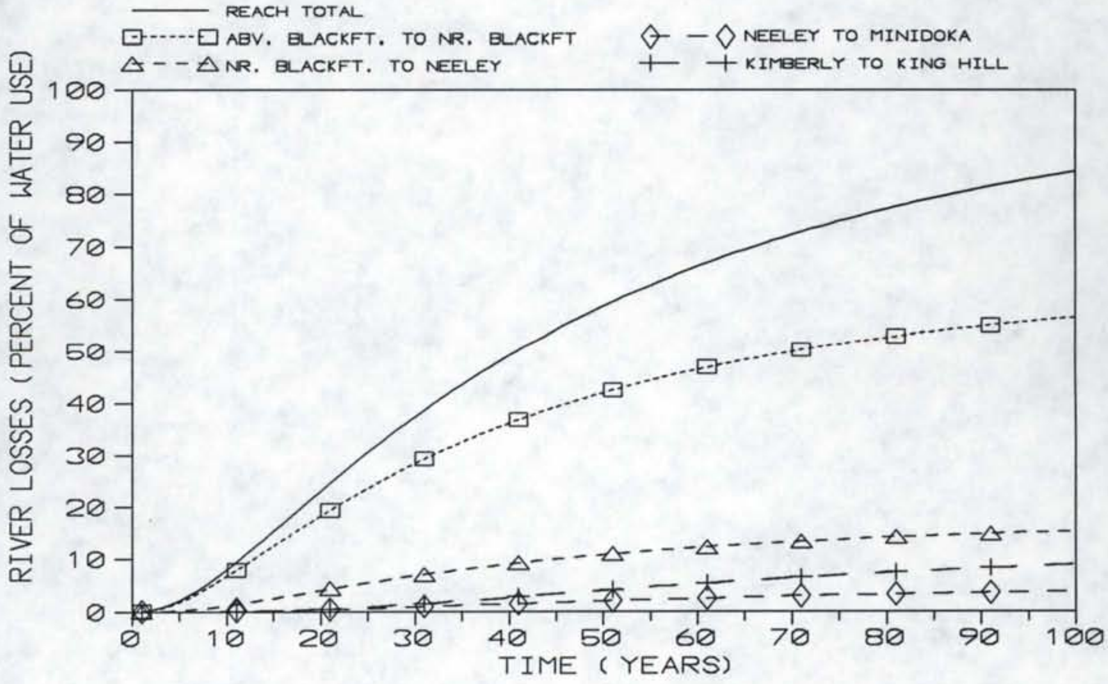

Figure 21. Snake River Losses Resulting From Water Use Site 18.

representations and model grid coordinates are as presented in table 2.

Table 2. Water Use Locations and Representation

Site	Grid Coordinates Row	Col.	Township, Range	Representation
1	10	9	8S,16E	3 mi. W. of Jerome
2	18	14	4S,18E	Mouth of Camas Creek
3	13	14	6S,19E	6 mi. SE of Shoshone
4	20	17	4S,22E	Mouth of Little Wood
5	9	23	8S,23E	3 mi. N. of Rupert
6	16	25	4S,24E	24 mi. NE of Rupert
7	5	25	10S,24E	Mouth of Raft River
8	29	28	3N,26E	Mouth of Big Lost
9	11	34	7S,29E	12 mi. W. of Am. Falls
10	21	35	2S,29E	33 mi. NW of Pocatello
11	31	36	5N,30E	Mouth of Birch Creek
12	35	40	7N,32E	Near Birch Creek
13	28	42	3N,33E	24 mi. W. of Idaho Falls
14	16	45	4S,35E	6 mi. N. of Pocatello
15	36	45	7N,35E	6 mi. NE of Terrington
16	28	49	3N,37E	6 mi. NW of Idaho Falls
17	24	49	1N,37E	6 mi. S. of Idaho Falls
18	30	51	4N,39E	Near Lorenzo

Effects on the Snake River are expressed as a percentage of the rate of water use at the specific locations on the Snake River Plain. The depletion of flow in the Snake River is proportional to the magnitude of the water use. The proportionality concept is nearly ubiquitous in ground-water flow theory. Darcy's Law provides for flow in proportion to hydraulic gradient, and the Theis equation defines pumping drawdown as proportional to well discharge. Since the ground-water flow equation, and the finite-difference representation in the model are based on Darcy's Law, it follows that drawdowns and interchange between the aquifer and river will be proportional to the magnitude of induced stresses, or water use. The proportional relationship is valid as long as springs discharging to the river do not dry up, and the river does not become perched above the Snake River Plain aquifer.

The presented graphs may be applied to individual water uses or may be applied to predict cumulative effects of multiple, simultaneous water uses. The effects of individual uses are additive, consequently, the cumulative effect of multiple water use activities is the sum of the individual effects. For example, if the combined effects of all ground-water pumping were of interest, it would be possible to sum the effects of pumping in a series of blocks representing the areal and temporal distribution of the pumping activities.

The river depletion graphs can be applied to most locations and water use activities in the Snake River Plain. For example, Figure 4 shows how river flow in each of the four reaches may be depleted over time after the onset of pumping at a location near Site 1, which is located three miles west of the City of Jerome. The horizontal scale of the graph represents the time since pumping began. The vertical scale represents the amount of losses that the Snake River is expected to suffer, expressed as a percentage of the water use. That is if water is pumped at a continuous (or average annual) rate of 10 cfs at Site 1, then according to figure 4, after 10 years of pumping, the flow in the river would be 8.7 cfs (87 percent of 10 cfs) less than it would be if no pumping had ever occurred at Site 1.

The "Water Use" term used in the graphs may represent any of several activities. In concept, it represents a change in the amount of water recharging or being withdrawn from the Snake River Plain aquifer at a specific location. It may represent ground-water pumped and consumptively used for irrigation or other purposes. It may represent the diminished ground-water recharge resulting from more efficient irrigation practices such as conversion from surface to sprinkler irrigation. When taken as recharge impacts, "water use" may represent the increase or gain in the Snake River resulting from artificial recharge of the aquifer at a specific location. If water use is interpreted as ground-water pumping for irrigation; then it is important that the effects be determined based on the amount of water used by the crop, not the amount pumped; since about 20 percent of the pumpage may return to the ground-water as deep percolation. In summary, "Water Use" as applied in this report may represent any activity that results in a change in aquifer recharge or discharge.

Evaluation of Irrigation Pumping Impacts

Eleven sites were chosen to illustrate the impacts of ground-water pumpage on the Snake River. Of the sites presented in Figure 3 and listed in Table 2, the following are used to illustrate the effects of ground-water pumping: Sites 1, 3, 5, 9, 14, 15, 16, and 17. The areal distribution of these sites was chosen to represent areas employing relatively large rates of ground-water pumping. The sites were chosen based on the irrigated acreage and well locations presented by Bigelow, Goodell and Newton (1987). Most of the ground-water pumpage occurs near the edges of the plain. Those areas adjacent to tributary streams entering the plain are discussed in the section on tributary valleys.

Site 1 is located about 3 miles west of Jerome (Figure 3). The depletion graph for this well is presented in Figure 4. The spring flows in the Kimberly to King Hill reach of the Snake River are depleted by fifty percent of the pumping rate after about 1.5 years. Only about one percent of the water was derived from the three other reaches of the Snake River. After 100 years of water use, the total flow in the river at King Hill is reduced by about 95 percent of the water use rate. Spring flows in the Kimberly to King Hill reach are predicted to be reduced by about 93 percent of the water use rate at Site 1. The remaining 2 percent results from depletion of spring flows and increases in river seepage in the other three reaches.

Site 3 is located six miles southeast of Shoshone and the river depletion graph is presented in Figure 6. Total flow in the Snake River at King Hill is diminished by 50 percent of the water use rate at Site 3 after about 10 years. Spring flows in the Kimberly to King Hill reach are depleted by 46 percent of the water use rate. The other three Snake River reaches combined are depleted by less than 5 percent of the water use rate. After 100 years of water use, flow in the Snake River at King Hill (graph representing total river losses) is depleted by 95 percent of the water use rate. Spring flows in the Kimberly to King Hill reach are depleted by 72 percent of the water use rate at Site 3. River losses are increased (or river recharge decreased) to about 10 percent of the water use rate in the Above Blackfoot to Near Blackfoot reach and in the Neeley to Minidoka reach. River losses in the Near Blackfoot to Neeley reach are predicted to be about 5 percent of the water use rate.

Site 5 is located about 3 miles north of Rupert (Figure 3). The depletion graph for this well is presented in Figure 8. Total flow in the Snake River at King Hill (represented by the "Reach Total" curve) is depleted by 50 percent of the water use rate at Site 5 after about 23 years of water use. Spring flow in the Kimberly to King Hill reach is predicted to be depleted by about 30 percent of the water use rate. River losses in the Neeley to Minidoka reach are expected to increase by about 11 percent of the water use rate. Losses in the Above Blackfoot to Near Blackfoot, and the Near Blackfoot to Neeley reaches should increase by less than 5 percent of the water use rate at Site 5. After 100 years of water use, the river flow at King Hill is predicted to be depleted by 91 percent of the water use rate at Site 5. Spring discharge in the Kimberly to King Hill reach is expected to decline by about 50 percent of the water use rate.

Site 9 is located about 12 miles west of American Falls (Figure 3). The river depletion graph for this well is presented in Figure 12. Flow in the Snake River at King Hill is predicted to be depleted by about fifty percent of the water use rate after about 8 years of water use at Site 9. The Snake River reach between U.S. Geological Survey gaging stations Above Blackfoot and Near Blackfoot will be depleted by about 32 percent of the water use rate. The reach between Neeley and Minidoka will lose about 13 percent of rate of water use. After 100 years, the combined losses of all Snake River reaches (depletion in river flow at King Hill), represented by the solid line in Figure 12, will be about 93 percent of the water use rate at Site 9. About 38 percent of the water use rate will be compensated by lost flows from Blackfoot to Neeley, 17 percent from the reaches between Above Blackfoot and Near Blackfoot and the Neeley to Minidoka gages, and 8 percent from Kimberly to King Hill reach.

Site 14 is located about 6 miles north of Pocatello (Figure 3). The river depletion graph for this well is presented in Figure 17. Flow in the Snake River at King Hill will be depleted by about 50 percent of the water use rate after 12 years with nearly all of the water lost from the river reach between the Above Blackfoot and Near Blackfoot gaging stations. Losses in the other three reaches after 12 years will be less than 1 percent of the water use rate at Site 14. After 100 years of water use, 90 percent of the water use rate water is compensated by depletion of the Snake River in the Above Blackfoot to Near Blackfoot reach. The combined gains and losses in the remaining three river reaches are depleted by less than 3 percent of the water use rate.

Site 15 is located six miles northeast of Terrington. The river depletion graph is presented in Figure 18. Water use near Terrington results in a depletion of the Snake River flow at King Hill of 50 percent of the water use rate after about 59 years of water use. Most of the reduction in river gains or increase in the river losses (35 percent of water use rate) are expected in the Above Blackfoot to Near Blackfoot reach. After 100 years of water use, 74 percent of the water use rate is being compensated by depletion of the Snake River with about 50 percent from the Above Blackfoot to Near Blackfoot reach, 14 percent from the Near Blackfoot to Neeley reach, 3 percent from the Neeley to Minidoka reach, and 7 percent from the Kimberly to King Hill reach.

Site 16 is located about 6 miles northwest of Idaho Falls (Figure 3). The depletion graph for this site is shown in Figure 19. The flow in the river at King Hill (total losses for all reaches) is depleted by 50 percent of the water use rate after about 28 years, with 37 percent of the water use rate compensated by water obtained from the Above Blackfoot to Near Blackfoot reach. After 100 years of water use, 88 percent of the water use rate is compensated by losses from depletion of the Snake River, with 59 percent coming from the Above Blackfoot to Near Blackfoot reach, 16 percent from the Near Blackfoot to Neeley reach, 10 percent from the Kimberly to King Hill reach, and 5 percent from the Neeley to Minidoka reach.

Site 17 is located about 6 miles south of Idaho Falls. The river depletion graph for this well is presented in Figure 20. Flow in the Snake River at King Hill is predicted to be depleted by 50 percent of the water use rate at Site 17 after about 24 years of water use. Most of the depletion (38 percent of water use) results from losses in the Above Blackfoot to Near Blackfoot reach. After 100 years of water use, total flows are depleted by 90 percent of the water use rate. Sixty percent of the water use depleted in the Above Blackfoot to Near Blackfoot reach, 15 percent in the Near Blackfoot to Neeley reach, 9 percent of water use in the Kimberly to King Hill reach, and 5 percent in the Neeley to Minidoka reach.

Water Use from the Central Portion of the Snake River Plain

Pumping wells (or water use) were simulated at three sites located in the center of the plain (Sites 6, 10 and 13 in Table 2). Although no major water use exists in the area, these sites were included to provide a more uniform areal coverage across the plain.

Site 6 is located about 24 miles northeast of Rupert (Figure 3). The depletion graph for this well is presented in Figure 9. Half of the water use rate is compensated by total losses from all reaches of the Snake River above King Hill after 25 years of water use. After 100 years, 45 percent of the water use rate is being lost from the Kimberly to King Hill reach, 18% of the water use rate is lost from the Above Blackfoot to Near Blackfoot Reach, 12% from the Neeley to Minidoka reach, and 8% from the Near Blackfoot to Neeley reach.

Site 10 is located about 33 miles northwest of Pocatello. The depletion graph for this well is presented in Figure 13. Snake River flow at King Hill (curve representing total losses) is depleted by 50 percent of the water use rate after about 19 years of water use. After 100 years of water use, 91 percent of the water use rate is compensated by total losses from the four reaches with 56 percent from the Above Blackfoot to Near Blackfoot reach, 18 percent from the Near Blackfoot to Neeley reach, 12 percent from the Kimberly to King Hill reach, and 6 percent of water use compensated by river losses from the Neeley to Minidoka reach.

Site 13 is located about 24 miles west of Idaho Falls (Figure 3). The depletion graph for this well is presented in Figure 16. Snake River flow at King Hill, representing combined losses from all four reaches, is predicted to be depleted by 50 percent of the water use rate at Site 13 after about 24 years of water use. After 100 years, 90 percent of the pumped water is compensated by losses from the four river reaches, with 59 percent from the Above Blackfoot to Near Blackfoot reach, 13 percent from the Near Blackfoot to Neeley reach, and less than 10 percent from the Neeley to Minidoka and Kimberly to King Hill reaches.

Evaluation of Water Use Changes in Tributary Valleys

Nine sites represent the effects of water use in tributary valleys on flow of the Snake River. The sites were selected to represent water use in or near valleys formed by the Camas Creek and Big Wood River (Site 2); Little Wood River (Site 4); Big Lost River (Site 8); Little Lost River (Site 11); Birch Creek (Site 12); Medicine Lodge, Beaver, and Camas Creek (Site 15); South Fork and Henry's Fork of the Snake River (Site 18); Portneauf River (Site 14); and Raft River and Goose Creek (Site 7). Sites for simulated water use are located on Figure 3 and described in Table 2. Effects of water use at Sites 14 and 15 were described in the section describing irrigation impacts, and the descriptions are not repeated in this section of the report.

Simulation results at the selected sites represent local water use from the Snake River Plain aquifer and also, to a lesser degree of accuracy, in the nearby tributary valleys. Tributary valleys contribute water to the Snake River Plain aquifer both through ground-water underflow and through surface water flows that ultimately seep downward into the Snake River Plain aquifer. Water use in tributary valleys may impact ground-water underflow to the Snake River Plain aquifer, or may impact surface water flows that either recharge the regional aquifer or are directly tributary to the Snake River. In all cases, water use within a tributary valley may affect the recharge to the Snake River Plain aquifer and ultimately will affect Snake River gains or losses in a manner similar to that discussed for water use in irrigated areas. Evaluation of water use in tributary valleys presents the additional complication that the attenuation of effects are influenced by surface and ground-water interaction within the tributary valley, and the flow characteristics of the stream and local aquifer. The results presented in this investigation can be taken to represent the maximum expected effects, and the minimum expected delay time for tributary valley water use to affect ground-water flows to or from the Snake River.

Water use in some tributary valleys depletes recharge to the Snake River Plain aquifer in an amount equal to the amount of water use. The Big Lost and Little Lost river valleys are examples of this situation. All water consumptively used in these valleys will ultimately cause a depletion of the recharge to the Snake River Plain aquifer, since the ultimate destination of all ground-water underflow and surface flow is to the Snake River Plain aquifer. Consequently, impacts to Snake River flows will be similar to those predicated for irrigation on the Snake River Plain, with additional time delay and attenuation attributed to flow through the Lost River surface and ground-water system.

Water use in other tributary valleys may not be effective in reducing recharge to the aquifer. Some of the streams, such as Big Wood River discharge to the Snake River. Water use within these valleys directly depletes the flow to the Snake River. Deep percolation from irrigation water use in these valleys probably results in increased recharge to the Snake River Plain aquifer. Ground-water pumping in these tributary valleys contributes to depletion of the ground-water resource and may be interpreted in a fashion similar to that described for the Big and Little Lost River valleys.

The graphs presented in this report may be applied in reverse to ground-water recharge situations. That is, the "River Losses" may be interpreted as river gains resulting from increased ground-water recharge due to irrigation. The "water use" is interpreted not as the amount of water diverted, but as the amount of water recharging the aquifer. For example, if surface water irrigation out of Big Wood River results in 10 cfs per year of ground-water recharge near Site 2, then according to Figure 5, that recharge will result in a 5 cfs (50 percent) of additional Snake River flow from the combination of the four Snake River reaches after about 32 years of continuous irrigation.

Simulated water use at Site 2, located on the west side of Wood River, results in a total Snake River depletion of about 90 percent of the rate of water use after 100 years (Figure 5). Depletion is greatest in the Kimberly to King Hill reach where losses are predicted to be about 60 percent of the water use after 100 years. Predicted losses from each of the other three reaches are less than 12 percent after 100 years. Since surface water in this drainage is directly tributary to the Snake River, surface water use probably results in ground-water recharge rather than discharge, and the depletion graphs may be interpreted as graphs of river gains. Ground-water pumping results in river losses to the extent that water use is not locally replenished by increased seepage from the local streams.

Site 4 is located on the west bank of the Little Wood River south of the mouth of the valley. Continuous water use results in an estimated total depletion of 90 percent after 100 years of water use (Figure 7). Depletion in the Kimberly to King Hill reach is estimated to be about 50 percent of the water use after 100 years.

Depletions in each of the other three reaches are less than 20 percent.

Site 8 is located a few miles west of the Big Lost River near the northern boundary of the Snake River Plain aquifer, and responds to continuous, prolonged water use with nearly equal depletion in all four simulated reaches of the Snake River. For the first 15 to 20 years, little or no depletion is apparent. Following the early years of water use, the depletion losses become gradual although the total loss is high. Depletion losses in this location total 75 percent after 100 years (Figure 11) and are less than losses in other locations with the exception of Site 15.

Site 11 is located slightly west of the mouth of Birch Creek valley. Water use at this site results in significant losses in the Snake River primarily in the reach from Above Blackfoot to Near Blackfoot, where losses represent approximately 55% of the rate of water use after 100 years. Total simulated depletion of the Snake River was 85 percent of the water use rate after 100 years (Figure 14). Losses in the other three reaches are gradual and of less magnitude. Depletion effects in the Near Blackfoot to Neeley reach are about 15 percent, in the Kimberly to King Hill reach are about 10 percent, and in the Neeley to Minidoka reach are about 3 percent after 100 years.

During the first five years of simulated water use at Site 12, near Birch Creek, river losses are negligible. Depletion of the Snake River becomes increasingly apparent with time to achieve a total depletion (change in discharge at King Hill) of 80 percent of the water use rate after 100 years of water use (Figure 15). The greatest losses (52 percent of water use) are experienced in the Above Blackfoot to Near Blackfoot reach. The three other simulated river reaches show depletion losses less than 15 percent of the water use rate after 100 years. Water use at this location is depleting water originating from the Bitterroot Mountain watershed that would have recharged the aquifer and ultimately drained into the Snake River. Since surface water from this drainage is tributary to the aquifer, 100 percent of the water use, whether surface or ground water, is applied toward estimates of Snake River depletion.

Water use at Site 18, located between the Snake River and Dry Bed near Lorenzo, results in greatest river losses in the reach between the Above Blackfoot and Near Blackfoot gages. Depletion in this reach is predicted to be 50 percent of water use after 100 years (Figure 21). The total Snake River depletion for all four reaches is about 85 percent after 100 years of water use. Water use at this site is intended to represent the effects of water use in the tributary valleys of the Henry's Fork and South Fork of the Snake River. The graphs presented in Figure 21, however, are representative of a situation where ground-water in the Rigby alluvial fan and the tributary rivers are not hydraulically connected with the Snake River Plain aquifer. It is likely that the aquifer in the alluvium (e.g. Rigby fan) merges into the Snake River Plain aquifer and a hydraulic connection between the Snake River Plain aquifer and the South Fork and Henry's Fork probably does exist. Consequently, the graphs of Figure 21 do not present what is possibly the most significant river depletion associated with Site 18, that in the Henry's Fork and South Fork of the Snake River.

Site 7 is located on the south edge of the Snake River Plain aquifer near the Raft River and Goose Creek drainages. Water use in this area results in a total Snake River depletion of about 84 percent of the water use after 100 years (Figure 10). Approximately 48 percent of the water use is depleted from the Neeley to Minidoka Reach. Twenty-five percent comes from the Kimberly to King Hill Reach with the other two comprising less than 10 percent each. Depletions in the Neeley to Minidoka reach occur almost immediately, while those from the other reaches are not apparent until after several decades of water use. Effects of ground-water use in the nearby tributary valleys will be attenuated more than those illustrated in Figure 10.

Assessment of Significance of Trust and Non-Trust Areas

Results of several ground-water pumping simulations have significant implications to the notions of "Trust" and "Non-trust" waters established as part of the Swan Falls settlement with Idaho Power Company (Figure 1). The Trust area was defined as ground waters that are tributary to the Snake River below Milner Dam. Additional constraints have been applied to ground-water development in the Trust area relative to the non-trust area.

The Trust and non-trust area delineation was based on estimation of recent flow patterns in the Snake River Plain aquifer. In concept, however, flow patterns change in response to pumping, and ground-water flow lines do not impede propagation of well pumping or ground-water use effects. The cone of depression resulting from ground-water pumping will traverse a ground-water divide without alteration, unless the divide is a result of variations in the physical properties of the aquifer such as a fault or change in formation materials. Consequently, a ground-water divide separating Snake River Plain aquifer water tributary above and below Milner Dam will not prevent affects of pumping in non-trust areas from affecting aquifer discharge to the river in downstream reaches.

The similarity of ground water use effects in Trust and Non-Trust areas on the Snake River are demonstrated by comparison of simulation results at Sites 16 and 17 (Figure 3). The near identical configuration of graphs from Site 16 (Figure 19) and Site 17 (Figure 20) demonstrate that the trust boundary does not represent a divide which affects the propagation of ground-water pumping effects or other water use changes. After 100 years of water use, the depletion in the Kimberly to King Hill reach (water tributary below Milner Dam) is approximately 10 percent of the rate of water use at both locations. Site 16 is located in the trust area about 6 miles northeast of the city of Idaho Falls and Site 17 is in the non-trust area, about 15 miles south of site 16.

Intermittent Water Use Effects

The difference in stream depletion from a continuously pumping well and a intermittent pumping well was examined by Jenkins (1968) and is presented in Figure 22. The figure presents the volume of water obtained from a river due to ground-water pumpage in both intermittent and continuous water use situations. In Figure 22, line "V1" shows the effects of continuous pumping at 1.5 acre-feet per day for 42 days. Line "V2" shows the effects of intermittent pumping at a higher rate (5.25 acre-feet per day) for three equal length pumping periods but with unequal intervals between pumping. The volume of water pumped, and the average pumping rate, over the 42 day time period is the same in both scenarios. The similarity of the two lines shows that the depletion from the two scenarios is approximately the same, provided the average pumping rates are equal.

Depletion estimates of this report were made by simulating continuous water use for a period of 100 years. Although in many cases this situation may not be realistic, an intermittent water use scenario closely approximates the effects of continuous water use, when large distances separate the river and the point of water use. The presented graphs may be applied to seasonal water use conditions by utilizing the average annual water use instead of seasonal values. For example, if an irrigator near Site 16 pumps 8 cfs for three months during the growing season, but has no water use during the rest of the year; then the average annual water use is 2 cfs. Appling Figure 19, it is determined that after about 27 years, the Snake River (total for all reaches) is being depleted by 50 percent of his water use, or 1 cfs.

Residual Impacts of Water Use

Ultimately all water used on the Snake River Plain must be compensated for by diminished flows in the Snake River. According to the concepts employed in the Snake River Plain model, only two conditions will be affected by changes in water use: 1) the volume of water stored in the aquifer (water table elevation), and 2) the

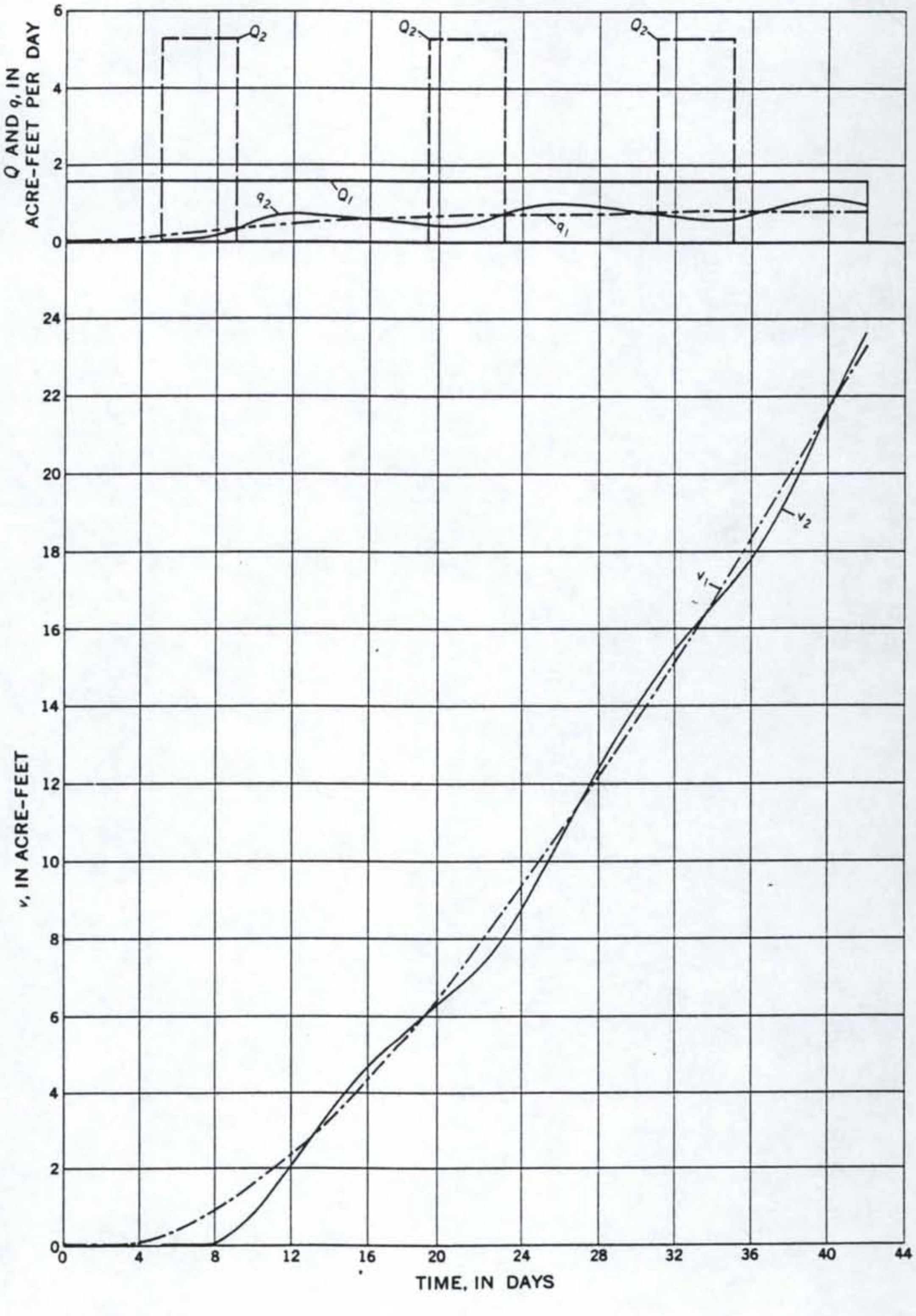

Figure 22. Comparison of Stream Depletion from Continuous and Intermittent Ground-Water Pumping (from Jenkins, 1968).

amount of water seeping from or recharging to the Snake River. Changes in the volume of water stored in the aquifer are temporary and ultimately have the affect of attenuating the water use effects on flow in the river.

Depletion of the Snake River will continue after the water use is discontinued. Residual effects are demonstrated by simulating continuous water use for 30 years at a specific location, then discontinuing the water use for the remainder of the 100 year simulation (Figure 23). At Site 6, 25 miles northeast of Rupert, the depletion in all reaches of the Snake River increases during years of water use, then gradually diminishes shortly after water use is ended. After 70 years of not pumping, the effects of past pumping are continuing to impact flows of the Snake River. The total flow of the Snake River at King Hill is depleted by about 10 percent of the rate of ground-water use 70 years after pumping was discontinued.

Residual water use impacts are prolonged as the distance between the water use location and the river reaches increases. At Site 15, near Mud Lake, total water use impacts on the river continue to increase for about 15 years after water use is discontinued (Figure 24). The total Snake River depletion was about 25 percent of the water use rate when the water use was terminated after 30 years. Total river depletion peaked at about 32 percent of water use 45 years after the well was turned off, and after 70 years of not pumping, river depletion was still occurring at a rate equivalent to 15 percent of the average pumping rate during the 30 years of service.

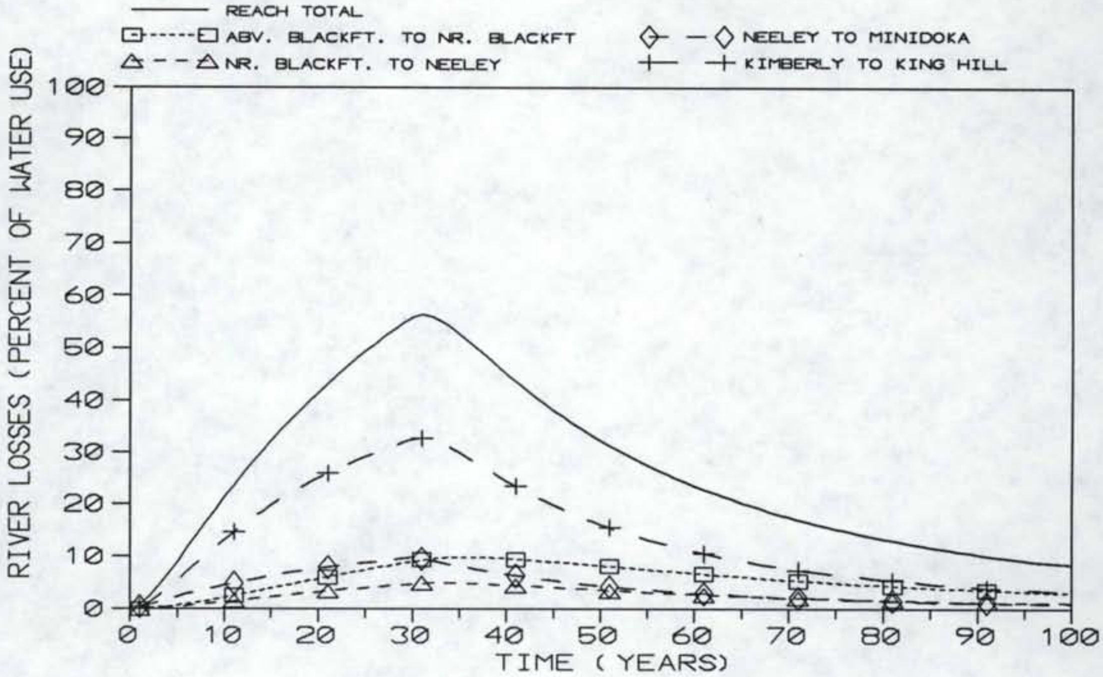

Figure 23. Residual Effects of 30 Years of Water Use at Site 6.

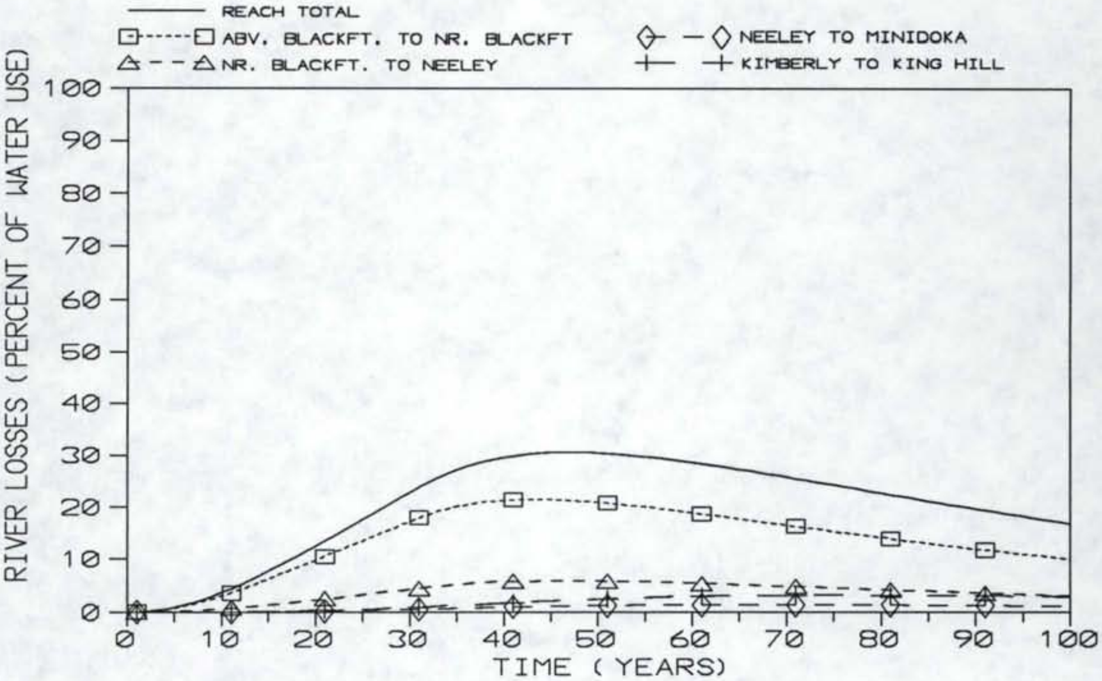

Figure 24. Residual Effects of 30 Years of Water Use at Site 15.

VALIDITY OF RESULTS

General Discussion

The results presented in this report represent estimates of how water use on the Snake River Plain will ultimately affect flow in the Snake River. The results are estimates, not exact predictions because of the following factors: 1) Inexact simulation of the interaction between the aquifer and the Snake River and other surface water bodies, 2) inexact approximation of aquifer boundaries, 3) uncertainty in model input values of transmissivity and storativity, and 4) simulation error associated with numerical procedures and descretization error. Each of these factors compromises the accuracy and validity of the simulation predictions to differing degrees. These factors are discussed individually in each of the following sections.

Aquifer-River Interconnection

The most critical element of simulation of the impacts of ground-water use on flow of the Snake River is probably the validity of concepts employed in modelling the interconnection between the river and the aquifer. Surface waters are largely isolated from and independent of ground-water resources (perched) in areas where the bed of a river or other surface water body is elevated above the surrounding water table. The surface water body may leak water downward to the aquifer, but the rate of leakage is not dependent on the height of the water table. When the water table elevation is near that of a surface water source, then the rate of interchange between the surface water and ground water is proportional to the hydraulic gradient. Under these conditions decreases in the water table elevation result in increased losses from, or decreased recharge to, the surface water source.

The simulations employed in this investigation applied an assumption that four reaches of the Snake River are interconnected with the Snake River Plain aquifer. The four interconnected reaches have been identified by previous modelers within IDWR and the University of Idaho based on comparison of elevations of the river and water table, as well as measured gains and losses in the Snake River between gaging stations. No other surface water bodies nor other aquifers are simulated as interconnected with the Snake River Plain aquifer; however, two additional potential interconnections should be examined.

Of greatest significance is the likely hydraulic interconnection with ground-water in the alluvial materials surrounding the Henry's Fork and South Fork of the Snake River, known as the Rigby fan. Wytzes (1980) found that ground-water levels in the Rigby fan merged with those found in the basalts of the Snake River Plain aquifer on the western edge of the Rigby fan, implying hydraulic connection between the two aquifer systems and the rivers. In this situation, pumping from the Snake River Plain aquifer has an affect on ground-water elevations in the Rigby fan and ultimately will increase losses from the South Fork and Henry's Fork of the Snake River above Idaho Falls. If simulations discussed in this report had represented this interconnection, ground-water use in the eastern portion of the Snake River Plain would show a more immediate and greater river depletion in these upper river reaches than was determined for the four lower reaches.

A hydraulic interconnection is also likely to exist with streams and surface water bodies in the Mud Lake - Market Lake area, at least in some years. This interconnection is most important to local surface water users in the Mud Lake area. Lower water table elevations in the Mud Lake area are likely to result in greater surface water losses from the lower reaches of Camas Creek and related surface water bodies. Consequently, surface water users in the Mud Lake area may be impacted by ground-water pumping in the Snake River Plain aquifer. The inclusion of surface water interconnection in the Mud Lake area in simulations of this investigation would probably have little affect on the responses determined for the Snake River reaches, except possibly for water use sites in the near vicinity of Mud Lake.

Aquifer Boundary Assumptions

The entire periphery of the Snake River Plain aquifer is simulated as a no-flow boundary except in the Kimberly to King Hill reach where the Snake River is simulated as the aquifer boundary. The assumption of a no-flow boundary is probably valid in most boundary areas. It is generally accepted that the mountains surrounding the Snake River Plain are of much lower permeability than the Snake River Plain aquifer. They are condsidered to be barriers to ground-water flow, and modelled as no-flow boundaries.

No-flow boundaries are possibly not appropriate in the peripheral areas where tributary valleys join the Snake River Plain aquifer. If large hydraulic gradients exist where smaller valley aquifers are tributary to the Snake River Plain aquifer (such as in Big Lost River valley near Arco) then either unsaturated flow conditions exist or transmissivity in the transition zone is sufficiently small that the situation probably approaches that of a no-flow boundary. In tributary valleys such as the Rigby fan, however, where the valley aquifer water levels gradually merge with those of the regional Snake River Plain aquifer, a no-flow boundary is not appropriate. Use of a no-flow boundary in these areas results in simulations that predict greater losses in the four hydraulically connected reaches of the Snake River than will actually occur. The presence of an artificial no-flow boundary in these areas also fails to predict the impacts of Snake River Plain aquifer water use on surface water sources within the tributary valleys. For example, the simulations as they were conducted, with no-flow ground-water boundaries along the Rigby fan, will fail to show how pumping near Roberts may affect flows of the Henry's Fork.

The extreme northeast boundary of the Snake River Plain is also simulated as a no-flow boundary, when in actuality the aquifer probably continues for several miles to the northeast. The consequence of this modelling convenience is that simulations of water use in the northeast portion of the Plain will slightly overestimate Snake River depletion in the four identified hydraulically connected reaches. This effect is limited in magnitude and in areal extent and is not of great concern.

Aquifer Property Estimation

Aquifer properties estimated for this study include transmissivity and storativity. These properties, especially transmissivity, vary greatly over the Snake River Plain and are never known with certainty. The estimates applied in this investigation were the result of recent ground-water flow model calibration by the Idaho Department of Water Resources. Model calibration, however, is an inexact process that often produces non-unique areal distributions of transmissivity and storativity.

Aquifer properties estimated by IDWR during model calibration are expected to be approximately correct when averaged over a sufficiently large scale. At specific model grid cells, the calibrated properties may not be valid representations of real aquifer properties. When averaged over several grid cells, however, the average values of aquifer storativity and transmissivity probably better approximate real conditions. Consequently, predictions are probably more realistic for situations where the location of water use is at a great distance from the hydraulically connected reaches of the Snake River than for water use locations very near hydraulically connected reaches.

Simulation Errors

Numerical modelling does not yield an exact solution to any ground-water flow problem. Finite-difference models are used to iteratively approach a solution to a problem which cannot be solved directly. The numerical accuracy of the solution is partially controlled by the modeler, who establishes the closure criterion at which the result is considered "close enough". The MODFLOW simulations conducted for this investigation used a closure criterion of 0.01 feet. This criterion means that the largest tolerated difference in simulated aquifer head at any model node, between iterations, is 0.01 feet. If head differences greater than

0.01 feet existed then additional iterations were run. This closure criterion resulted in minimal variability in results and satisfactory mass balances in all simulations. Numerical error was estimated by examining the gains and losses of the Snake River under flat water table conditions and simulation of no water use. The greatest variability in gains and losses resulting from numerical error were found in the Kimberly to King Hill reach where errors were found as large as 600 cubic feet per day. This magnitude of error, however, represents less than 0.01 percent of the magnitude of the simulated water use.

Discretization error results from simulating continuous events and media, such as time and aquifer characteristics, as averaged discrete increments. Generally, the smaller the increments the more accurately the continuous system is represented. The discretization of aquifer properties into homogeneous blocks or cells for the purpose of simulation has resulted in some error in the presented results. In addition to normal discretization error resulting from numerical modelling, an additional error was introduced by conversion from the IDWR model code to MODFLOW. These two models differ in the way in which aquifer transmissivity is averaged between model cells, and consequently the averaged transmissivities in the MODFLOW simulation are less than in the IDWR model. The MODFLOW simulations therefore will tend to attenuate the water use effects more than corresponding simulations using the IDWR Model. The differences are not expected to be significant considering the accuracy of model calibration which was the source of the original transmissivity values used in the IDWR model.

Simulations conducted for this investigation applied the concept of superposition of effects (initially flat hydraulic gradient). Superposition modelling imposes no additional errors on the simulation results. The differential equations of ground-water flow and boundary conditions are linear and therefore appropriate for application of superpostion techniques (Reilly and others, 1987).

In summary, numerical modelling produces approximate predictions. In addition to the inexact knowledge of aquifer physical properties that are input to the model, the solution process itself is inexact. The magnitude of the numerical errors and error associated with the assumption of an initially flat water, however, are expected to be small relative to the errors resulting from uncertainty in model inputs representing aquifer properties.

SUMMARY AND CONCLUSIONS

The impacts of Snake River Plain aquifer water use on flow of the Snake River were examined through application of a ground-water flow model. Simulations were conducted using model inputs from the IDWR Snake River Plain aquifer model, altered to a flat water table situation with no initial gradient between the river and aquifer. Four reaches of the Snake River were simulated as hydraulically connected to the aquifer. Along these reaches, changes in the water table affect the amount of water gained or lost from the river or springs. River gaging stations provided end points of the following four hydraulically connected reaches taken from the IDWR model:

1) Above Blackfoot to Near Blackfoot,
2) Near Blackfoot to Neeley,
3) Neeley to Minidoka,
4) Kimberly to King Hill.

No other surface waters are simulated as hydraulically connected with the Snake River Plain aquifer, although an indirect connection probably exists with the Henry's Fork and South Fork of the Snake River through the Rigby Fan aquifer.

Simulations were performed to illustrate the impacts of ground-water use at 18 specific sites on flows in each of the four river reaches. River impacts are described graphically as a river depletion, expressed as a percentage of the average water use rate. The graphs display the degree to which recharge or discharge from each river reach is expected to change over a period of approximately 100 years of nearly constant water use. Site locations were selected primarily to represent areas of concentrated irrigation activity and impacts of development in valleys tributary to the Snake River Plain.

Simulation results indicate that the total losses from the Snake River (e.g. the sum of losses in the four reaches) ranges from about 75 to 95 percent of the rate of water use after 100 years of water use. Effects are much more variable after shorter time periods. After 20 years of water use the total river losses range from 20 percent to 90 percent of the water use. The reach most impacted by the water use is generally the reach nearest the point of water use, with some variation due to the degree to which each reach is simulated as interconnected with the aquifer.

Intermittent water use produces nearly the same river depletion as continuous water use, provided the source of use is not near the river and frequency of the on/off water use cycle is not greater than a few years. The impacts of water use on the Snake River Plain are shown to continue for several decades after water use is discontinued.

Water use, as it is applied in this investigation, may be interpreted as any activity affecting recharge to, or discharge from, the Snake River Plain aquifer. When the graphs are applied to indicate river losses, "water use" may represent seasonal ground-water pumping for irrigation, a diminished recharge due to removal of surface water irrigated lands from production, conversion from surface to sprinkler irrigation, lining of canals, or a decrease in ground-water underflow from a tributary valley due to water use within the tributary valley. The graphs may be applied in reverse to indicate river gains when the simulated "water use" represents an increase in aquifer recharge such as development of additional surface water irrigated acreage, or artificial recharge activities. Impacts of ground-water use on the river are apparent throughout the Plain, regardless of political divisions such as the Trust and Non-Trust areas established as part of the Swan Falls settlement.

This investigation has produced the following conclusions:

1) Water use at all locations within the Snake River Plain will ultimately affect flow of the Snake River. The attenuation of the river impacts increases with distance from the river, but after 100 years of water use, the river flow at King Hill is diminished by at least 75 percent of the rate of ground-water use for all simulated water use locations within the Plain.

2) Superposition modelling using zero-gradient initial conditions is useful for evaluating changes in river flow due to specific changes in aquifer recharge or discharge.

3) Results of these simulations, and similar simulation efforts are strongly affected by the simulated hydraulic interconnection of specific reaches of the Snake River and other surface water sources.

4) Changes in river flow can be expressed as a percentage of the change in rate of ground-water recharge or discharge (e.g. water use rate) for specific locations.

5) Water use in valleys tributary to the Snake River Plain will also affect flow of the Snake River. The magnitude of the effects will be dependent on the degree to which the water use affects the recharge to the Snake River Plain aquifer from the tributary valley.

6) Administrative divisions of ground-water flow, such as the Trust/Non-Trust boundary established as part of the Idaho Power Swan Falls settlement are artificial and have no bearing on aquifer-river interactions. The divisions do not distinguish between ground-water pumping locations which may or may not impact river flow in specific reaches.

RECOMMENDATIONS

This investigation has produced the following recommendations for further research and regulation of water resources in the Snake River Plain:

1) An examination should be made of the possible interconnection of the Snake River Plain aquifer and local tributary aquifer systems and surface water sources. Conceptual improvements in the ground-water/surface water and inter-aquifer connection should be included in future modelling efforts aimed at evaluating ground-water use impacts on the Snake River. Of particular importance is the interconnection of the Snake River Plain aquifer with ground water in the Rigby Fan and the Henry's Fork and South Fork of the Snake River.

2) A more detailed investigation of effects of water use changes should be performed using superposition modelling methods. The simulations should include an improved conceptual basis for interconnection of the Snake River Plain aquifer and ground-water in the Rigby fan and a changed inter-node transmissivity averaging method in MODFLOW to be compatible with the IDWR model. Results should be presented in more detail, such as areal contouring of water use impacts on the river. Specific examples of residual and intermittent water use effects should be determined for multiple locations throughout the Plain.

3) Subsequent modelling investigations should evaluate lumped effect of water use changes as well as the impacts of specific changes, and should include results that describe river impacts in terms of absolute changes in river flow, as well as relative to the magnitude of the simulated stress or water use change. Simulations should examine impacts of all water use changes including changes in irrigation practices and water conservation efforts as these activities may negatively impact

ground-water recharge.

4) An improved comparison should be made of the IDWR ground-water flow model with other established model codes. The comparison with MODFLOW should include changing the IDWR model code to calculate intra-node transmissivity by the same procedure used in MODFLOW.

4) The Snake River and Snake River Plain aquifer are a single resource throughout much of the Plain. Water use in tributary valleys also affects ground-water recharge and ultimately flow in the Snake River. Future comprehensive management plans must include conditions for relating tributary valley water use to water use in the Snake River Plain and water use from the Snake River.

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