Application of Steady State Response Ratios to the Snake River Plain Aquifer

By

Gary S. Johnson

Donna M. Cosgrove

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

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ABSTRACT

Conjunctive management of surface and ground water is complicated by two basic physical phenomena: 1) effects of ground-water stress (pumping or recharge) propagate in all directions (assuming the aquifer is continuous in all directions), and 2) effects of aquifer stresses on surface water may be attenuated over periods of years or even decades. Response functions and ratios provide a means of understanding and mathematically quantifying spatial and temporal variation of aquifer pumping or recharge effects on surface water. Stream-aquifer response ratios, representing cause and effect relationships in steady state, have been developed for each active cell of the Snake River Plain aquifer model grid (SRPAM1.1). The response ratios for the 51 head dependent river cells representing the Snake River have been aggregated into six reaches bounded by gaging stations. Model cells representing the Snake River Plain aquifer have been grouped into 20 zones based on similarity of response function values to each of the six river reaches. Median steady state response ratios are provided for each zone for subsequent incorporation into integrated surface and ground-water models.

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INTRODUCTION

Idaho water law, similar to the law of many western states, is founded in the Prior Appropriation Doctrine. This doctrine allocates water to users according to a priority system based upon when the water was first put to beneficial use. Earlier applications have senior priority, entitling them to their full appropriation, which may be at the expense of junior water rights holders in times of water shortage. Thirteen of the 18 western states, including Idaho, have some form of integrated management of surface- and ground-water rights (Tellman, 1996). In many of these states, surface- and ground-water rights are conjunctively managed within the same priority system provided the two sources are hydrologically linked.

Joint administration of surface- and ground-water rights is complicated by two basic physical phenomena: 1) effects of ground-water pumping (or recharge) propagate in all directions (assuming the aquifer is continuous in all directions), and 2) effects of pumping on other surface or ground-water users may be lagged by years or even decades (Hubbell and others, 1997). Consequently, the relatively simple concepts employed to help administer surface water rights (i.e. evaluate the effects of a surface-water diversion on downstream flows and users) are ineffective in the evaluation of surface- and ground-water interference issues. Simple but representative tools are needed to assess the impacts of ground-water use on surface water bodies.

Analytical tools such as the stream depletion factors described by Jenkins (1968) and related methods such as Glover (1968) provide a simple method for estimation of the effects of ground-water pumping on flow of a stream. These analytical methods, however, employ a large number of restrictive assumptions. The stream depletion method of Jenkins (1968) requires assumptions of a straight and fully penetrating stream and a homogeneous aquifer of infinite extent. These assumptions may be acceptably representative of some physical situations, but may cause unacceptable levels of error in cases where aquifer heterogeneity and boundaries are significant. The equivalent methods described by Glover (1968) are equally restrictive and have been applied and accepted for conjunctive management in some areas in Colorado (MacDonnell, 1988).

Numerical models are probably the best available tool for estimating changes in aquifer water level or in stream gains and losses as a result of aquifer stress (i.e. recharge or discharge). The use of numerical models avoids many of the restrictive assumptions necessary with analytical techniques. Numerical model simulations, however, describe the entire system response to a general recharge and discharge scenario. It is often not feasible to conduct numerical model simulations to evaluate individual impacts of the perhaps thousands of ground-water users on the surface water resources. In addition, the understanding of how physical characteristics, such as transmissivity and storativity, control the response of the system is often lost through the complicated interpretation of the many system recharge and discharge components. Response ratios and functions provide a means of incorporating the computational power and accuracy of numerical models in a more simplified method. Presentation of the spatial variability is also an excellent tool to portray how the distribution of river and aquifer physical characteristics control system response to imposed stresses.

The purpose of this paper is to introduce the concepts of response ratios and response functions and describe how these tools can be integrated into surface water models and assist in conjunctive administration of surface and ground water. Response functions and ratios can be used to describe response of either aquifer water levels (i.e. drawdowns) or surface water interactions (i.e. stream depletion). This paper, however, focuses on applications to stream depletion. An application of steady state stream depletion response ratios for the eastern Snake River Plain in southern Idaho is described to demonstrate the usefulness of the procedure. Median response ratios for 20 aquifer response zones are provided as a quantitative tool to integrate ground-water systems into a surface water model. This work was performed by the University of Idaho, Idaho Water Resources Research Institute, with funding from the U.S. Bureau of Reclamation, under the Snake River Resources Review (SR3) program.

DESCRIPTION OF RESPONSE RATIOS

General Concepts

At the onset of ground-water pumping in an unconfined aquifer, the water is taken primarily from ground-water storage, resulting in a localized decline in water levels. As time progresses, the effects propagate radially outward until they intersect an aquifer boundary or head-dependent recharge or discharge mechanism (i.e. hydraulically connected with the aquifer). The head-dependent mechanism may be springs, rivers, streams, canals, or wetlands that are hydraulically connected with the aquifer. Ground-water pumping will ultimately deplete head-dependent surface water resources. Recharge activities would produce similar but opposite effects.

Response ratios and functions are a means of describing cause and effect relationships within stream-aquifer systems based solely on estimates of the physical characteristics of the system. They describe stream depletion at one point in the system resulting from a unit stress at a second point. They are based on the concept of superposition (Reilly and others, 1987) in which the solution of a more complex problem containing the multiple linear inputs is equal to the sum of the solution to individual components of the multiple linear problems. This concept provides a powerful tool that is commonly used in ground water analysis and modeling. For example, the application of image well theory relies upon the concept of superposition.

The response relationships may be based on either analytical or numerical models. Those based on numerical models are less constrained by assumptions than those based on analytical techniques and are the focus of this paper. Response functions and ratios assume that the system is governed by linear equations, consequently, the cause-effect relationships can be scaled to any level of stress (within limits to be discussed in the section *Assumptions Required for Use of Response Ratios*). The assumed linearity of the system also allows superimposing effects of multiple, simultaneous stresses.

The concepts and previous applications of response functions can be traced back to several earlier works. Maddock (1972) proposed a similar concept as "algebraic technologic functions". Morel-Seytoux and Daly (1975) describe the parallel concepts of the "discrete kernel approach". Illangasekare and Morel-Seytoux (1982) applied the superposition concepts in stream-aquifer modeling. Maddock and Lacher (1991) developed a MODFLOW (McDonald and Harbaugh, 1988) variation that generates response function values. Fredericks and Labadie (1995) used response functions to integrate surface and ground-water models. Similar ideas have also been applied in optimization efforts such as that conducted by Ejaz and Peralta (1995). Despite the fact that the concepts of response functions have been used in earlier work, their application has not reached its full potential.

This paper distinguishes between response functions and response ratios. Response ratios express cause and effect relationships at a single point in time. Response functions describe the relationships including the temporal variation. A response function is essentially composed of a series of response ratios representing different time periods. The response functions and ratios may be developed for a continuous stress, or one of finite duration. Both response ratios and response functions are useful tools for examining aquifer and river system response to a single stress, in isolation of all other stresses that may be simultaneously occurring.

Figure 1 shows a generalized example of two response functions relating stream depletion to ground-water pumping. The response functions represent the effects at river reaches A and B of a continuous unit withdrawal at a specified location over time. The effects are expressed as the time-variant ratio of depletion to the unit stress. The response ratio is the value of the response function at a specific time. The magnitude of the response ratio (and function) will vary with distance between the withdrawal and the affected point. At any given time, it would be expected that the response at reach A would be greater than the response at reach B, due to the distance between pumping location and river reach (assuming relatively homogeneous aquifer conditions). The magnitude of the response ratio varies with time as the effect of the applied stress is propagated through the aquifer. The content of this paper, and the eastern Snake River Plain application that is discussed in subsequent sections, is primarily based on response ratios at a single point in time (steady state for the eastern Snake River Plain application).

Response ratios are generated with the assumption that the system is linear, consequently, responses on the same river reach from stresses at different locations at the same time are additive and proportional to the magnitude of the individual stresses. For example, assume the relationship between ten years of continuous pumping and stream depletion at a given pair of locations is represented by a response ratio of 0.3. Then, after ten years of continuous pumping at a rate of 10 cfs at the prescribed location, the stream reach is depleted by 3 cfs. If the stress were doubled to 20 cfs, the response ratio would still be 0.3 but the depletion after ten years would be 6 cfs. Response ratio application is equally valid for aquifer withdrawal or recharge. Steady state response ratios express the rate of stream depletion (relative to a unit stress) that will result if the pumping continues for an infinite period of time.

The value of the tool lies in the relatively simple means of quantitatively expressing relationships between ground-water use (or recharge) and spring and stream depletion (or accretion). Johnson and others (1993) presented response functions in a graphical format for 18 locations (Figure 2) to enhance the conceptual understanding of ground-water and surface-water relationships in the eastern Snake River Plain in Idaho. The example presented in Figure 2 shows that ground-water pumping at selected locations will deplete springs and seeps along two reaches of the Snake River by varying amounts depending upon time and proximity to the reach. This type of illustration is invaluable in relating conjunctive use concepts to the public. The simple quantitative form of response ratios and functions also facilitates incorporation of ground-water cause and effect relationships into integrated resource models.

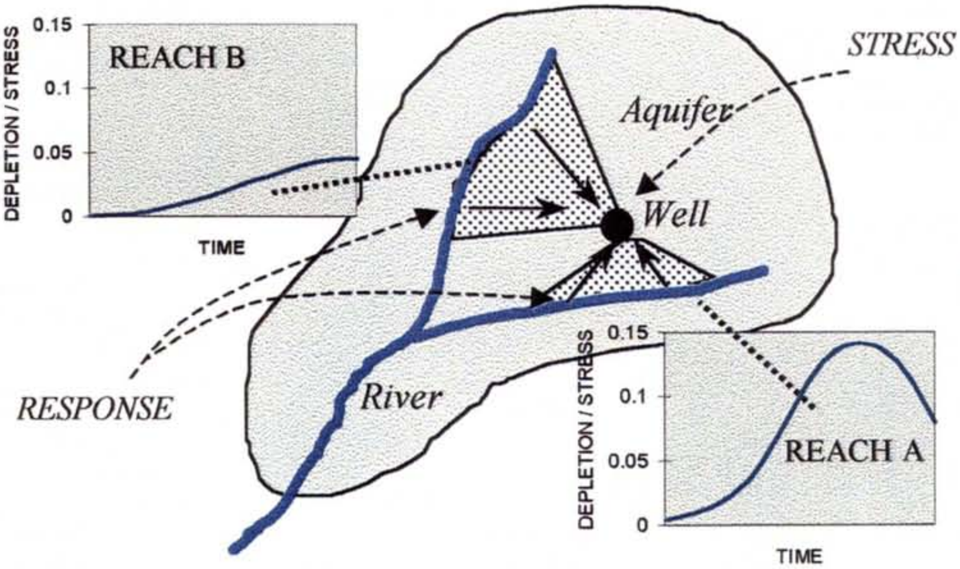

Figure 1. Generalized Response Function Example.

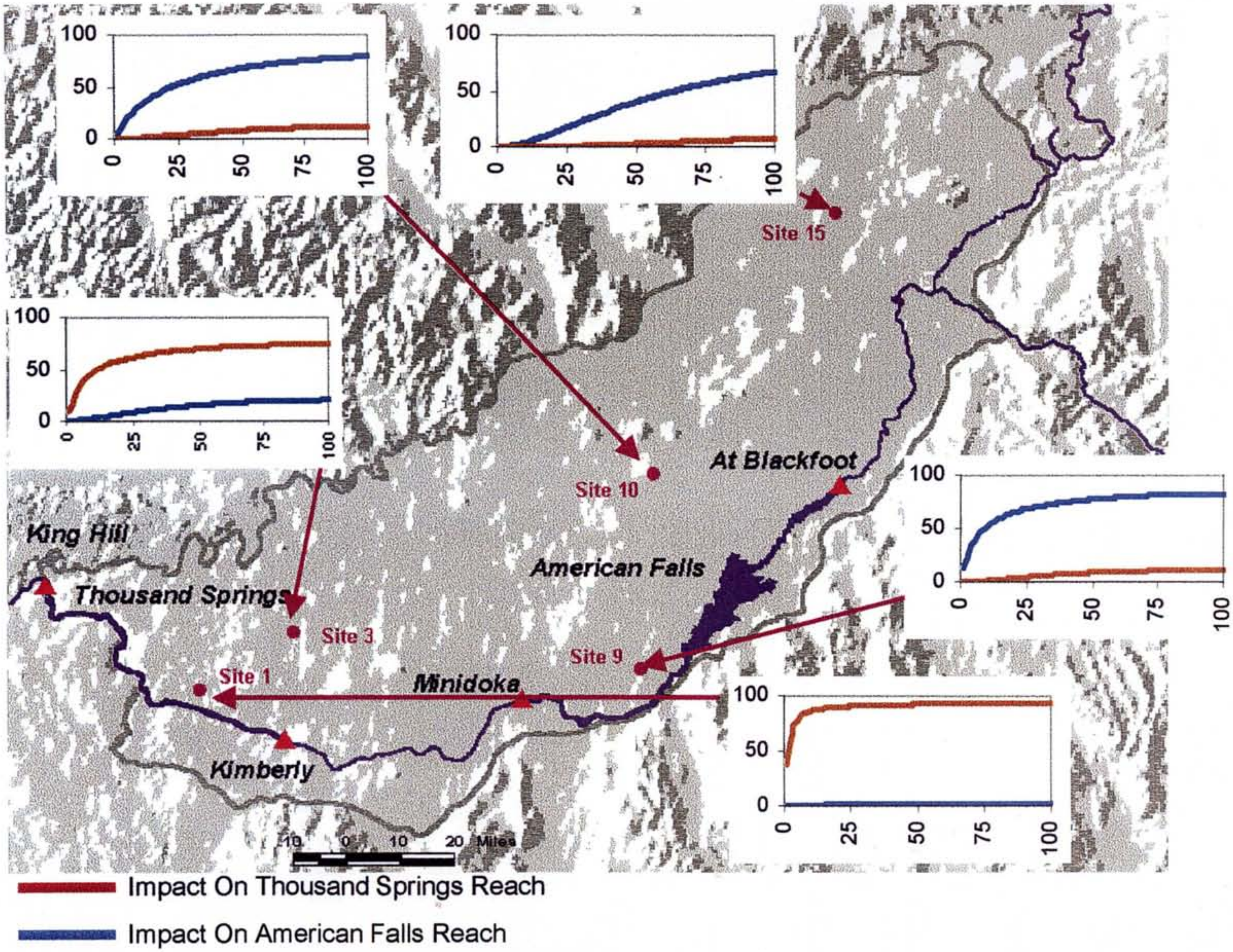

Figure 2. Example Response Functions in the Eastern Snake River Plain. Vertical axis is the percent of pumping appearing as stream depletion, horizontal axis is time in years (after Johnson and others, 1993).

By generalizing the problem and determining the response of the system to unit stresses applied throughout the aquifer system, the hydrologic interactions of the whole aquifer system are described. Response ratios can be calculated once, stored in a database or spreadsheet, and the effects of various scenarios can be easily calculated by scaling and summing the response ratios, enabling the analyst to quickly predict response of the system to a wide variety of stresses at varying locations.

Assumptions Required for Use of Response Ratios

The most essential assumption in the application of response ratios is the assumption of system linearity. Fundamental to the theory of response ratios is the concept of superposition, which is completely valid only for purely linear systems. Most stream-aquifer systems include non-linear elements, but may be treated as linear under a constrained set of conditions with simplifying assumptions.

The governing equations of numerical models of confined aquifer systems are linear with the exception of some boundary conditions. Representation of head-dependent rivers and drains are often piece-wise linear, as shown in Figure 3 (adapted from McDonald and Harbaugh, 1988). When aquifer water levels are above the river bottom elevation, river seepage is represented by a linear function based on the difference between aquifer water level and river bottom elevation, and the conductivity of the river bed sediments. When the aquifer water level drops below the river bottom elevation, the river seepage becomes constant. Non-linearity is introduced as the water level passes through the elevation of the river bottom. In numerical ground-water models, head-dependent drains are often handled similarly to rivers, as a piece-wise linear system.

The equations governing flow in unconfined aquifers are non-linear, because the equations are based on aquifer transmissivity, which is dependent upon saturated aquifer thickness. Saturated thickness changes as stresses are imposed, resulting in non-linearity of the governing equations. Response ratios (and functions) can be legitimately applied to these situations when changes in aquifer thickness are small relative to total saturated thickness. This requires that the user of response ratios have some prior understanding of the degree that the system will be affected by stresses and the degree of non-linear response that may result. In many cases, the degree of error introduced by violating the

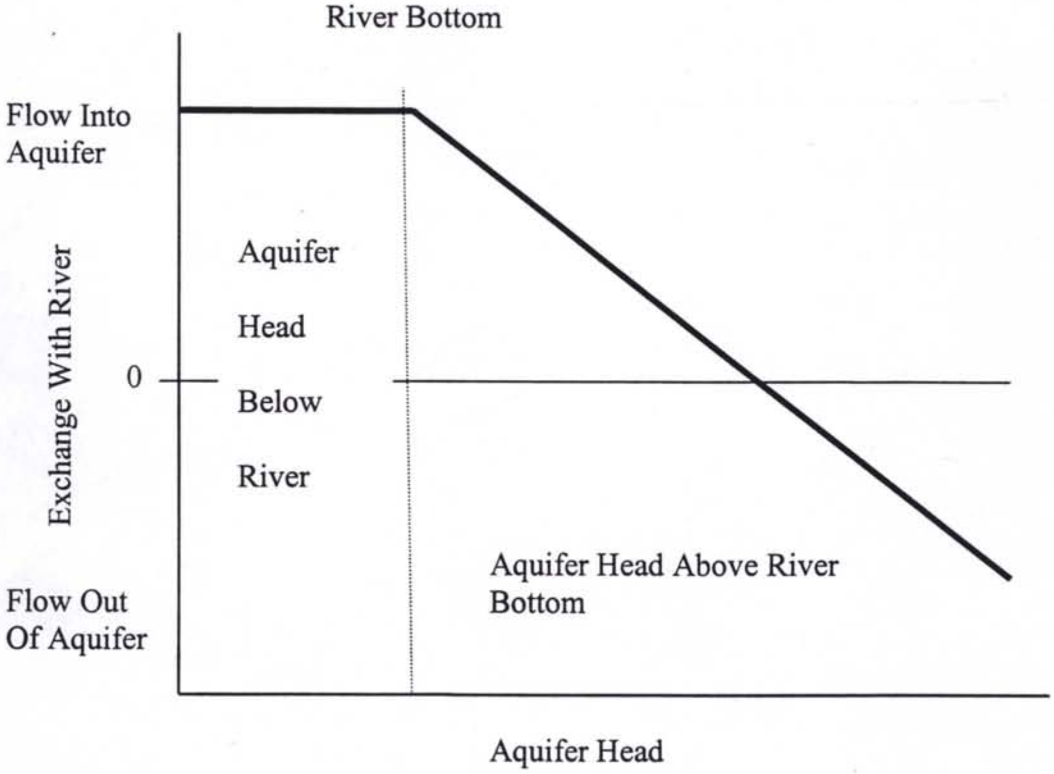

Figure 3. Piecewise Linear Function Representing River Seepage (after McDonald and Harbaugh, 1988).

requirement of linearity is small relative to the error introduced through the uncertainty in aquifer properties such as hydraulic conductivity, aquifer thickness and storativity.

GENERATION OF STEADY STATE RESPONSE RATIOS

Steady state response ratios can be generated using any of three basic methods. All of the methods require the use of a calibrated numerical model for the basin. Although response ratios can also be generated from analytical methods, that approach is not discussed.

Response ratios can be generated by differencing the results of two or more simulation scenarios. This method requires estimation and input of the full recharge and discharge distribution for the basin. Results of an initial baseline scenario, with a standard (e.g. average year) set of recharge and discharge inputs is subtracted from the results of scenarios run with an additional stress superimposed on the standard conditions. Dividing the change in surface water flux at a given time period by the magnitude of the additional stress produces the response ratio for that location and time. These ratios could be the result of changes in river seepage for hydraulically connected river cells or drain seepage for hydraulically connected drains at cells of interest. The drawback in using this technique is the amount of time and expertise required for calculating recharge and discharge for the scenarios and for interpreting and differencing results.

A second method of calculating response ratios is through the use of a calibrated numerical model, but with no initial hydraulic gradient in the river-aquifer system. All sources of recharge and discharge to the model are set to zero (except for the point of evaluation). The simulation is evaluated based on a stress applied in a single model cell and its effect on flux with head-dependent sources, such as rivers. The resulting flux with head-dependent sources is divided by the magnitude of the stress imposed to determine response to a unit stress. Johnson and others (1993) used this method to calculate the responses shown in Figure 2. This method avoids the restrictive assumptions of analytical techniques and the cumbersome input requirements and post-simulation analysis of calculating the difference between multiple full model simulations.

A third method of calculating response ratios is through the use of specially designed programs such as MODRSP (Maddock and Lacher, 1991). MODRSP is a modification of the MODFLOW ground water simulation code. MODRSP provides an automated method of calculating response ratios very similar to the second method described. MODRSP uses modified MODFLOW input files for a calibrated ground-water flow model. All recharge and discharge terms are removed and river, drain, and starting water table elevations are preset to zero. A unit stress is applied in a single model cell. MODRSP is then run to either steady state (or for the specified transient stress periods) and responses ratios (or functions) are generated. MODRSP allows the user to specify which system response to calculate (e.g. changes in river gains/losses, drawdown).

MODRSP assumes that aquifer conditions are confined. For an unconfined aquifer, the hydraulic conductivity in each model cell must be converted to transmissivity by multiplying by saturated thickness. As long as changes in aquifer thickness are small (for situations in which response functions are applied) relative to the total saturated thickness, this is a valid approximation for unconfined aquifer conditions.

MODRSP is designed to enable the user to sequentially calculate response ratios for multiple model cells. Response ratios can be calculated for every active model cell by setting up a control file containing all of the active model cells. Use of MODRSP requires relatively little data preparation other than generation of the control file specifying the cells for which response ratios will be generated. Once the response ratios are generated, the ratios can be read into a database or spreadsheet, where specific scenarios can be analyzed or the results can be graphically displayed to illustrate the spatial variability of ground-water and surface-water interaction. The calculated response ratios are equally valid in analyzing scenarios of aquifer recharge or discharge or a combination of recharge and discharge.

EASTERN SNAKE RIVER PLAIN STEADY STATE RESPONSE RATIOS

The following sections describe the development and application of response ratios in the eastern Snake River Plain. In this paper, the aquifer underlying the eastern Snake River Plain will be referred to as the Snake River Plain aquifer.

Steady state response ratios were generated for the Snake River Plain aquifer in eastern Idaho using a MODRSP application to the Snake River Plain Aquifer Model (SRPAM1.1) documented in Cosgrove and others (1999). The following sections contain a brief description of the Snake River Plain aquifer, the SRPAM1.1 model, and the resulting steady state response ratios.

Description of the Snake River Plain Aquifer

The Snake River Plain extends in a crescent shape across most of southern Idaho and into eastern Oregon. The plain is divided into eastern and western portions based primarily on ground-water hydrology. The eastern Snake River Plain is the focus of this study and occupies an area of about 10,800 square miles extending northeast from King Hill to near Ashton (Figure 4). Elevation of the eastern plain varies from about 2600 feet above sea level in the southwest to over 5000 feet in the northeast.

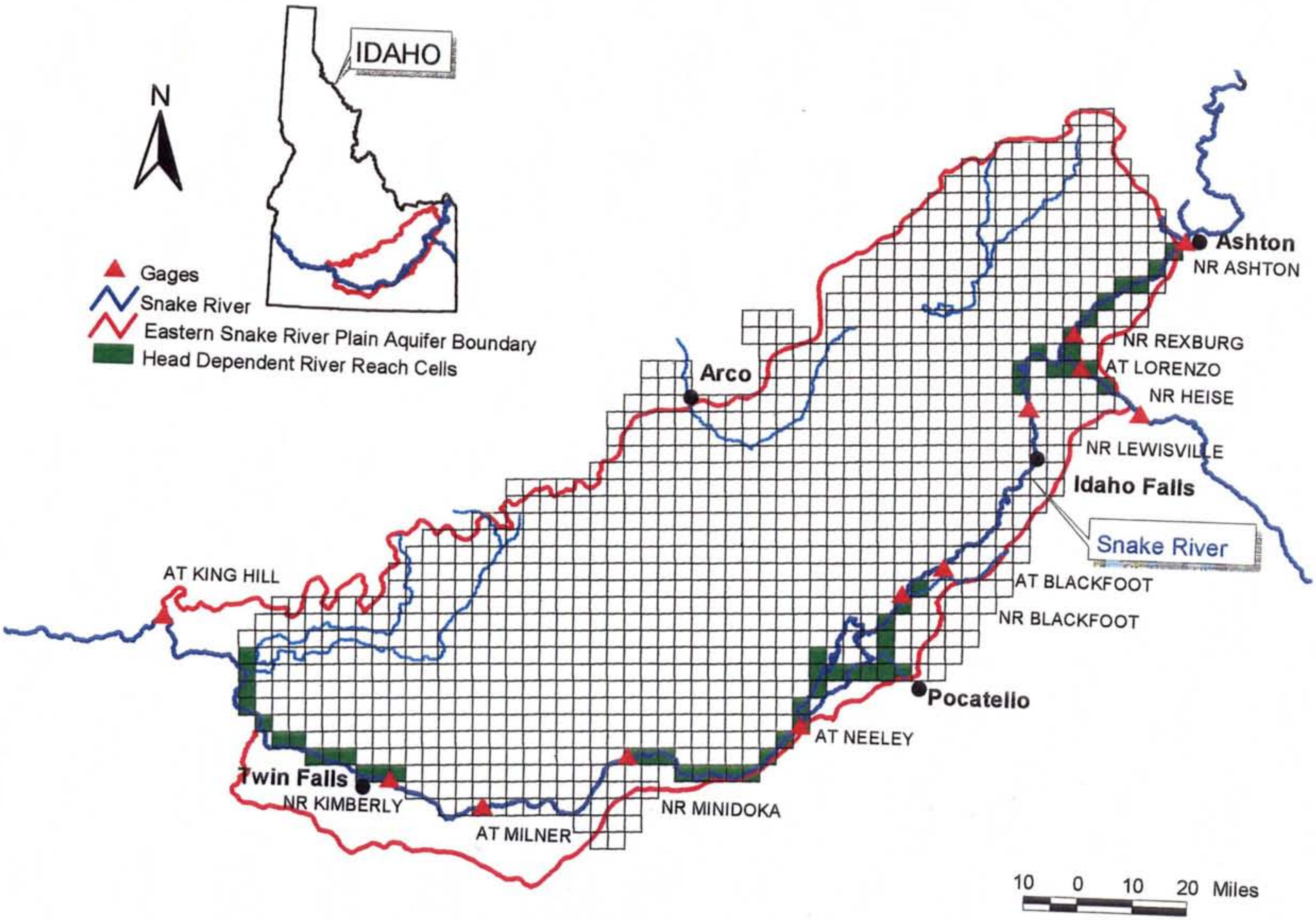

Figure 4. Eastern Snake River Plain Aquifer and Model Grid.

The climate of the eastern Snake River Plain is arid to semi-arid temperate. Precipitation ranges from about 8 to 14 inches per year, falling predominantly in the colder months. Consequently, irrigation is required for agricultural production. The crops grown vary with location. The major crops include potatoes, wheat, barley, alfalfa, and sugar beets. Dry edible beans and peas are grown in the southwest part of the valley.

The highly productive Snake River Plain aquifer is hosted in fractured basalts and interbedded sediments. The primary conduit for ground-water flow appears to be the highly permeable rubble zones that formed at the tops of the numerous basalt flows that comprise the Snake River Plain. Garabedian (1992) reports median specific capacity on a county basis for 176 wells across the eastern plain. The median values ranged from 4 to 950 gpm per foot drawdown, with the largest values occurring in counties near the center of the plain where Quaternary basalts are thickest. The lower values were found near the plain margins where Tertiary basalts and sediments predominate.

Although the collective thickness of the basalt flows may be in excess of several thousand feet in places, the active portion of the aquifer is thought to be limited to the upper several hundred feet of saturated thickness. The Snake River Plain aquifer is generally considered unconfined; however, in some locations and under certain conditions the aquifer responds as a confined system. In some areas, low permeability lakebed sediments create local confining layers (Spinazola, 1994). The layered basalts and interbedded sediments may also produce conditions that appear locally confined, at least when subjected to short duration stress (Frederick and Johnson, 1996).

The Snake River Plain aquifer is recharged by irrigation percolation; canal, stream, and river seepage; subsurface flow from tributary valleys; and precipitation directly on the plain. The aquifer discharges to springs along the Snake River and to ground-water pumping, primarily for irrigation. Aquifer recharge incidental to irrigation is a significant component of the water budget and has varied as irrigation practices have evolved.

Natural discharge from the Snake River Plain aquifer is primarily to the Snake River along two reaches: Kimberly to King Hill, and Blackfoot to Neeley. These reaches are defined by gaging stations shown in Figure 4. Other reaches of the Snake River are also hydraulically connected to the aquifer. In these segments, the river may gain or lose water, depending on river stage and the water level in the aquifer. The Neeley to Minidoka reach both gains and loses water, with gains generally exceeding losses. Further upstream, between Heise and Lorenzo, the Snake River is a seasonally losing stream (Kjelstrom, 1995). Contours of the potentiometric surface indicate ground-water flow direction generally parallel to the axis of the plain, from the northeast to the southwest.

The SRPAM1.1 model grid, shown in Figure 4, consists of one unconfined layer of uniform 3.1 mile (5 km) square grid cells with 48 rows, numbered progressively increasing to the north, and 63 columns, numbered increasing to the east. The model is run using the U.S. Geological Survey's MODFLOW code (McDonald and Harbaugh, 1988) and was calibrated to transient conditions of April, 1980 to March, 1981 (IDWR, 1997; Cosgrove and others, 1999). Model boundaries include no-flow and specified flux (underflow) along the margins of the plain and a head-dependent representation of some segments of the Snake River. For more information on the Snake River Plain aquifer or the SRPAM1.1 model, the reader is referred to Cosgrove and others (1999).

Response Ratio Determination

Steady state response ratios for the eastern Snake River Plain were generated using MODRSP. A personal computer version of MODRSP source code was obtained from Colorado State University Department of Civil Engineering and modified to include logarithmic averaging of interblock transmissivity, as is used in the SRPAM1.1 model and as is available in the BCF-3 package of MODFLOW. MODRSP was also modified to generate output of response ratios in a format more suitable for the desired method of post-processing. Response ratios were generated running a Lahey Fortran Compiler executable MODRSP code on an IBM-compatible desktop system under Windows 95 DOS 4.0.

Steady state response ratios were calculated for each of the 1083 active model cells in the SRPAM1.1 model. The closure criterion of the strongly implicit solver package was set to 10^{-11} to achieve acceptable mass balance errors with application of a single unit stress. MODRSP calculated the response of river seepage in 51 hydraulically connected river cells to a unit stress for each active model cell (a result matrix of 51 x 1083). Response ratios for the 51 river cells were then aggregated to represent the response of six river reaches in the eastern Snake River Plain (matrix of 6 x 1083). The six river reaches (Figure 4) for which steady state response ratios were calculated were Heise to Lorenzo, Ashton to Rexburg, Lorenzo/Rexburg to Lewisville, At Blackfoot to Neeley, Neeley to Minidoka, and Kimberly to King Hill. For each of the six reaches, the response ratio values were mapped for each cell using ARCView 3.0. Figures 5 through 10 show the distribution of steady state response ratios for the six respective river reaches. The response ratios are color-coded in increments of one tenth.

A steady state response ratio of 0.2 for a given model cell and a given river reach means that once equilibrium is reached (after an infinite amount of time), 20% of any pumping stress from that model cell will be derived from that given river reach (decreased river gains, diminished spring discharge, or increased river losses). The reverse effects would apply for recharge. At steady state, the six river reach response ratios for any specific model cell sum to 1.0. This reflects the fact that in infinite time, the whole withdrawal is expected to come from streamflow (Jenkins, 1968). Figure 11 shows the six river reach responses for a single model cell at Location A. As can be seen in Figure 11, a unit stress at Location A has the strongest effect on the At Blackfoot to Neeley reach, with a response ratio of 0.76. At steady state, however, pumping from Location A has a measurable effect both upgradient and down-gradient. As can also be seen in Figure 11, the response ratios for Location A sum to 1.0 for the six reaches.

Figure 12 shows the river reach that is most affected by pumping within each model cell. This figure was generated by determining which of the six river reach response ratios was greatest for each model cell and color-coding the cells accordingly. Figures 5 through 10 and Figure 12 provide powerful tools for analyzing hydrologic connections within the eastern Snake River Plain. Representations such as these have potential use for water managers for setting up water user districts and for establishing ground-water/surface-water interference mitigation plans that are based on the aquifer characteristics.

Zones of Response Ratio Effects

The model cells were grouped into 20 zones, based on areas of similar hydrologic response to the six river reaches. Figure 13 shows the selected zones based on the steady state response ratios. The median value of response ratios for the six river reaches for all of the model cells within each zone is presented in Table 1. The median and range of

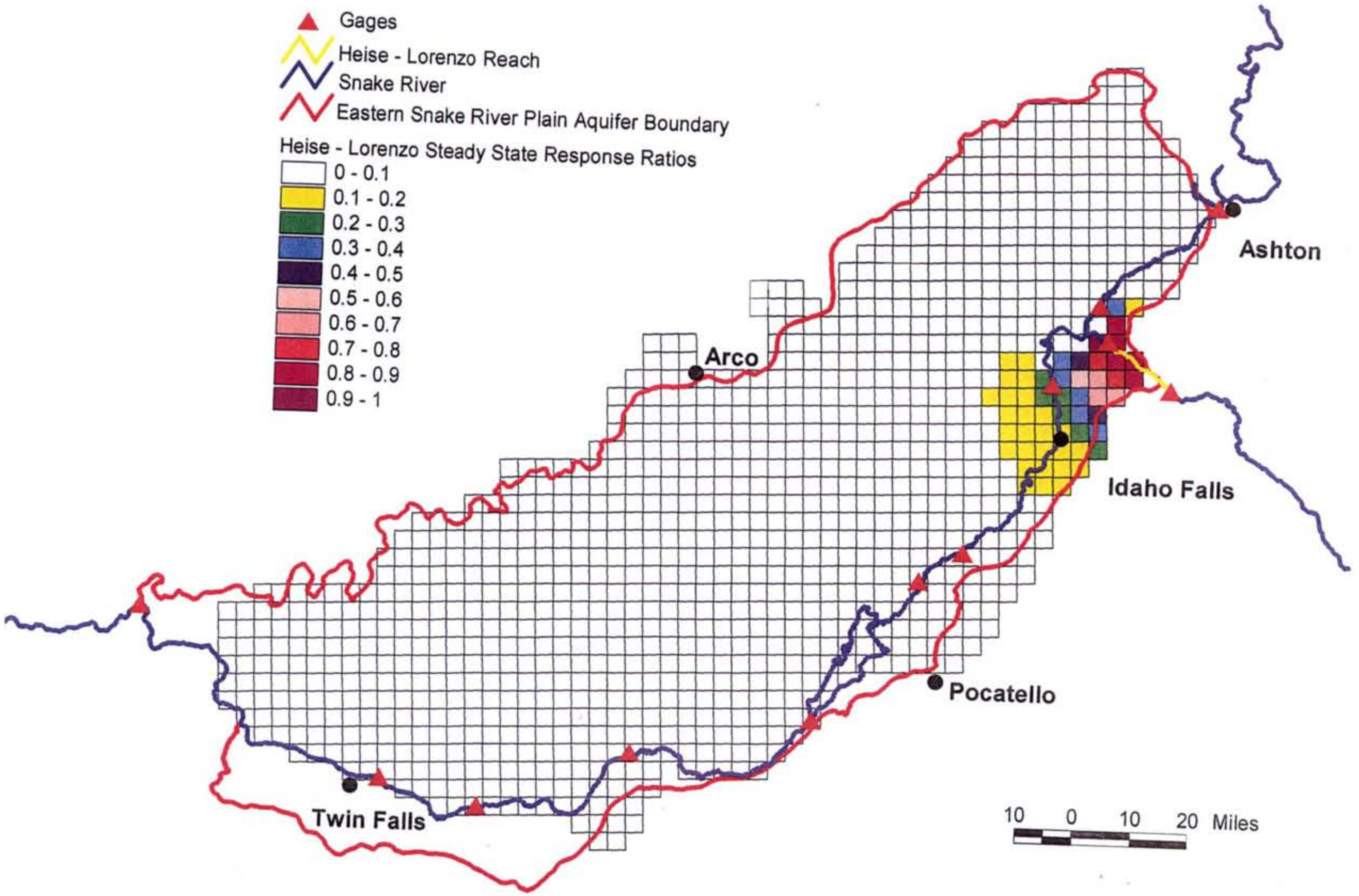

Figure 5. Steady State Response Ratios, Heise to Lorenzo Reach.

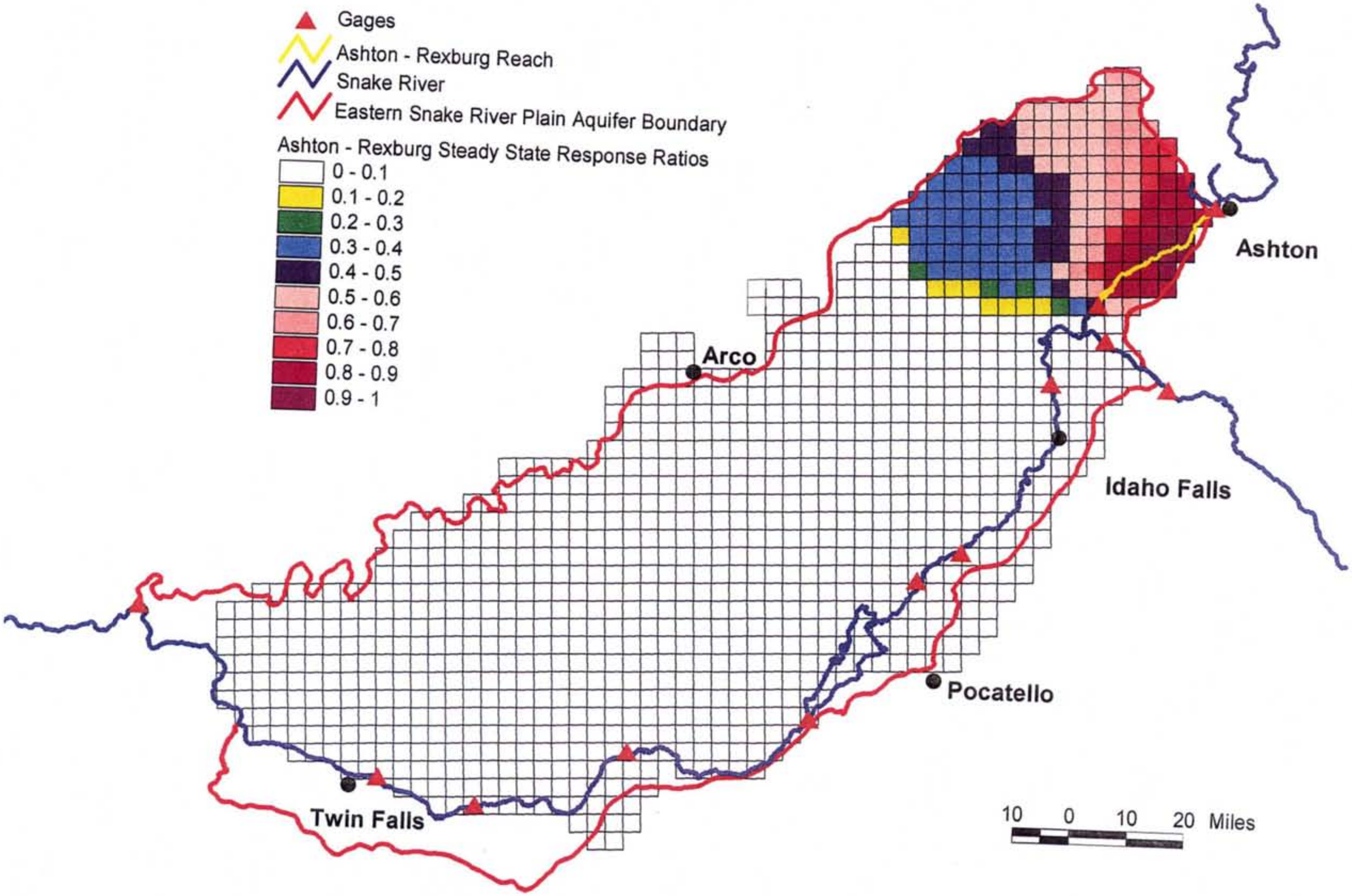

Figure 6. Steady State Response Ratios, Ashton to Rexburg Reach.

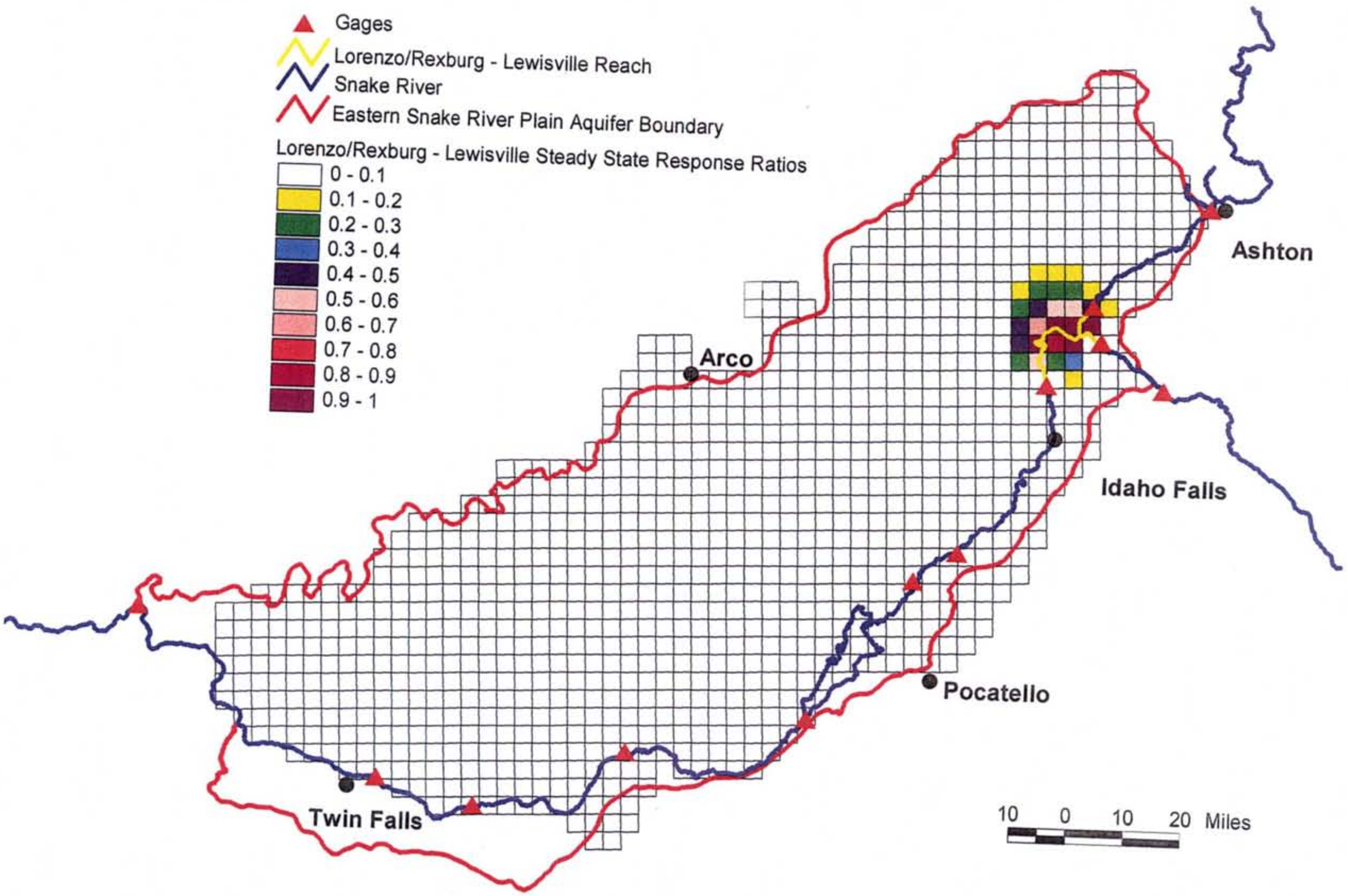

Figure 7. Steady State Response Ratios, Lorenzo/Rexburg to Lewisville Reach.

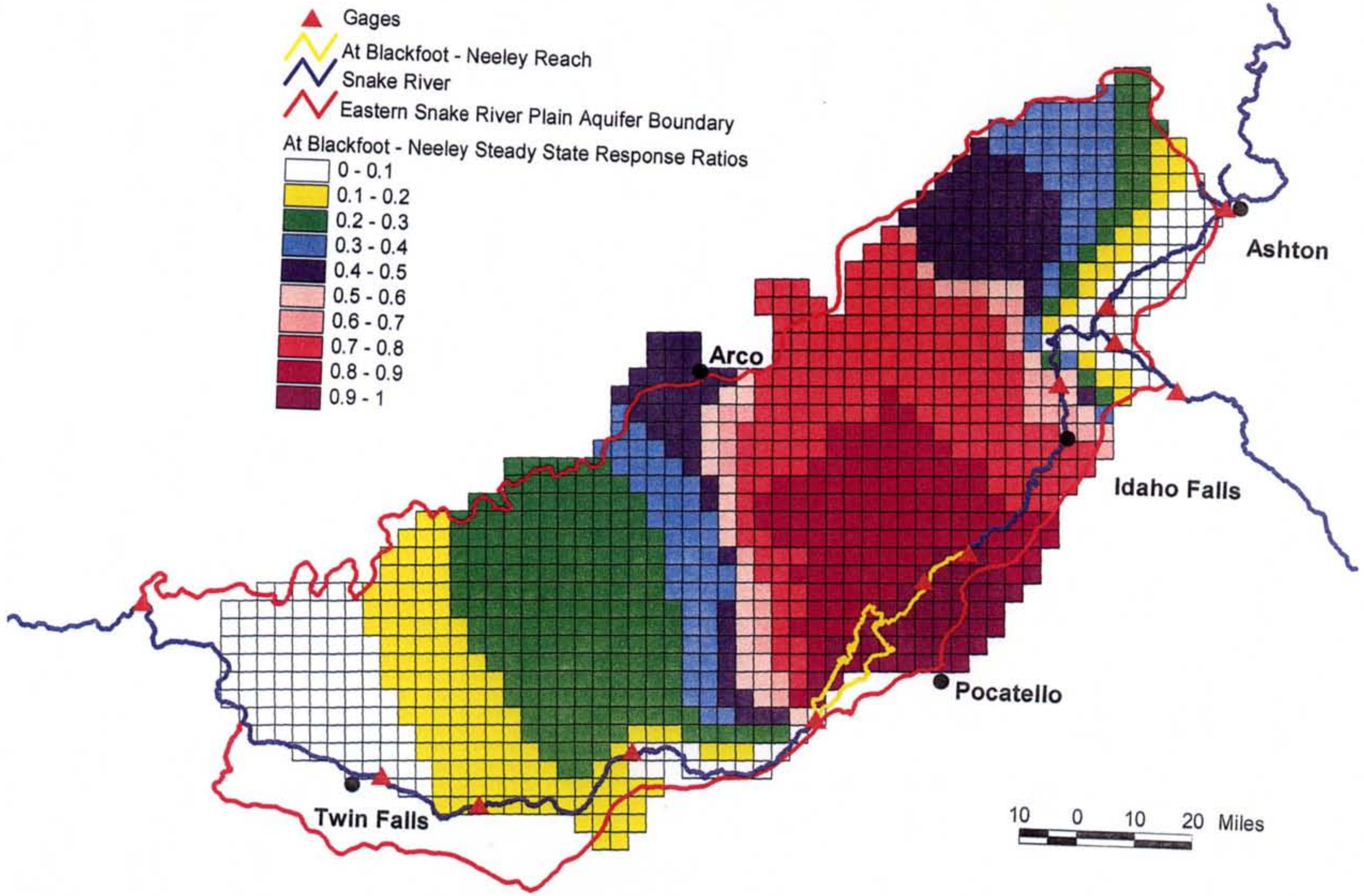

Figure 8. Steady State Response Ratios, At Blackfoot to Neeley Reach.

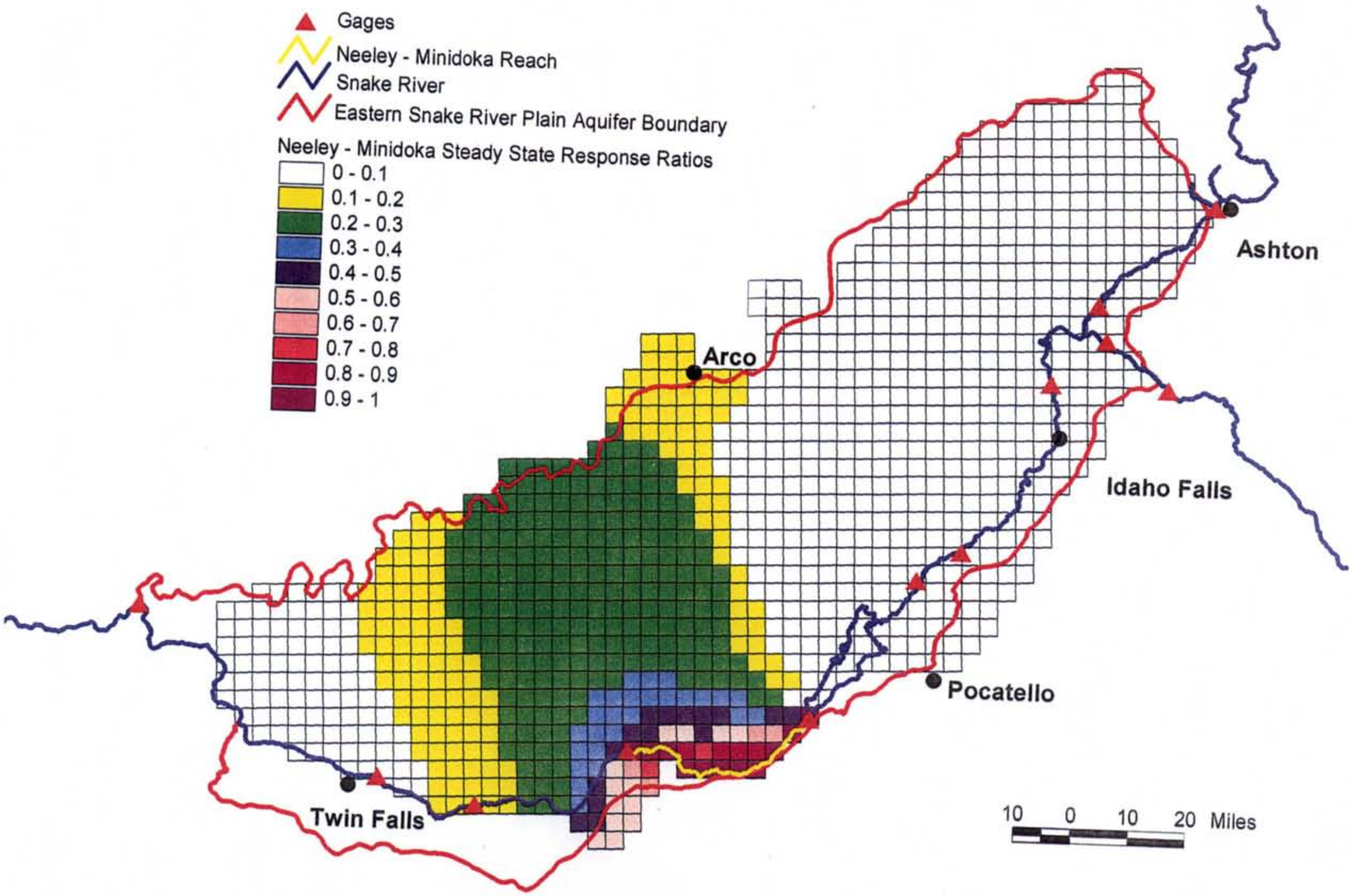

Figure 9. Steady State Response Ratios, Neeley - Minidoka Reach.

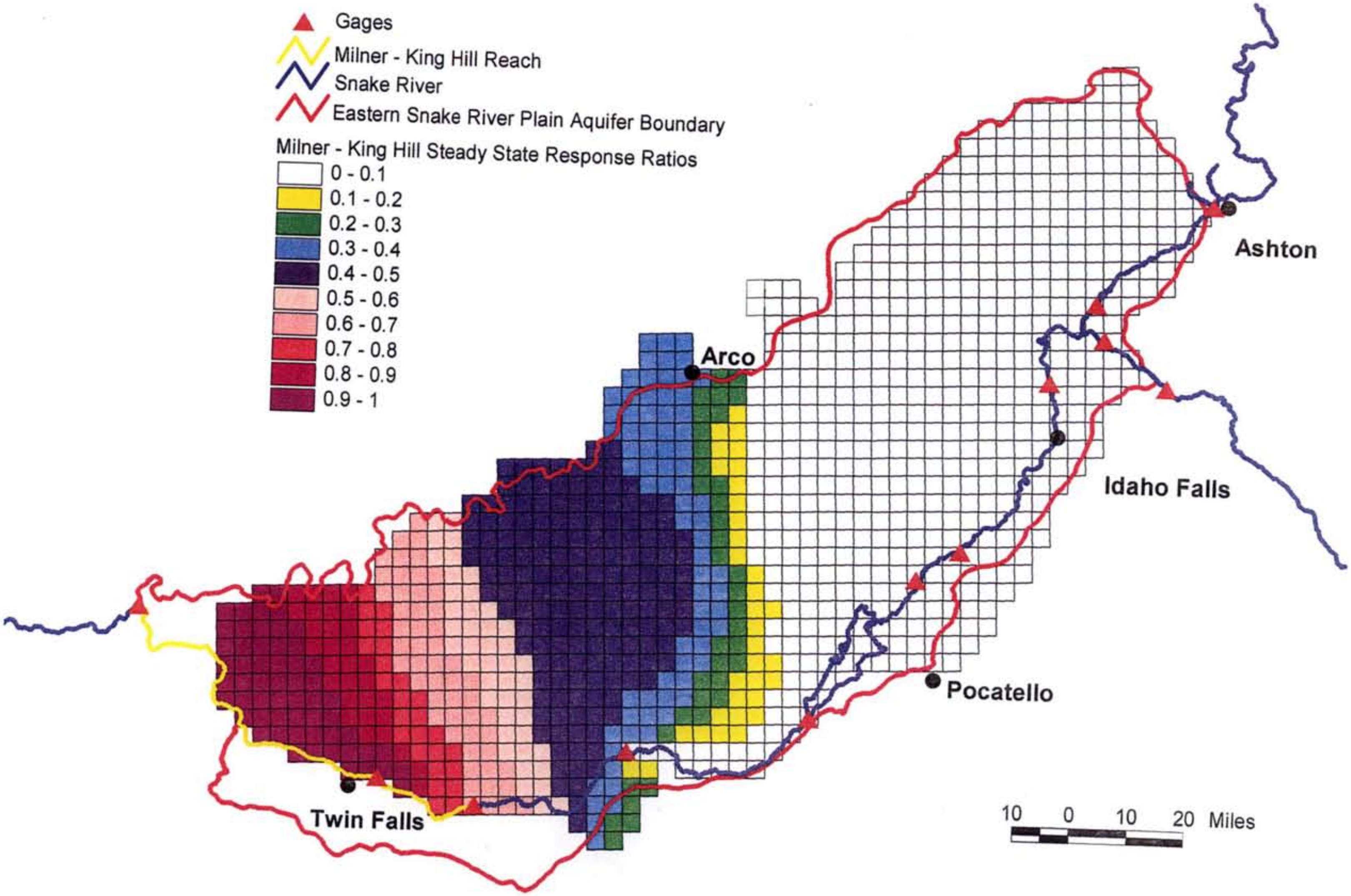

Figure 10. Steady State Response Ratios, Milner to King Hill Reach.

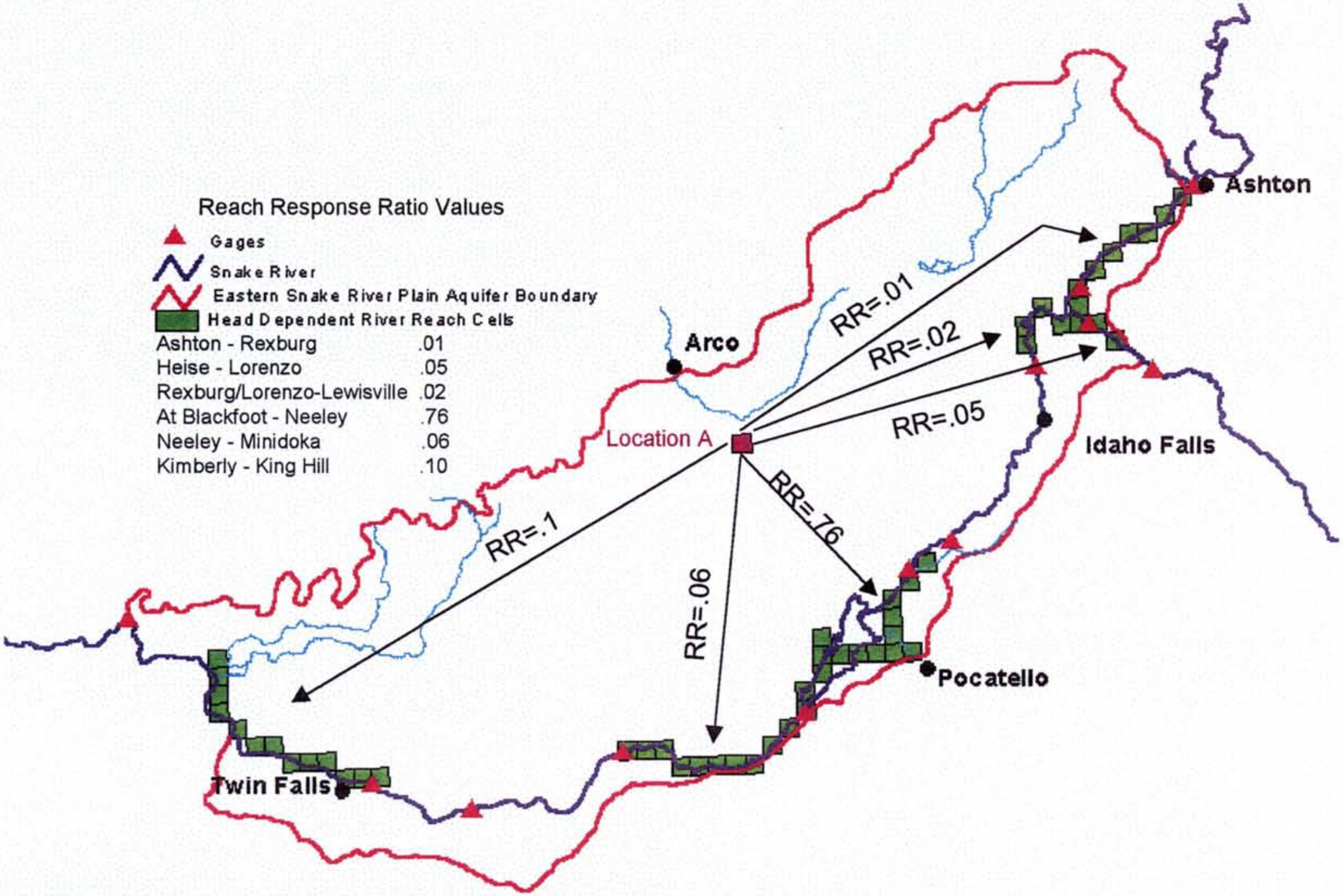

Figure 11. Steady State Response Ratios for a Selected Model Cell.

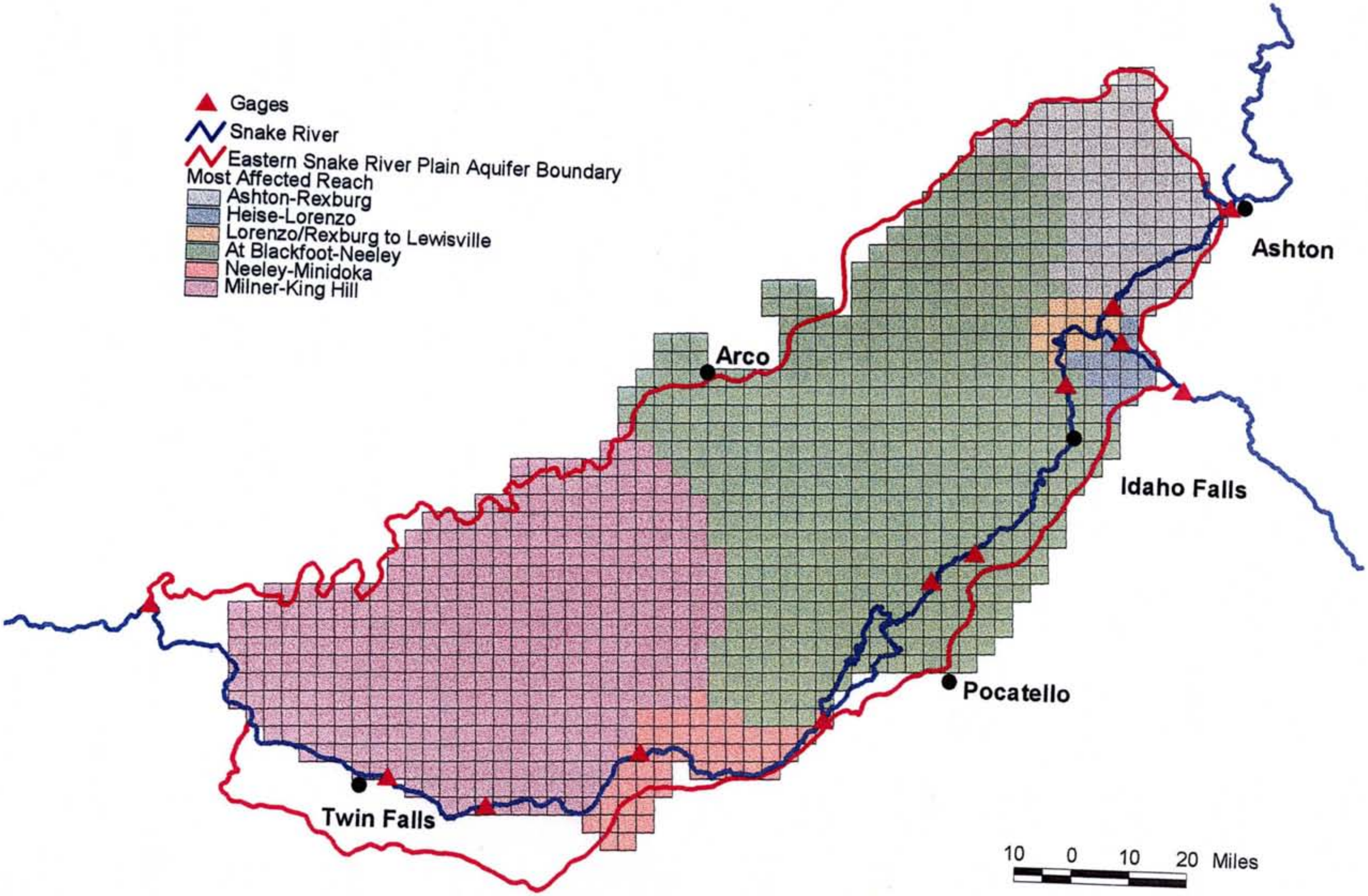

Figure 12. Most Affected River Reach for each Model Cell.

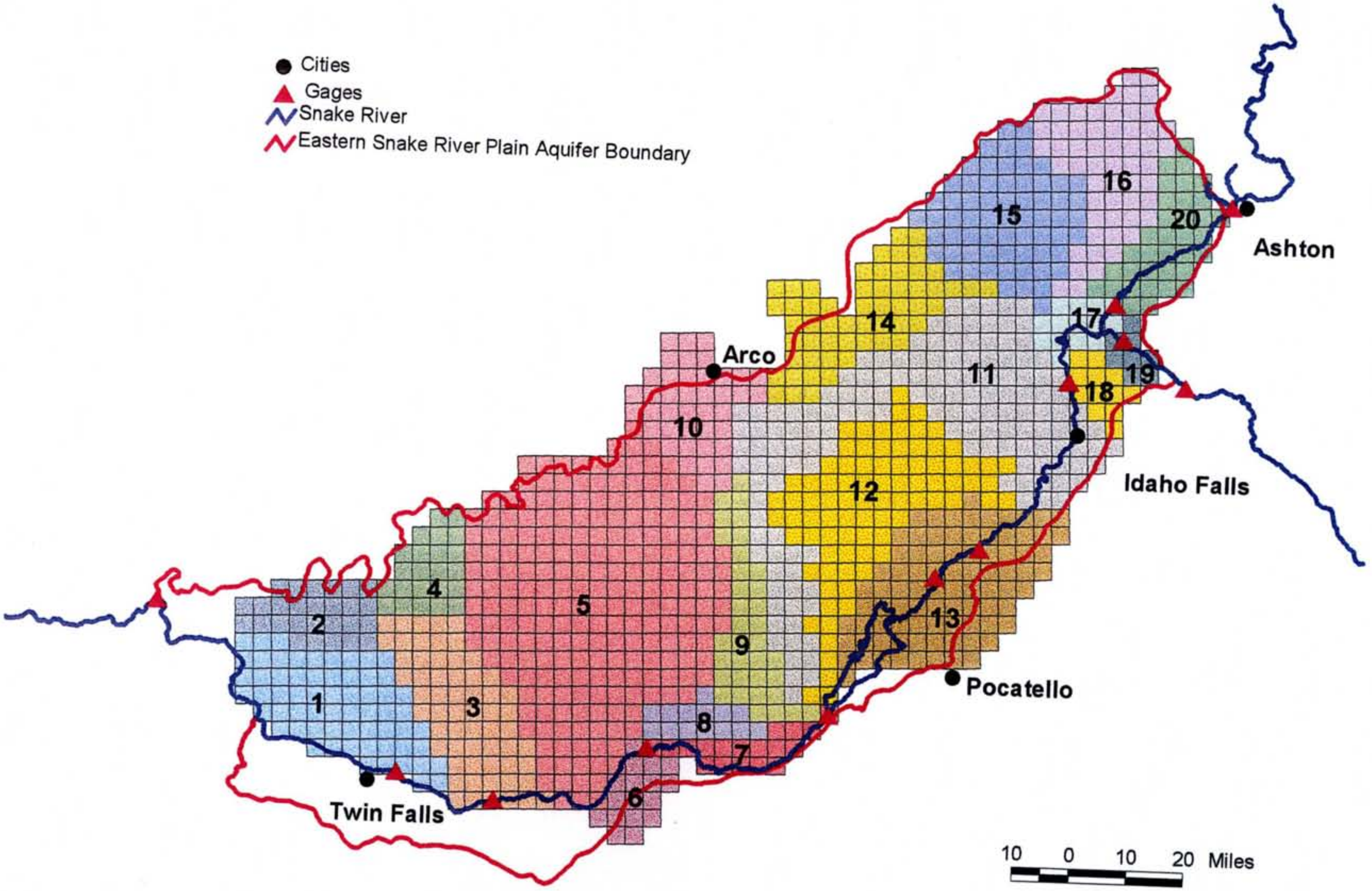

Figure 13. Aquifer Response Zones.

Table 1. Median Response Ratios for Snake River Plain Aquifer Zones.

Zone	Ashton to Rexburg	Heise to Lorenzo	Rexburg & Lorenzo to Lewisville	Shelley to Neeley	Neeley to Minidoka	Milner to King Hill
1	2.63E-04	1.05E-03	3.48E-04	2.17E-02	2.42E-02	9.50E-01
2	6.87E-04	2.36E-03	7.80E-04	4.67E-02	4.68E-02	9.05E-01
3	2.02E-03	7.01E-03	2.32E-03	1.40E-01	1.53E-01	6.94E-01
4	2.51E-03	8.77E-03	2.90E-03	1.75E-01	1.76E-01	6.34E-01
5	3.70E-03	1.30E-02	4.30E-03	2.59E-01	2.46E-01	4.58E-01
6	2.07E-03	7.19E-03	2.38E-03	1.43E-01	5.45E-01	3.05E-01
7	6.34E-09	1.20E-07	6.88E-08	1.20E-04	9.98E-01	1.78E-06
8	2.86E-03	1.00E-02	3.32E-03	2.44E-01	4.47E-01	2.69E-01
9	5.62E-03	2.00E-02	6.59E-03	4.72E-01	2.14E-01	2.50E-01
10	8.44E-03	2.64E-02	8.88E-03	4.65E-01	1.74E-01	3.14E-01
11	1.85E-02	7.27E-02	2.55E-02	7.61E-01	3.54E-02	5.35E-02
12	1.33E-02	4.72E-02	1.56E-02	8.19E-01	4.18E-02	6.38E-02
13	5.75E-03	2.26E-02	7.26E-03	9.16E-01	1.73E-02	2.53E-02
14	3.42E-02	5.90E-02	2.19E-02	7.75E-01	4.11E-02	6.41E-02
15	3.76E-01	5.92E-02	5.06E-02	4.55E-01	2.08E-02	3.15E-02
16	5.67E-01	4.80E-02	4.46E-02	2.99E-01	1.38E-02	2.11E-02
17	4.27E-02	4.84E-02	6.39E-01	4.41E-02	1.99E-03	3.20E-03
18	1.43E-02	4.36E-01	8.75E-02	3.57E-01	1.48E-02	2.21E-02
19	1.15E-02	8.48E-01	7.64E-02	5.87E-02	2.73E-03	4.47E-03
20	8.52E-01	2.63E-02	2.30E-02	6.67E-02	2.63E-03	3.81E-03

response ratios in each of the zones for each of the six river reaches are shown in Figure 14.

These selected zones will be used to integrate the steady state response ratios with a surface water model of the Snake River. Changes in aquifer recharge or discharge in each zone, multiplied by the respective median response ratio provides estimates of long-term change in river gains and losses. These can then be integrated with surface model inputs to more accurately reflect ground-water/surface-water interactions. Similar zones may become the basis for conjunctive management policy and for mitigation plans.

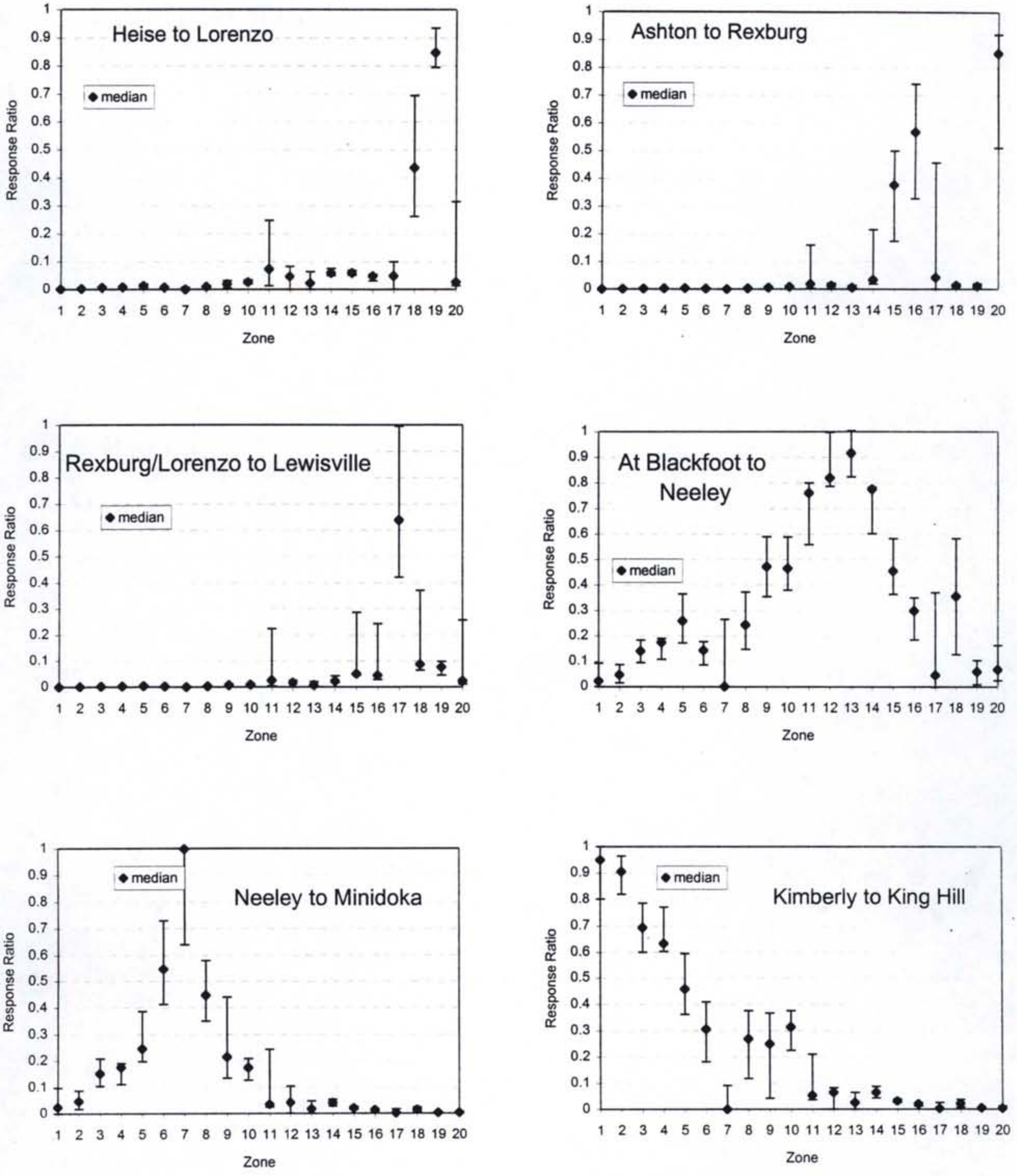

Figure 14. Median Response Ratios for Snake River Plain Aquifer Zones (vertical bars show the range of values within each zone).

CONCLUSIONS

Response ratios provide water managers with a powerful, flexible tool for analyzing ground-water/surface-water interactions within a stream-aquifer system. The tool is easy to apply in a basin with a calibrated numerical model and does not require extensive data input or analysis. Analysis of response ratios can provide new insight into the hydrologic characteristics of the basin. The tool has great potential for enabling relatively easy evaluation of basin scenarios and for integration with surface water models. From a basin management standpoint, response ratios offer the opportunity of establishing basin management and mitigation rules that are technically based and easy to apply.

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