Abstract

To be supplied. Will include brief summary of model limitations or pointer to section on model limitations in addition to report summary.

Introduction

Background and Study Objectives

This project was initiated as a joint effort between groups of eastern Snake River Plain (ESRP) water interests with a goal of enhancing and rebuilding the ground-water model used to support management decisions on the eastern Snake River Plain. The study was funded jointly by Idaho Power, the State of Idaho, the U.S. Bureau of Reclamation, with in-kind services from the U.S. Geological Survey (USGS). Technical oversight and input from representatives of water user groups were incorporated in an effort to create the best possible technical tool for management of ground water resources on the eastern Snake River Plain, which all parties could agree was an unbiased representation of the complex aquifer system. This would allow water disputes to remain in the realm of water management and not the scientific tools used to support these management decisions. Appendix A describes the process which was established for allowing oversight and technical input from the interested parties.

In addition to the primary objective of creating a model which all disputing parties could participate in and agree to, the project has several other objectives. These objectives are: a) to create a numerical ground-water model of the eastern Snake River Plain which is calibrated to a sufficient time period to represent a wide range of aquifer stresses, b) to improve the model representation of river/aquifer interaction, c) to fully document the new model including major design decisions and data, and d) to create the model using state of the art model development methods.

Project Scope

The scope of this project was limited to the reformulation and re-calibration of the ground-water model used for water management on the eastern Snake River Plain. This entails the accurate accounting of aquifer recharge and discharge for the modeled period, an accurate assessment of water use on the eastern Snake River Plain, and creation and calibration of a numerical model to represent the Snake River Plain aquifer. The scope of the project was limited to model creation and calibration and did not entail generation of water management scenarios.

ESPAM Model Version

During the preparation of this final project report, some data entry errors were discovered in the original model calibration, requiring model re-calibration. The data entry errors were centered around the calibration targets used for the river reaches in the upper Snake River. The most significant data entry errors were that the measured irrigation return flow percentages had not been integrated into the model calibration targets and there was a mismatch in reach integration between the model-predicted and observed values for the Shelley to Near Blackfoot and Near Blackfoot to Neeley reaches. These data entry errors were corrected and the model was re-calibrated in May, 2005, resulting in the release of ESPAM Version 1.1, which is described in this report. These data entry errors did not significantly affect results of the model simulation.

Acknowledgements

Study Area Description

The Snake River Plain extends in an arcuate shape across most of southern Idaho and into eastern Oregon. The plain is divided into eastern and western regions based primarily on ground-water hydrology. The eastern Snake River Plain is the focus of this report and entails an area of about 10,000 square miles extending from Ashton, Idaho in the northeast, southwest to King Hill, Idaho (Figure 1). The boundaries of the plain, shown in Figure 1, were originally defined by the U.S. Geological Survey's Regional Aquifer- System Analysis (RASA) program (Lindholm, 1993) and were modified for this study (see Geographic Boundary Conditions section). The model boundary shown in Figure 1 is the modified boundary used for this study. Elevation of the eastern plain varies from about 2600 feet above sea level in the southwest to over 5000 feet in the northeast.

Population within the plain is generally sparse, with most of the population residing along the eastern and southern margins of the plain in an agriculturally productive band near the Snake River. Much of the remainder of the plain is federal land managed primarily by the U.S. Bureau of Land Management. Extensive portions of the plain are covered by rugged basalt outcroppings that include the Craters of the Moon National Monument.

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

Irrigation on the eastern Snake River Plain began in the late 1800s using water from the Snake River and its tributaries. Garabedian (1992) describes changes in surface-water and ground-water irrigated areas on the eastern Snake River Plain that are shown graphically in Figure 2. Acreage irrigated by surface water has been declining since the mid-1940s. Since the onset of ground-water irrigation in the 1950s, the number of acres irrigated by ground water increased steadily until the early 1990s.

Irrigation practices are continually changing in response to technology and economic factors. Furrow, flood, and sub-irrigation were the dominant methods of water application into the second half of the twentieth century. In the 1980s and 1990s sprinkler systems have commonly replaced surface application methods, with a resulting decrease in the amount of water diverted per acre of agricultural land.

Significant legal developments in the 1990s have dramatically affected water use on the Snake River Plain. A basin-wide adjudication of water rights was initiated in 1987 (Idaho Water Resources Board, 1996). The Idaho State legislature enacted legislation affecting the adjudication, including recognition of enlargements in irrigated acreage that occurred before 1987. A moratorium on expansion of irrigated acreage has been in effect for the Snake River Basin since 1992. The moratorium includes both surface and ground water irrigated lands within the basin (Idaho Water Resource Board, 1996). Conjunctive management rules were adopted by the Idaho Department of Water Resources (IDWR) in 1994, essentially linking administration of ground- and surface- water rights. Water measurement districts were established in 1996 to provide records of ground-water pumpage for irrigation. Managed recharge of the Snake River Plain aquifer has also been supported by the Idaho legislature. Estimates for managed recharge, which has occurred at various locations through existing irrigation facilities, are listed in Table 1.

The onset of drought conditions in 2000 caused multiple legal actions to be initiated accelerating the conjunctive administration of surface and ground water resources. It was widely agreed that the old numerical model of the eastern Snake River Plain was not sufficiently documented to support conjunctive management decisions.

Model History

Numerical ground-water flow models of the Snake River Plain aquifer have been developed and applied by state and federal agencies, universities, and private interests. The models vary in purpose, extent, and the computer code employed. The first numerical model of the aquifer was developed by the University of Idaho for IDWR and the U.S. Bureau of Reclamation (deSonneville, 1974). The original IDWR/UofI model has undergone multiple revisions and improvements, described below.

The finite-difference model code developed by the University of Idaho and evolved by the University and the IDWR will be referred to as the IDWR/UI Ground Water Flow Model Code. The application of this code to the Snake River Plain aquifer will be referred to as the IDWR/UI Ground Water Flow Model, following the convention established by the IDWR (IDWR, 1997a). The IDWR has applied various versions of this model as a planning and management tool for over two decades.

In the early 1980s, the IDWR/UI Ground Water Flow Model was re-calibrated to 1980-1981 conditions. This re-calibration was able to capitalize on the extensive data collection effort which the USGS did in support of the Regional Aquifer-System Analysis

(RASA) study of the Snake River plain during that period. In the early 1980s, the USGS also created a model of the eastern Snake River Plain aquifer for scientific investigations (Garabedian, 1992).

In 1999, the IDWR/UI Ground Water Flow Model was converted to use one of the most widely used and accepted ground-water modeling codes, MODFLOW (McDonald and Harbaugh, 1988). The conversion to MODFLOW was not intended to create a new model, but to develop an equivalent model using a different code. Model representation of physical properties such as aquifer transmissivity, storage and streambed conductance were preserved in this conversion of the IDWR/UI Ground Water Flow Model to the MODFLOW code. This MODFLOW application to the Snake River Plain aquifer will be referred to as the Snake River Plain Aquifer Model (SRPAM), with the most recent version being SRPAM1.1. There were several benefits gained from conversion to the MODFLOW code including: a) the MODFLOW code is accepted as an industry standard, b) MODFLOW includes algorithms that simulate physical processes and have been verified against analytical solutions, c) MODFLOW is more familiar to a wider group of scientists and engineers, d) numerous user interfaces have been developed for MODFLOW, e) MODFLOW capabilities are continuously increasing, f) MODFLOW has a significant capability for treating more advanced features such as three-dimensional flow and variable grid spacing, and g) the MODFLOW code is well documented.

In addition to conversion of the IDWR/UI Ground Water Flow Model to the MODFLOW code, the model was modified to improve model representation of the physical system. This was achieved primarily by expansion of the model domain to include segments of the Snake River and tributaries in the northeast portion of the plain that were not previously simulated. Additionally, model documentation was significantly enhanced (Cosgrove and others, 1999; Johnson and others, 1999).

With the potential for rising conflict between surface water and ground water users on the eastern Snake River Plain, in 2000, IDWR embarked upon a full reformulation and re-calibration of the ground water model. This effort resulted in the model which is documented in this report. The resulting model is called the Enhanced Snake Plain Aquifer Model (ESPAM).

Hydrogeology

Geologic Framework

The surface of the Snake River Plain consists primarily of volcanic rocks, which, in most areas, are covered by a veneer of windblown or fluvial sediments. Sediment deposits overlying the basalt vary in thickness from zero to tens of feet. Exposed volcanic rocks are predominantly basalt, which in places such as the Craters of the Moon National Monument, cover expansive areas.

The eastern Snake River Plain is composed of a series of relatively thin basalt flows and interbedded sediments. Flows range in thickness from a few feet to tens of feet. Welhan and Funderberg (1997) report median flow thickness near the Idaho National Laboratory ranging from about 7 to 25 feet. Individual flows typically have a rubble or clinker zone at the top and bottom with a more massive interior containing fewer vesicles. Vertical fractures in the flow interiors form columnar basalt in some locations (Garabedian, 1992). Individual basalt flows generally are not extensive (Welhan and Funderberg, 1997). The collective thickness of basalt flows of the eastern Snake River Plain is estimated to exceed several thousand feet in places (Whitehead, 1986). More detailed descriptions of the geology of the eastern Snake River Plain are provided by Anderson (1991), Whitehead (1986), and Kuntz and others (1992).

The eastern plain is bounded structurally by faulting on the northwest and downwarping and faulting on the southeast (Whitehead, 1986). The plain is bounded by Yellowstone Group rhyolite in the northeast and Idavada volcanics in the southwest. Granitic rocks of the Idaho batholith, along with pre-Cretaceous sedimentary and metamorphic rocks, border the plain to the northwest (Garabedian, 1992).

Surface-Water Hydrology

The Snake River passes along the southern margin of the eastern Snake River Plain and is the exclusive surface water discharge mechanism for the eastern plain. Ground water underflow from the eastern plain into the western plain is assumed to be minimal, due to the more extensive low hydraulic conductivity sedimentary deposits of the western plain. Consequently, flow of the Snake River at King Hill is widely considered to be the equivalent of basin discharge, excluding evaporation. Annual discharge of the Snake River at King Hill is shown in Figure 3. The cumulative discharge line in Figure 3 shows little long-term change in slope. This indicates that despite significant changes in water use during the last several decades, there has been little change in basin outflow. A possible reason for the stability of the slope of the cumulative graph in Figure 3 is that human activities have apparently had a greater temporary impact on aquifer storage than on basin outflow.

The Snake River is intensively managed for irrigation and hydropower generation. The average annual flow, major inflows and diversions at different points within the system are illustrated by river width in Figure 4. The flow in the Snake River is noticeably depleted at Milner Dam where substantial diversions are made for irrigation. A gradual increase in river flow below Milner Dam is due largely to aquifer discharge in the form of springs emitting from the wall of the Snake River canyon. North of Idaho Falls, in the eastern part of the plain, the Henrys Fork (locally referred to as the North Fork) joins the Snake River, locally referred to as the South Fork, shortly downstream from Lorenzo, Idaho. The origin of the Henrys Fork is in the Island Park area to the northeast of

the Snake River Plain. Headwaters of the Snake River (South Fork) are in Yellowstone Park in Wyoming. On average, yield of the Snake River at Lorenzo is about triple the yield of the Henrys Fork near Rexburg.

Several reservoirs have been constructed on the Snake River and its tributaries for the purposes of irrigation, flood control, hydropower generation, and recreation. In some years, spring snowmelt exceeds system storage capacity and irrigation demands and water is spilled past Milner Dam. On average, about two million AF of water are discharged annually past Milner Dam (Figure 5).

Direct tributaries to the Snake River occur primarily from the east and south sides of the basin. Several streams along the northern margin disappear through seepage before flows can reach the Snake River (Figure 4). Only flows of the Big and Little Wood Rivers, Silver Creek (not shown in Figure 4, but tributary to the Big Wood River), and Camas Creek may eventually reach the Snake River from the northern margin of the plain. Other streams on the northern margin of the plain, such as the Big and Little Lost Rivers, contribute recharge to the Snake River Plain aquifer, but do not directly discharge to the Snake River.

An extensive network of irrigation canals provides water for approximately 1.0 million acres of surface-water irrigated land on the eastern Snake River Plain. Different reports provide different estimates of surface water irrigated land due to: 1) differences in the area being evaluated, 2) difficulties discriminating between ground-water and surface-water irrigated land in some locations, and 3) the application of adjustments for non-productive lands (e.g. homesteads, roads, ditches) within an area that appears irrigated in satellite images. In 1980, the U.S. Geological Survey reported 2.1 million acres of irrigated land (both surface- and ground-water) on the eastern Snake River Plain (Garabedian, 1992) within the RASA aquifer boundary. For the current study, it was estimated that there are 1.0 million acres irrigated by surface water and 1.1 million acres irrigated by ground water, for a total of 2.1 million irrigated acres.

Irrigation diversions consume a large proportion of the flow of the Snake River during irrigation season. Diversions of surface water for irrigation in the eastern Snake River Plain (including all tributaries) have diminished by about 20 percent from the nearly eight million AF/yr diverted in the early 1970s (IDWR, 1997a). Irrigation diversions both deplete and affect the timing of flows in the river, with some of the diverted water returning to the river as either surface or ground water return flows. In addition, surface water diverted for irrigation also has a major effect on recharge of the Snake River Plain aquifer as will be discussed in the following section.

Ground-Water Hydrology

The Snake River Plain aquifer underlies the eastern Snake River Plain. This highly productive 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 which 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 gallons per minute per foot of 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 margins of the plain 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 often is thought to be limited to the upper several hundred feet of saturated thickness. Robertson (1974) states that "Although the real aquifer system is probably more than 1,000 feet thick, a thickness of 250 feet is used in this study based on the apparent layering effects of the aquifer." Based on the presence of low permeability sedimentary layers encountered in a well drilled on the Idaho National Laboratory, Mann (1986) suggests that the aquifer is 450-800 feet thick. Model studies by the U.S. Geological Survey (Garabedian, 1992) represent the aquifer as four layers with a collective thickness ranging from 500 to over 3,000 feet. Modeling by the IDWR and the University of Idaho (deSonneville, 1974; Newton, 1978; IDWR, 1997a) represents the aquifer as a single layer ranging from 200 to 1,700 feet thick.

The Snake River Plain aquifer generally is 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 also may 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 losses; subsurface flow from tributary valleys; and precipitation directly on the plain. The aquifer discharges to the Snake River, springs along the Snake River and to ground-water pumping, primarily for irrigation. The relative magnitudes of the recharge and discharge components were evaluated by the USGS (Garabedian, 1992) and, more recently, for this study. Estimates from the USGS represent conditions in 1980 for the entire Snake River Plain (Figure 6). Estimates from the current study represent an average of 1980 through 2001 conditions (Figure 7). The USGS estimates of water budget components include portions of the plain not included in the current estimate due to differences in model boundaries (model extent is discussed in a later section).

Incidental aquifer recharge from irrigation is a significant component of the water budget and has varied as irrigation practices have evolved. The 1980 water budget of the USGS (Garabedian, 1992), shown in Figure 6, shows that surface water irrigation contributes more than 50 percent of the total recharge to the aquifer. Historically, recharge from surface water irrigation increased as more land was brought into production up to the 1970s. Since the 1970s, a gradual conversion to sprinkler irrigation methods reduced the amount of incidental recharge from irrigation.

Natural discharge from the Snake River Plain aquifer is primarily to the Snake River along two reaches: Kimberly to King Hill, and Near Blackfoot to Neeley. These reaches are defined by gaging stations shown in Figure 1. Spring discharge has varied in response to changes in precipitation, irrigated acreage, and irrigation practices. Overall, discharge in the Kimberly to King Hill reach appears to have been impacted more than in the Near Blackfoot to Neeley reach (Figure 8), although the Near Blackfoot to Neeley reach shows more seasonal variation since approximately 1970. The effects of weather variation and irrigation recharge are apparent from the short-term variation of spring discharge. Maximum discharge occurs around October, near the end of the irrigation season. The seasonal variation in the Blackfoot to Neeley and Milner to King Hill reaches is about 15 and 20 percent of the respective maximum reach gains (from interpretation of Kjelstrom, 1995).

Other reaches of the Snake River also are 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 South Fork of the Snake River is a seasonally losing stream (Kjelstrom, 1995a). Average annual loss of this reach was 150 ft^3/sec in the 1980 water year. During that same period, the Lorenzo to Lewisville reach of the main stem of the Snake River and the lower Henrys Fork reach were estimated to have gained 290 and 120 ft^3/sec, respectively (Garabedian, 1992).

Contours of the potentiometric surface indicate that ground-water flow direction generally is parallel to the axis of the plain (Figure 9). Steep hydraulic gradients are apparent near the margins of the plain due to tributary valley inflow and lower transmissivity relative to the center of the plain. Steep gradients also are apparent near the Kimberly to King Hill discharge area due to convergence of flow lines and probable aquifer thinning. Near the center of the plain and near Mud Lake, steeper gradients presumably result from decreased transmissivity due to the volcanic rift zone and thick sediment deposits, respectively. Garabedian (1992) used transmissivities ranging from $4x10^3$ to $1x10^7$ ft^2/day. The SRPAM model had transmissivities which ranged from $2x10^4$ to $5x10^6$ ft^2/day. These ranges of values are consistent with published values for fractured basalt.

Aquifer storage in the eastern Snake River Plain aquifer is reasonably high due to the highly fractured nature of the system. Garabedian (1992) used specific yield values ranging from .05 to .2 (unitless ratio). Specific yield values used in the SRPAM model were higher, ranging from .08 to .26. The specific yield values used by Garabedian and the SRPAM model are consistent with published specific yield values for fractured basalts in unconfined systems, although the SRPAM values are generally thought to be high.

Aquifer water levels have changed significantly over the past several decades in response to changes in irrigation and variations in weather. Figure 10 shows the water level changes on the eastern Snake River Plain for the period from spring, 1980 to spring, 2002. This change in water level corresponds approximately to the change in aquifer storage shown in Figure 7 (Figure 7 shows the change in storage up through 2001). During that period, water levels across the plain generally declined between 5 and 15 feet, with some areas experiencing declines as great as 20-25 feet. The greatest changes in water level appear in a band traversing the south-central portion of the plain. Figure 11 shows water level declines between spring, 2001 and spring, 2002, the last year of the period shown in Figure 10. The reader will note that water level declines shown in Figure 11 are almost half of the total decline in the 1980-2002 period, reflecting a rapid aquifer response to the drought conditions of the year 2001-2002. This would indicate that under long-term, average conditions (1980-2001), water use on the eastern Snake River Plain was reasonably in balance with use slightly exceeding supply. The rapid decline in the 2001-2002 year indicates that additional water level declines occur rapidly under drought conditions. This general decline in water level is consistent with observed declines in aquifer discharge to the Snake River.

Model Description

Governing Equations and Model Code

The mathematical equations governing unconfined flow are non-linear due to the fact that saturated thickness and, therefore, transmissivity, change with time. In confined systems, saturated thickness is constant, therefore the mathematical representation is linear.

The ESPAM model is a confined representation of the eastern Snake River Plain aquifer. This decision was made by the ESHM Committee and was consistent with field observations of the propagation of pumping impacts through the aquifer (Frederick and Johnson, 1996). Additionally, the deep saturated thickness supports the representation of a generally unconfined aquifer as confined since drawdowns in the highly transmissive aquifer will be less than 10% of total saturated thickness in most management applications (Anderson and Woessner, 1992). The confined representation of the eastern Snake River Plain aquifer allows a more stable numerical simulation of the aquifer during automated model calibration. ESPAM Design Document DDM-019 discusses the confined representation of the ESPAM model.

The general equation governing confined, steady state, anisotripic, heterogeneous flow in two dimensions is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)=0 \qquad \text{(Eq. 1)}$$

where:

K_{xx} is hydraulic conductivity in the x-dimension (ft/d)

K_{yy} is hydraulic conductivity in the y-dimension (ft/d)

h is aquifer head (ft)

The general equation governing confined, transient, anisotropic, heterogeneous flow in two dimensions is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \text{(Eq. 2)}$$

where:

K_{xx} is hydraulic conductivity in the x-dimension (ft/day)

K_{yy} is hydraulic conductivity in the y-dimension (ft/day)

h is aquifer head (ft)

W is the rate of aquifer recharge (1/day)

S_s is specific storage (1/ft)

t is time (days)

The ESPAM model comprises both a steady state and transient, two-dimensional, isotropic representation of the eastern Snake River Plain aquifer. The isotropic representation means that $K_{xx} = K_{yy}$. In a numerical model, individual model cells are homogeneous. Heterogeneity is represented by the spatial variation of properties such as transmissivity, on a cell by cell basis. Therefore, the governing equations for a numerical model are the same as for a homogeneous system. Multiplying Equations 1 and 2 by b/T, where b is saturated thickness (ft) and T is aquifer transmissivity (ft^2/day), yields the following:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} - W\frac{b}{T} = 0 \quad \text{(Eq. 3)}$$

and

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} - W\frac{b}{T} = \frac{S}{T}\frac{\partial h}{\partial t} \quad \text{(Eq. 4)}$$

where:

T is aquifer transmissivity (ft^2/day)

h is aquifer head (ft)

W is the rate of aquifer recharge (1/day)

S is storativity (dimensionless)

t is time (days)

b is aquifer thickness (ft)

Equations 3 and 4 represent the governing equations used for representing groundwater flow in the ESPAM steady state and transient models, respectively.

Flow between the aquifer and river or drain cells is governed by equations which are based on Darcy's law. Darcy's law is:

$$Q = -KA\frac{dh}{dl} \quad \text{(Eq. 5)}$$

where:

Q = discharge (ft^3/day)

A = cross-sectional area (ft^2)

K = hydraulic conductivity (ft/day)

dh/dl = hydraulic gradient (dimensionless)

In a numerical model, for both river and drain cells, the hydraulic conductivity term represents the conductivity of the river-bed or drain sediments which controls the flow between the river/drain and the aquifer. The gradient (dh/dl) represents the head differential between river stage (or drain elevation) and aquifer level.

In a finite-difference model, the ground-water flow equation is solved for each individual model cell and river or drain cell, preserving the mass balance of water. Each model cell can have individual properties representing aquifer transmissivity and storage. Similarly, all river and drain cells can have individual properties representing river/drain elevation and conductance. At every time step of the model, the equations are solved simultaneously using a numerical solver.

The ESPAM model was constructed using MODFLOW2000, a finite-difference code widely used for ground-water modeling which was created by the U.S. Geological Survey (McDonald and Harbaugh, 1988, Harbaugh and others, 2000). The ESPAM model was constructed using the Link-Module Gradient (LMG) solver (Mehl and Hill, 2000), however, the model can also be run using the Pre-Conjugate Gradient solver (Hill, 1990). With the LMG solver, the water budget closure criterion is .00001 and the dampening parameter is 1.0. The parameter estimation code, PEST version 8.3 (Doherty, 2004) was used to assist with model calibration.

MODFLOW2000 was selected because it is considered an industry standard for finite difference ground-water models. PEST was selected because of adaptability to the complexity of the model calibration where model results were compared with thousands of aquifer measurements during the calibration process.

Discretization

Finite difference modeling consists of breaking a large physical area into small volumes, which are called model cells, and simultaneously solving the numerical problem (Equations 3, 4 and 5) for each model cell. Additionally, if the model is transient, the total simulation time is also broken down into smaller time periods and the problem is solved at the end of each time period. In the case of ground-water modeling, the problem is being solved to determine aquifer head at each of the model cells and flux to drains and to/from rivers. This process of breaking the larger pieces down into smaller pieces is referred to as discretization.

For a uniform grid, the estimated aquifer head for each model cell represents the head at the center of the cell. If the cells are very large and the gradient is steep, interpolating head at locations other than at the center of the cell can introduce significant error.

Spatial Discretization

The spatial discretization of the model study area is the representation of the eastern Snake River Plain aquifer system in small volumes. The study area was overlain by a uniform 1 mile x 1 mile grid. The grid was intersected with the model boundary. Any cell within the model boundary was considered an active cell, or a cell for which aquifer head would be computed using the model. Any cell outside of the model boundary was considered an inactive model cell and not part of the calculation of aquifer head.

Model Grid

The ESPAM grid consists of 104 rows and 209 columns. The grid rows are numbered with row 1 at the top of the grid. The grid columns are numbered from west to east, with column 1 being the west-most column. The grid origin is at the outside corner of model cell (1,1), the most northwest point of the model grid, and is at Idaho Transverse Mercator (IDTM) coordinates x=378416.2 m and y=233007.2 m (in feet: x=1241523 and y=764459.2, latitude = 43.118806°, longitude=-115.49619 °). The reader should note that these IDTM coordinates are in the original IDTM system (IDTM 27) and not the IDTM83 system which was adopted in 2004. For more information on IDTM coordinates, the reader is encouraged to contact IDWR.

The model grid is rotated 31.4° counter-clockwise relative to an east-weat orientation. The rotation is selected to minimize the number of inactive model cells. Figure 12 shows the model grid, the origin and the orientation. The grid is comprised of model cells which are 1 mile x 1 mile square cells (5280 ft x 5280 ft). There are 11,451 active model cells. Selection of the 1 mile x 1 mile grid size was consistent with the density of data available for the study area and the steepness of gradients in the Snake River Plain aquifer. Figure 13 shows a close-up of the model grid in the Thousand Springs area (between the Kimberly and King Hill gages) and the density of observation wells in that area. This gives the reader a sense of the density of available data relative to the model grid size. Details of the model grid design are available in ESPAM Design Document DDM-015.

Model Layers

The ESPAM model of the eastern Snake River Plain aquifer is a single-layer model. Previous models of the aquifer have contained both single (Cosgrove and others,

1999) and multiple (Garabedian, 1992) layers. It is generally agreed that the regional eastern Snake River Plain aquifer resides in a single large stratigraphic unit, consistent with a single layer model.

There are localized lenses of sediments in some locations on the plain (the Rigby Fan and the Burley-Rupert area), which may contain locally elevated water levels. When the ESPAM model was being designed, it was agreed among the ESHMC that the option of adding a top layer to represent the sedimentary units would be explored only if time permitted and data were available. Investigation showed that there are little data available to support calibration of separate layers representing these locally elevated zones and ESHM Committee members agreed that a single layer model was sufficient. More information on the choice of using a single layer representation is available in ESPAM Design Document DDM-003.

Temporal Discretization

The ESPAM includes both a steady state and a transient model. Steady state simulation does not involve a time factor (Eq. 3). For a transient model, it is necessary to select a) the total time span for the model calibration period, b) the model stress period interval and c) the number of time steps in each stress period for which aquifer head and river gains will be calculated. Decisions on model calibration time span and temporal discretization were made by the ESHM Committee.

The criteria used to select the model calibration period included a) the period should have a wide range of recharge and discharge, b) reliable data should be available for the period, c) the period should be long enough to allow the ground-water model to adequately predict long-term aquifer trends and d) the period should reflect current land use and irrigation practices. The ESHM Committee selected a model calibration period of 22 years, from May, 1980 through April, 2002. The starting date was selected to coincide with the extensive data collection effort on the eastern Snake River Plain which was done by the USGS as part of the RASA project. The end date was originally set one year earlier (April, 2001); however, since the 2001-2002 water year was an extreme drought year, the choice was made to extend the model end period by one year to include the 2001-2002 water year. This decision had the added benefit of allowing the modelers to use field measurements from the 2001-2002 water year. The period of May, 1980 through April, 2002 includes the wettest year on record (1997), early drought years (1987-1990) and the starting years of the current drought period (2000-2002). A calibration period with a wide variation of recharge and discharge results in calibration targets (river gains, spring discharges and aquifer water levels) which provide a better constraint on the calibrated model parameters (aquifer transmissivity and storativity and riverbed conductance).

In a MODFLOW model, a stress period is the length of time during which aquifer recharge and discharge (aquifer stresses) are held constant. In the ESPAM model, because the hydrology is dominated by irrigated agriculture, 6-month stress periods (182 days during the irrigation season and 183 days during the non-irrigation season) were selected. The irrigation season stress period starts on May 1 and ends on October 31 and the non-irrigation season starts on November 1 and ends on April 30. The ESHM Committee agreed that, if calibration were successful with the 44 6-month stress periods, an attempt would be made to calibrate with 6-month stress periods representing the first 21 years and twelve 1-month stress periods representing the last year. This was attempted during model calibration; however, there was insufficient resolution in many components of the recharge and discharge data to support the 1-month stress periods. Hence, the final calibrated ESPAM transient model has 44 6-month stress periods. Table 2 lists the dates represented by each of the 44 transient stress periods.

In ground-water modeling using MODFLOW the stress period is subdivided into time steps. The ground-water flow equations are solved at every time step. Even though the same aquifer stress is being applied during the whole stress period, aquifer water levels and river gains are changing throughout the stress period (the aquifer water levels and river gains are responding to the applied stress). By further discretizing time using time steps, the model predicts these intermediate aquifer water levels and river gains, allowing comparison of predicted water levels and river gains with measured values and reducing uncertainty in model predictions. For ESPAM model calibration, 10 time steps of equal length (18.2 days during the irrigation season and 18.3 days during the non-irrigation season) are used for each model stress period. Since each time step is 18.2 or 18.3 days in length, the net result is that aquifer water levels and river gains are estimated by the model every 18.2 or 18.3 days during the 22-year calibration period.

Model Boundary Conditions

In a numerical ground-water model, the boundary conditions can exert a great amount of control on the model solutions, particularly for steady state solutions. The selection of boundary conditions is a critical element of the conceptual design of any ground-water model.

The ESPAM model employs several types of numerical model boundary conditions. No-flow boundaries are used around most of the perimeter of the model, simulating the physical contact between the aquifer and impermeable geologic formations. Specified flux boundaries are used to represent tributary underflow, non-Snake River reaches, wells where water is not locally applied for irrigation, recharge from precipitation on non-irrigated lands, irrigation conveyance loss and net recharge/discharge from surface- and ground-water irrigation. Head-dependent boundaries, where the rate of discharge to or from the aquifer is driven by a head differential between the aquifer and a hydraulically connected water body (such as a river reach or spring), are employed to represent some reaches of the Snake River and springs immediately tributary to the Snake River.

Geographic Boundary Conditions

The ESPAM model boundary is based on the SRPAM and RASA aquifer boundaries, with some modifications. Figure 14 shows the ESPAM model boundary, the RASA boundary, the SRPAM model boundary and irrigated areas. Because the ESPAM model is intended for the conjunctive management of ground- and surface-water resources, the SRPAM and RASA boundaries were evaluated based on inclusion of irrigated areas. Modifications were made to expand the original aquifer boundaries to include irrigated acreage in the Kilgore, Rexburg Bench, American Falls and Oakley Fan areas (Figure 14). The Twin Falls tract, which is within the RASA boundary but not the SRPAM boundary, was excluded since the Snake River is deeply incised between Kimberly and King Hill, so there is no communication between the aquifers on the north and south sides of the Snake River.

In the King Hill area, the RASA boundary extends several miles further to the west than the SRPAM boundary. The decision was made to include that area in the

ESPAM boundary, allowing inclusion of the King Hill gage on the Snake River. The model boundary was extended up the Big Lost River drainage to Mackay Dam in order to simplify the estimate of tributary underflow in that drainage. A result of the expansion of the model grid (beyond SRPAM) was the inclusion of approximately 294,000 acres of irrigated lands, which had a significant impact on the model water budget (addressed in a later section). The ESHM Committee felt, however, that this was necessary to support the need for model use for conjunctive management of surface- and ground-water resources.

In addition to the areal extent of the study area, an analysis was done of the bottom of the aquifer. In hydrogeology, the aquifer transmissivity (T) is equal to the saturated thickness (b) multiplied by the aquifer hydraulic conductivity (K). Since the bottom of the aquifer is unknowable in many locations, the imperfect understanding of the saturated thickness is compensated for by adjustments to K during model calibration. Stating this another way, it is the combined parameter, transmissivity (T=K*b) which is critical to understanding the movement of water in the aquifer. Neither the hydraulic conductivity nor the saturated thickness must be individually well understood. Although not overtly necessary to calibration of a model, knowledge of the bottom of the aquifer is of interest when interpreting modeling results. An estimate of the bottom of the aquifer allows the modelers to determine an estimate of hydraulic conductivity based on T and b. Additionally, when analyzing the potential non-linearities in an aquifer system, an understanding of the magnitude of saturated thickness relative to aquifer drawdown is critical.

Whitehead (1986) published basalt thickness maps for the eastern Snake River Plain. The maps were based on borehole logs and geophysics at a limited number of locations. The ESHM Committee agreed that a delineation of the bottom of the eastern Snake River Plain aquifer which was based on Whitehead's work with an assumption of a minimum aquifer thickness at the aquifer margins of 200 ft was a reasonable approach. Figure 15 shows the kriged surface of the bottom of the aquifer assumed for the current study. More details about the determination of the bottom of the aquifer can be obtained in ESPAM Design Document DDM-012.

Hydrologic Boundary Conditions

Hydrologic boundary conditions are used to represent the interaction of the aquifer with rivers, streams, lakes and springs. Strictly speaking, the representation of aquifer recharge and discharge is also a hydrologic boundary condition. The following sections discuss how rivers, streams and springs are represented in the ESPAM model. As previously mentioned, some reaches of the Snake River and some springs discharging to the Snake River are represented as head-dependent flux boundaries. Tributary underflow, non-Snake River streams and rivers, and irrigation conveyance loss are represented as specified flux boundaries. All other components of aquifer recharge and discharge (e.g. wells and net recharge/discharge from surface- and ground-water irrigation) are represented as a specified flux in each model cell. Estimation of aquifer recharge and discharge is discussed in the section on Model Water Budget.

MODFLOW Representation of Head-Dependent Boundaries

Head-dependent boundaries are boundaries where the rate of flux between the surface water body and the aquifer is dependent upon the head gradient between the surface water body and the aquifer. Head-dependent boundaries are used to represent surface water bodies which are hydraulically connected to the aquifer. These surface water bodies can be either gaining water from or losing water to the aquifer. In the case of springs, the model representation is strictly a discharge out of the aquifer through the spring.

The flow between the aquifer and a hydraulically connected surface water body is governed by Equation 5. In the MODFLOW River Package, Equation 5 is implemented in terms of a) stage of the surface water body, b) aquifer water level and c) a conductance term describing the hydraulic conductivity of the riverbed (or spring) sediments and the wetted areas of the riverbed. The user specifies river stage, elevation of the bottom of the river sediments and conductance of the riverbed sediments. As long as the water level in the aquifer is above the elevation of the bottom of the river sediments, the discharge to (or from) the river is calculated as:

$$Q_{riv} = C_{riv}(h_{riv} - h_{aq}) \quad \text{(Eq. 6)}$$

where:

Q_{riv} is the discharge to or from the river (ft^3/day)

C_{riv} is the riverbed conductance (ft^2/day)

h_{riv} is the head in the river (ft)

h_{aq} is the head in the aquifer (ft)

Figure 16 shows conceptually how river leakage is calculated in MODFLOW. As long as the aquifer head is above river bottom, the discharge to or from the river is calculated based on the head differential. When the aquifer water level drops below the bottom of the riverbed sediments, the river becomes perched and leaks at a constant rate.

Springs in the ESPAM model are represented using the MODFLOW Drain Package. The Drain Package is identical to the River Package with one important distinction: the drain package only allows water to exit the aquifer. When the aquifer water level drops below the drain (spring) elevation, the drain or spring shuts off until the aquifer water level recovers. The equation governing aquifer discharge to drains in MODFLOW is:

$$Q_{drn} = C_{drn}(h_{aq} - el_{drn}) \quad \text{(Eq. 7)}$$

where:

Q_{drn} is the discharge to the drain (ft^3/day)

C_{drn} is the drain conductance (ft^2/day)

h_{aq} is the head in the aquifer (ft)

el_{drn} is the drain elevation (ft)

ESPAM Head-Dependent River Boundaries

Head-dependent river boundaries are used in the ESPAM model to represent most of the Snake River above Milner Dam. Two hundred and thirty river cells were established to represent the Snake River above Milner Dam. Since riverbed conductance is a lumped parameter (ie. it represents multiple physical attributes) and impossible to measure, it is commonly estimated during model calibration. Figure 17 shows the ESPAM model head-dependent river cells and the aggregation into reaches. The reach between Minidoka and Milner is perched and has virtually no leakage, so it is not represented in the model. Table 3 lists the model cells used in the MODFLOW River Package and the assigned reach.

The MODFLOW River package requires river stage, elevation of the river bottom and riverbed conductance for each river cell. Determination of river stage and river bottom elevation will be discussed in this section. The estimation of riverbed conductance will be discussed in the section on model calibration. River stage (or elevation of the river surface) was determined by projecting a GIS coverage of the Snake River onto the 10 meter digital elevation models (DEMs) available from the USGS. Once this projection was accomplished, the river elevation was digitized from the DEMs. The 95% confidence interval on deriving elevations using 10 m DEMs is estimated at 1.21 ft +/- 1.17 ft.

Elevation of the river bottom is important, particularly in reaches which may transition between hydraulically connected and perched. Estimation of the river bottom elevation carries a high degree of uncertainty, as it is difficult to measure and may vary greatly at different locations. Elevation of the river bottom is typically only known at gaging stations. The ESHM Committee decided that the best approach for estimating the elevation of the river bottom was to interpolate river bottom depth between the known points at gaging stations. Using this method, the differential between river stage and the bottom of the riverbed ranged between 33 feet and 63 feet. For more information on estimation of river stage or the elevation of the bottom of the riverbed, the reader is referred to ESPAM Design Document DDM-010.

Head-Dependent Spring Representation

In the ESPAM model, springs discharging to the Snake River in the Thousand Springs region (between the gaging stations at Kimberly and King Hill) are represented using the MODFLOW Drain Package. As previously discussed, the Drain Package is very similar to the River Package in that discharge from the aquifer through the drain is calculated based on the head differential between the aquifer water level and the drain elevation. If the aquifer water levels drop below the drain elevation, discharge from the drain ceases until the aquifer water levels recover. In the Thousand Springs region, the Snake River flows through a deeply incised canyon, allowing little opportunity for water to discharge from the river to the aquifer. Therefore, selection of the Drain Package is consistent with the physical system.

Forty-five drain cells were used to represent spring discharge in the Thousand Springs area. Unlike the river cells which represent the upper reaches of the Snake River, the drain cells are not contiguous along the Thousand Springs area. The drain cells were sited by mapping springs with significant discharge from the Covington and Weaver (1990) maps published by the USGS. The Covington and Weaver maps were also used to establish initial drain elevations; however, drain elevations were modified during calibration (see the section on model calibration). Table 4 lists the model cells represented with the MODFLOW Drain Package.

Discharge of individual springs or individual drain cells is difficult to represent with a regional scale model. Consequently, the ESHMC agreed that drain cells should be aggregated into reaches that were more consistent with the scale of the model. Aggregation of the drain cells into reaches was accomplished based on an analysis of a) discharge of individual groups of springs and b) cumulative discharge of springs along the entire Thousand Springs reach. Figure 18 shows the cumulative spring discharge along the Thousand Springs reach starting at Devils Washbowl. Inspection of Figure 18 shows that there are some natural changes in the slope of cumulative discharge which supported aggregation of groups of springs into reaches. In Figure 18, it can be seen that cumulative discharge progresses at a fairly constant slope between Devils Washbowl and Buhl. At approximately the Buhl gage, the slope of the cumulative discharge curve increases until the springs at the Thousand Springs power plant. The springs at the power plant have extremely high discharge, causing a dramatic rise in cumulative discharge. The slope of the cumulative discharge is lower between Thousand Springs and Malad, where the cumulative discharge curve has a second dramatic rise. Between Malad and Bancroft, the cumulative discharge curve again has a lower slope. Analysis of Figure 18 resulted in the springs being aggregated into the following six reaches, shown in Figure 19: Devils Washbowl to Buhl, Buhl to Thousand Springs, Thousand Springs, Thousand Springs to Malad, Malad, and Malad to Bancroft. The color-coded squares in Figure 19 represent individual model cells where MODFLOW drains are used to represent spring reaches.

Initial values of drain conductance for the drain cells along a spring reach were estimated based on the discharge for the group of springs and the estimated head differential between the aquifer and the spring elevation. Drain conductances were calibrated during model parameterization. This will be discussed further in the model calibration section. More details on the location of drain cells, aggregation of the spring reaches and estimation of initial drain conductance can be found in ESPAM Design Document DDM-018.

Specified Flux Boundaries

Specified flux boundaries are used to represent flow to or from the aquifer which occurs at an estimated rate and is not driven by a head differential. Specified flux boundaries are typically used to represent the interface between the aquifer and a water supply which is not hydraulically connected. In the ESPAM model, tributary basin underflow, percolation from irrigation and precipitation on non-irrigated lands, seepage from perched rivers and irrigation conveyance losses are represented using specified flux boundaries. This section describes the specified flux boundaries. The rate of specified flux used in the ESPAM model, including pumping, will be discussed in the Water Budget section.

Underflow from Tributary Basins

Tributary underflow represents the subsurface discharge of water from a tributary basin into the eastern Snake River Plain aquifer. Because tributary underflow is subsurface flow, it is difficult to estimate. Underflow from 22 tributaries is represented in the ESPAM model. Table 5 lists the tributary basins, for which underflow is represented in the ESPAM model. Figure 20 shows the location of each of the tributary basins on the Snake Plain. In Figure 20, the individual model cells which are used to enter the specified flux are highlighted. Appendix B contains a table listing the model cells associated with each tributary (Table B-1). The estimated flux for each tributary is evenly distributed across the model cells assigned to that tributary in each stress period. Estimation of the rate of tributary underflow discharge is discussed in the water budget section.

Perched River Seepage

The ESPAM model has 12 locations at which perched river seepage is represented. These reaches represent surface water bodies other than the Snake River. Perched reaches of the Snake River are represented using the MODFLOW River

Package. Table 6 lists the perched reaches. Strictly speaking, not all of the perched reaches are river reaches. Several flood control sites are represented in the same manner as perched river reaches. Figure 21 shows the location of each perched reach. The model cells in which perched seepage is represented are highlighted in Figure 21. Appendix B contains a table listing the model cells associated with each perched reach (Table B-2). The estimated flux for each perched reach is evenly distributed across the model cells assigned to that perched reach in each stress period. Estimation of the rate of perched seepage is discussed in the water budget section.

Irrigation Conveyance Loss

As irrigation water is delivered to fields, there is leakage from the canals and laterals. This is referred to as irrigation conveyance loss or canal leakage. The eastern Snake River Plain has approximately 1,000,000 acres of land irrigated by surface water which is delivered by canals and laterals. It would be impossible to characterize leakage from all of the canals and laterals, so leakage is only explicitly represented from the largest of the canals and canals where the seepage was determined to affect simulation of spring discharges. Other canal leakage is assumed to have approximately the same spatial distribution as incidental recharge from irrigation and is implicitly included in the irrigation recharge calculation. Canal leakage rates are estimated as a percentage of surface water diversions and are discussed in the water budget section.

Leakage from the larger canals is represented in the ESPAM model as specified flux boundaries. The ESPAM model has 5 locations at which irrigation conveyance loss is represented. Table 7 lists the represented canals. Figure 22 shows the location of each leaky canal and the model cells in which canal seepage is represented. Appendix B contains a table listing the model cells associated with each canal (Table B-3). The estimated flux for each canal is evenly distributed across the model cells assigned to that canal in each stress period.

Model Initial Conditions

Estimates of aquifer head for each model cell at the beginning of a simulation form the initial model conditions. Of primary concern are initial aquifer water levels or starting heads for the transient simulation. For the steady state ESPAM model, the starting heads are set at an arbitrary initial value of 7000 ft. Because a steady state simulation is run until there are no further changes in aquifer water levels, the starting heads are not important. The simulation will continue running and balancing the water flow between each model cell until the system reaches equilibrium and there are no further changes in water levels.

For the transient ESPAM model, the starting water levels are the ending heads from the steady state model. In the physical system, water levels fluctuate with location and with season, largely in response to irrigation practices. It is very difficult to accurately estimate the water levels throughout the aquifer at an instantaneous point in time, so the ESHM Committee agreed that using the ending heads from the steady state simulation was a reasonable point for starting heads for the transient simulation. The ending steady state heads will represent an average water level condition—high in some locations and low in others. As the transient model progresses in time, the water levels will be driven by the recharge and discharge and the physical aquifer properties (transmissivity, storativity and riverbed conductance). This means that changes in aquifer water levels during the first few years of transient simulation are less meaningful than the later years, after the initial head conditions have been overcome.

Model Water Budget

The model water budget is one of the most important elements of a ground-water model. The water budget comprises the accounting of all recharge and discharge to the aquifer both for the steady state period and for each model stress period. By definition, steady state means that there are no changes in aquifer water levels (which equates to no change in aquifer storage). Therefore, for steady state, the inflows must balance with the outflows (Eq. 3). For each transient stress period, the inflows minus the outflows must balance with the change in aquifer storage (Eq. 4).

Water use, and therefore the hydrology, on the eastern Snake River Plain is dominated by irrigated agriculture. The major sources of recharge to the aquifer are incidental recharge from surface water irrigation, tributary underflow, leakage from canals and rivers and recharge from precipitation on non-irrigated lands. The major sources of discharge from the aquifer are evapotranspiration and spring discharges to the Snake River (Figure 7). There is a lot of natural variation in water supply from year to year. Several large reservoirs on the Snake River help to buffer the water supply available for irrigation, but supply is still limited in some years.

Estimation of the water budget for the ESPAM model required estimation of all of the above-mentioned components. Estimation of some of these components entailed multiple steps. In addition to the major components of the water budget, there are several smaller components which were also estimated and are discussed below.

Land Use

One of the first steps in evaluating water use for a study area is an evaluation of land use. Recharge to the aquifer can vary greatly among different land uses. For example, on land irrigated with surface water, the amount of irrigation water applied generally exceeds the consumptive use, so there is a net recharge to the aquifer. On the other hand, on lands irrigated with groundwater and on wetlands, there is a net extraction from the aquifer to meet consumptive use. Identifying land use is an important part of estimating the water budget, particularly in an area where the water use is dominated by irrigated agriculture, such as in the eastern Snake River Plain.

To evaluate irrigated areas for the ESPAM model, multiple sources of data were evaluated. One of the problems with using land use analyses from different sources is that it is difficult to discern whether changes in land use reflect actual changes over time or different analysis techniques. The modeling team did an exhaustive job of comparing data from multiple sources and ground-truthing the land use analyses, as documented in ESPAM Design Document DDW-015. Initially, the ESHM Committee decided to employ land use analyses based on imagery from 1980, 1992 and 2000. The 1980 (RASA80LC, IDWR, 1980) analysis is a land classification of LANDSAT data performed by the Idaho Image Analysis Facility of IDWR (IDWR, 1982), using the "thematic mapper" LANDSAT sensor and Vicker's classification algorithms, which are not directly comparable with later LANDSAT data and methods (Morse, 2001). The 1992 (SNAKLC92, IDWR, 1997b) analysis is based on 1987 aerial photography and extensive field work. The 2000 (ESPAC2000, IDWR, 2002a) classification was performed by IDWR specifically for this project, using classification of multiple LANDSAT images, with a two-week to one-month image frequency. These three land use analyses were initially selected to represent the changes in irrigated area between 1980 and 2002.

During model calibration, comparison of the water budget with the aquifer water levels and spring discharges indicated that the slight trend of decreasing irrigated acreage over time, as evidenced by the land use analyses of these three sets of imagery, was inconsistent with trends in measured modeling targets. Inspection suggested that the differences in spatial distribution between the three land-cover data sets were minor and the differences were distant from river or spring reaches of concern. The decision was made by the ESHM Committee that the final model calibration would use the irrigated lands analysis which was based on the SNAKLC92 data set for the entire calibration period. The extensive ground-truthing which was done for the SNAKLC92 data set provided the highest confidence in the land use analysis.

The location of wetlands was derived from a 1991 analysis of LANDSAT imagery done by IDWR (SRBAS91LU, 1994). Some of the available land use analyses did not identify wetlands. For the land use analyses which did identify wetlands, known wetland locations were ground-truthed. The SRBAS91LU coverage had the most reliable identification of wetlands.

Identification of cities was compared among the available land use analyses. 2000 LANDSAT images of the City of Idaho Falls were compared with the analyses which did identify cities. The ESHM Committee agreed that the SRBAS91LU (IDWR, 1994) analysis provided the most accurate delineation of cities. For further details on the delineation of wetlands and cities, the reader is referred to ESPAM Design Document DDW-015.

Figure 23 shows a composite coverage of irrigated lands, wetlands, cities and soil types on non-irrigated lands (to be discussed in a later section). Figure 23 reflects the land use which was used in compiling the ESPAM recharge and discharge.

Estimation of Recharge/Discharge

Estimation of aquifer recharge and discharge includes estimation of many intermediate variables which are used to calculate the net recharge to the aquifer. For example, even though precipitation contributes to aquifer recharge, it is actually used as an intermediate variable for estimating recharge on surface-water irrigated lands, discharge from ground-water irrigated lands and recharge on non-irrigated lands. The reason it is treated as an intermediate variable is that some estimate must be made of the amount of precipitation which evaporates versus the amount which is available to recharge the aquifer. Similarly, evapotranspiration on irrigated lands, canal seepage, irrigation return flows, off-site pumping and crop mix are used as intermediate variables in the estimation of aquifer recharge and discharge associated with irrigation. The next sections will discuss how these variables are used in the estimation of net aquifer recharge as well as how these variables are estimated.

Other components of aquifer recharge and discharge are estimated directly. These include tributary basin underflow, perched river seepage, pumping for surface water replacement and recharge on non-irrigated lands.

The following sections describe a) the estimation of all of the components of the water budget including both intermediate variables and directly estimated components and b) how the various components are used in the water budget estimation.

Recharge on Irrigated Lands

Irrigated agriculture can result in a net recharge to the aquifer (surface-water irrigation) or a net discharge from the aquifer (ground-water irrigation). The land use analysis described above identified irrigated agriculture, but a separate analysis was required to delineate surface-water irrigated lands from ground-water irrigated lands.

Estimation of net recharge to the aquifer from surface-water irrigated lands requires surface water diversion, irrigation return flow, canal leakage, precipitation and evapotranspiration data. The calculation is as follows:

$$\text{Field Delivery} = \text{Diversions} - \text{Canal Leakage} - \text{Return Flows} \quad \text{(Eq. 8)}$$

$$\text{Net Recharge (surface)} = (\text{Field Delivery} + \text{Precipitation}) - (\text{ET x Adjustment Factor}) \quad \text{(Eq. 9)}$$

Ground-water pumping rates have only been measured since the mid-1990s on the ESRP. The measurement methods are not consistent throughout the plain, so measurement data is not yet reliable. Additionally, the data that do exist record gross pumpage and not net extraction. The lack of historical ground-water pumping measurement data and the lack of consistency in the measured data required an alternative method of estimating net discharge from ground-water irrigation. Net discharge from the aquifer from ground-water irrigated lands is estimated using evapotranspiration, offset by available precipitation. The rationale behind this method of estimation is that any ground water which is pumped in excess of crop demand (ET) will filter back into the aquifer. The calculation is as follows:

$$\text{Net Discharge (ground)} = \text{Precipitation} - (\text{ET x Adjustment Factor}) \quad \text{(Eq. 10)}$$

When the precipitation exceeds the demand, there will be a net recharge to the aquifer on ground-water irrigated lands. When demand exceeds precipitation, there will be a net discharge.

Precipitation

Precipitation for the study period was estimated using PRISM (Parameter-elevation Regressions on Independent Slopes Model) maps produced by the Oregon Climate Service and the Spatial Climate Analysis Service (Daly and Taylor, 1998). PRISM uses point data, a digital elevation model, and other spatial data sets to generate gridded estimates of several spatial and temporal climatic parameters, including precipitation. As of the time of calculating the ESPAM water budget, these data were available monthly for 1980 to 1997, but not available for 1998 to 2002. A summary of the steps taken to estimate precipitation is available below. For more detailed information on the estimation of precipitation for the ESPAM model, the reader is referred to ESPAM Design Document DDW-011.

PRISM distributes point measurements of monthly, seasonal, and annual precipitation to a geographic grid of four kilometers by four kilometers. By use of a resampling algorithm, two-kilometer by two-kilometer resolution grids can be estimated. These grids are produced in a GIS-compatible latitude-longitude grid or a gridded map projection.

Monthly PRISM maps for the study area for 1980 through 1997 were obtained from the Spatial Climate Analysis Service. As previously stated, as of the estimation of the ESPAM water budget, maps were not available for 1998 through 2002. For consistency in precipitation data estimation, a method was devised, with the concurrence of the ESHM Committee, to interpolate precipitation data between weather stations for the years 1998-2002. The method is described below.

Precipitation data for the years 1998 to 2002 were purchased from NOAA (http://lwf.ncdc.noaa.gov/oa/ncdc.html) for all NOAA stations on the eastern Snake River Plain. These data series include precipitation values, in inches, and the departure from normal values, in inches.

In order to maintain precipitation data consistency over the entire 22-year study period, 1998 to 2002 NOAA data were processed with 30-year average PRISM data to achieve consistent data formatting with the PRISM two-kilometer by two-kilometer grids for each monthly precipitation map. This 1998 to 2002 NOAA processed dataset was then used to supplement the 1980 to 1997 PRISM dataset. A detailed description of the NOAA data processing follows.

Using the NOAA departures from normal values and the NOAA monthly actual precipitation values, a normal for each NOAA station was calculated. Then, actual precipitation as a fraction of the normal was calculated for each NOAA station. This resulted in a multiplier which, when multiplied by the normal value, gave the actual NOAA precipitation value. A set of multipliers was calculated for each month for the timeframe of January 1998 to April 2002. Using ArcView3.2, the point-value multipliers were interpolated to a raster surface of NOAA multipliers. The NOAA multipliers were applied to the PRISM 30-year average monthly precipitation data using ArcView 3.2. The multiplier datasets were applied to the 30-year average PRISM rasters to produce monthly precipitation rasters for the 1998-2002 period.

Once monthly precipitation maps were generated for the full model period, the monthly rasters were summed into the same time periods as the ESPAM model stress periods. Figure 24 shows example PRISM precipitation maps for average precipitation for the 22-year model period, for both the irrigation season and the non-irrigation season. Inspection of Figure 24 shows the great difference between irrigation season and non-irrigation season precipitation on the ESRP. Figure 25 shows the annual total precipitation for each year of the study period. Inspection of Figure 25 shows that there is a great degree of annual variation in precipitation.

Crop Mix

Knowledge of the mix of grown crops is necessary for the estimation of evapotranspiration. Differences in crop mix can change average ET by as much as ten percent, which translates into 1.7×10^{10} ft^3 (400,000 AF), or approximately seven percent of the aquifer water budget, assuming two feet of ET on 2,000,000 irrigated acres and a 6,000,000 acre-foot aquifer budget. The final crop mix used for the ESPAM was calculated based on data from several sources of crop statistics data, as discussed below.

The primary data source is the National Agricultural Statistics Service (NASS) crop report data, which are based on county-wide surveys of farm operators. These data are available in three formats for the study area. These are the Published Estimates Data Base On Line (USDA, 2000), the US Agricultural Census (USDA, 1992, 1997) and the Idaho Agricultural Statistics (Idaho Department of Agriculture, 1981 - 2002) reports. The Published Estimates Data Base On Line (PEDB) version provides county-wide acres planted and harvested, by crop. These reports do not include alfalfa hay for the earlier years of the study, so 1982 and 1987 values from the US Agricultural Census (Ag

Census) version of the NASS data for alfalfa were used. The Idaho Agricultural Statistics (IAS) report was used to fill in gaps in the PEDB potato data. The Agricultural Census reports provide more detailed results, including details of irrigated and non-irrigated acreage by county, for the years 1982, 1987, 1992, and 1997. The IAS report is compiled from NASS data and includes yearly values for irrigated and non-irrigated acreage, by county, for major crops. As of the time of this study, the IAS data were available for years 1980 through 2001. Many of the county agents interviewed recommended the NASS/IAS data.

About half of the counties in the study area have farmed land both inside and outside the study area (Figure 26). It is possible that the crop mix outside the study area is different than the mix inside. The potential errors associated with these crop differences were first assessed by estimating a "reasonable" and "extreme" crop mix for lands inside the study area, and calculating volume of ET for each. The analysis was performed for Bonneville County and Cassia County. The result of the analysis was that "irrigated only" crop report data provided a better representation of the study area than did county-wide data. Therefore, whenever possible, "irrigated only" (agricultural census or IAS) data were used.

The final data compilation uses the published Idaho Agricultural Statistics (Idaho Department of Agriculture 1981 - 2002) data with some refinements, as detailed in ESPAM Design Document DDW-001. Final crop mix fractions by year and county are listed in Table B-4 in Appendix B. A more detailed description of the evaluation of crop mix for the ESPAM model can also be found in ESPAM Design Document DDW-001.

Evapotranspiration

One of the largest components of discharge on the ESRP is evapotranspiration, a combined variable encompassing evaporation and plant transpiration. Evapotranspiration is controlled by climate as well as crop and soil characteristics. Climate affects the evaporative power of the atmosphere, reflecting the energy available to drive evapotranspiration and the capacity of air to accept evapotranspired water. Soil and plant characteristics control the crop's ability to extract water from the soil, and biological characteristics of the crop control the transpiration response to evaporative power. Soil texture, surface wetness and condition and shading by crop plants control the soil's response to evaporative power. Although far more water evapotranspires during the growing season, there is still measurable evapotranspiration during the non-growing season. For the ESPAM model, growing season ET was estimated separately from non-growing season ET.

Growing season evapotranspiration was estimated primarily using an alfalfa reference ET scaled by crop coefficients. The alfalfa reference ET is available for each NOAA weather station within the ESRP. Allen (2002) evaluated five different ET calculation methods. The Kimberly-Penman Alfalfa Reference method was chosen as most suitable for the modeling application (Allen, 2003). This method was developed with Idaho empirical data and of the five methods is the most directly comparable to the reference ET reported in Estimating Consumptive Irrigation Requirements for Crops in Idaho (Allen and Brockway, 1983) data and to Agrimet (U.S. Bureau of Reclamation, 2003) estimates.

The selected data series provides only reference ET, but calculation of crop ET also requires crop coefficients (Kc values). Coefficients for individual crops were extracted from the original Allen and Brockway (1983) data by dividing individual crop ET by reference ET, for each weather station each month. The original data only include typically grown crops for each location. To avoid calculating zero ET if an atypical crop is grown, Kc values for all crops were assigned to all weather stations. Missing values were supplied from nearby stations. The spatial variation of Kc is low (Allen, 2003) and this substitution affects only the Kc value. Because the data for each county include values for all typically grown crops, missing values represent rarely-grown crops. Therefore, this substitution will affect only a few acres within any stress period and has a very low potential of introducing error. An average Kc value was determined for each county which was an average, weighted according to the proportion of crops, from the nearest NOAA station data. This was performed for each model stress period.

ET estimation for this project included a remote sensing analysis of ET using the METRIC algorithm (Allen and others, 2002; Allen and others, 2005; Morse and others, 2000) for the 2001 growing season. METRIC results were used to calculate ET adjustment factors. ET adjustment factors allow adjustment of ET to account for deviations from a perfectly managed crop such as a) water shortage, b) crop disease or c) post-harvest watering. ET adjustment factors may also reflect differences in ET due to source of irrigation water or method of application. Unique ET adjustment factors were evaluated for a) sprinkler or furrow application, b) ground water or surface water source and c) irrigation entity. The METRIC analysis indicated that the Kimberly-Penman estimates of ET are consistent with crops which are furrow-irrigated, but that crops irrigated with sprinklers have approximately 5% higher ET. For the ESPAM model calibration, ET adjustment factors were set at 1.0 for all furrow application and at 1.05

for all sprinkler application. For more information regarding ET adjustment factors, the reader is referred to ESPAM Design Document DDW-021.

Though crops do not actively transpire in the winter time, evaporation and sublimation continue. For the ESPAM model, winter-time ET is based on experiment data collected over several years at Kimberly, Idaho (Wright, 1993). The average winter ET from the Wright study is reported in Table 8.

Except for February, these values should generally be representative of the entire study area. The February value is representative of the lower-elevation portions of the study area, but February ET for higher elevation areas that are still snow covered in February is probably closer to the January average from Kimberly (Wright, 2003). Snow increases the reflection of solar radiation back into the atmosphere, reducing the energy available to drive evaporation or sublimation. To adjust for differences in snow cover, February ET was scaled by elevation. February ET at Twin Falls (3770 feet) was set to 1.0 mm/day, and at Rexburg (4920 feet) to 0.6 mm/day. ET at other locations was adjusted linearly from these points according to the equation:

$$\text{ET (mm/day)} = -0.0003478 \times \text{Elevation (feet)} + 2.3112 \qquad \text{(Eq. 11)}$$

For stations higher in elevation than Rexburg, December and January ET were adjusted to be no higher than the elevation-adjusted February value. November ET was adjusted to be no higher than 120% of the adjusted February value. Table 9 lists the resulting winter-time ET values for all stations, converted to feet per month.

Figure 25 shows the annual total evapotranspiration for each year of the study period. Inspection of Figure 25 shows that there is some degree of annual variation in evapotranspiration, however, ET is relatively constant.

Source of Irrigation Water

Net recharge from surface-water irrigation is the largest component of the water budget. The second-largest component of the water budget is net withdrawal (calculated as consumptive use, or evapotranspiration) due to ground-water irrigation. The source of water for individual parcels must be identified so that diverted volumes of surface water are applied to the appropriate spatial locations. In the ESRP, aquifer water levels respond to surface-water irrigation by rising during the irrigation season and declining during the non-irrigation season. Aquifer response to ground-water irrigation is exactly opposite.

The source of irrigation water also affects the calculation of consumptive use, which depends in part on evapotranspiration (ET) adjustment factors, application method (sprinkler or gravity), and the reduction factor for non-irrigated inclusions within irrigated lands. For an individual parcel, the ET adjustment factor and sprinkler percentage from the local surface-water irrigation entity or the local ground-water irrigation polygon are applied, depending on the water source identified for the parcel. The source of irrigation water by parcel is also required for model scenarios; for example, a hypothetical scenario might represent curtailment of a specific source of irrigation.

Water rights data provide the best information regarding source of irrigation water for each parcel of land. Many irrigated lands are either 100% surface-water irrigated or 100% ground-water irrigated. However, some irrigated lands have mixed ground water and surface water sources. This has typically occurred where surface water sources were inadequate, and supplemental ground water sources have been developed. The following sections describe the method used to determine the source of irrigation water and the method used to calculate recharge on mixed-source lands. A more detailed description of the assignment of irrigation source may be found in ESPAM Design Document DDW-017.

Geographic Information Systems (GIS) technology and Water Measurement District and Ground Water District records of actual well diversion volumes have recently become available. These sources were used for determining the source of irrigation water, in conjunction with Snake River Basin Adjudication data base records, which reflect varying degrees of resolution in the adjudication process. The adjudication data reflect accomplished changes not shown in water rights data. The adjudication data also represent legitimate "beneficial use" rights perfected before the statutory requirement to obtain a state permit for a water right. Adjudication claims are the users' representations of water use, and exist for the entire plain. Recommendations are Idaho Department of Water Resources' findings from investigation of claims. As of the time of this study, recommendations existed for about 2/3 of the study area. The court's determination of the adjudicated water right is called a partial decree. At the time of this study, partial decrees existed for a much smaller portion of the study area. Not all the partial decree data were available for automated electronic querying.

The map identifying water source by 40-acre quarter-quarter section is compiled from IDWR adjudication data with manual adjustments. Using GIS, the map identifying water source is combined with the map of irrigated lands (Figure 23) to identify irrigation water source for all irrigated-lands. Figure 27 shows the GIS map of water source used in model calibration.

There are some limitations to the available water rights data. The ground-water diversion volume data only cover the years 1997 through 2002, and may have missing values, especially for the earlier years. These data were used to verify irrigation water source assignment which was based on adjudication data. The adjudication claims are uninvestigated representations of water users. Recommendations and partial decrees reflect the legal authorization to use water, not necessarily the actual practice. Because of the common occurrence of overlapping water rights, the ratio of ground-water to surface-water rights in a quarter-quarter section is not useful for determining the mix ratio on mixed-source lands.

Potential errors in the mix ratio apply only to the 13% of the quarter-quarter sections identified as mixed-source in the adjudication data. The modeling team, in conjunction with the ESHM Committee, developed a method for apportioning the mixed-source lands to either ground-water or surface-water irrigated. Consumptive use for mixed-source irrigated lands was evaluated for each irrigation entity. Assuming a requirement of 4 feet of delivered water (to meet consumptive use, conveyance loss and irrigation inefficiencies), the team estimated how many acres could be satisfied by the recorded diversions. The balance of the irrigated acres was assigned to ground-water source. It was acknowledged that the actual split may change from irrigation season to irrigation season depending upon the surface water supply and that no record is kept of supplemental ground water use. This analysis resulted in approximately 63% of mixed-source lands within the study area being assigned to a ground-water source. The tests confirmed that applying this method to determine the split of the mixed-source lands introduces a minimal amount of uncertainty in the water budget (see ESPAM Design Document DDW-017).

Reduction for Non-Irrigated Inclusions

The irrigated lands shown in Figure 23 represent the spatial extent of irrigated areas. However, some portion of these areas is actually non-irrigated areas such as roads, homes, rock piles and canal banks. During the estimation of recharge and discharge, the actual square footage of irrigated area in each model cell is reduced by a factor which accounts for these non-irrigated inclusions. For the ESPAM calibration period, irrigated areas were reduced by 12%. The 12% was determined using a GIS analysis of individual parcels mapped by IDWR as part of the Snake River Basin Adjudication (Norquest, 2002). ESHM Committee members agreed that 12% was a reasonable estimate for reduction in irrigated area.

In the GIS/Fortran Recharge Tool, the capability exists to specify a reduction factor for each model stress period by application method. This enables the user to reflect a potential different reduction factor for sprinkler versus gravity irrigation for each time period. For the ESPAM model calibration, the consensus of the ESHM Committee members was that the estimate of non-irrigated inclusions derived from IDWR GIS data, which showed no statistically-significant difference between sprinkler and gravity application, represented the best available estimate for the irrigated lands reduction factor.

Aggregation of Canal Companies into Surface Water Entities

There are more than 100 surface water irrigation companies and numerous private surface water irrigators within the ESPAM model boundary. Many of these irrigation companies share common acreage. In order to treat all surface water irrigated areas in a consistent manner, these surface water irrigation companies are aggregated into a smaller number of 'irrigation entities.' The aggregated irrigation entities more accurately reflect the delivery of surface water to the irrigated areas by maintaining a level of resolution consistent with available diversion and return flow data.

A similar surface water irrigation company aggregation was performed for the original UI/IDWR SRPAM model. Because GIS software was not available at that time, the irrigation company aggregation was a more difficult process and took much longer to complete. The earlier aggregation resulted in approximately 172,000 acres assigned to an un-named surface-water entity.

For the current study, the process of aggregating surface water irrigation companies entailed evaluating each irrigation company to identify the point of diversion from the river and the likely corresponding irrigation return flow location. Adjacent irrigation companies were then examined for similar characteristics, including irrigation practice, points of diversion, common conveyance, location of irrigation return flow, soil type, water right priorities, common drainage area, and previous aggregation in the earlier UI/IDWR SRPAM model. If adjacent irrigation companies did not have any significant differences from one another, they were aggregated into the same irrigation entity.

Other criteria for aggregating irrigation companies together are shared point of diversion, common conveyance, or shared return flow. Two or more irrigation companies may share a diversion from the river or a point of return to the river, in which case the companies were aggregated together to maintain a level of irrigation company resolution consistent with the resolution of the diversion and return flow data. Similarly, if it appeared that runoff from one irrigation company was part of the supply for another company, the entities were aggregated to more correctly represent spatial distribution of recharge.

Most private water rights within the model boundary were aggregated with the organized irrigation companies. The private rights that were not aggregated with adjoining entities are: Camas and Beaver Creek (Basin 31), Birch Creek and Medicine Lodge Creek (Basin 32), and Little Lost River (Basin 33). The private rights in these three basins were aggregated separately from each other and from the irrigation companies because of different practices and water supply than the organized companies. Source of irrigation water was determined from IDWR adjudication data (see ESPAM Design Document DDW-017).

Three irrigation companies in the Mud Lake area, including Jefferson Irrigation Company, Monteview Canal Company Incorporated, and Producers Irrigation Company, do not use surface water for irrigation. These companies use off-site ground water pumping and were aggregated as a surface water irrigation entity for model purposes. With ordinary ground water irrigation, it is assumed for modeling that the pumping and the recharge occur within the same model cell. This is not the case for the aforementioned canal companies. The wells used to obtain water are miles from the place of use and conveyed by a canal. Therefore, in the model, the pumping and recharge would occur in different model cells. Because many irrigation companies that use off-site ground water pumping co-mingle the pumped ground water with the surface water in the canals, the ground water withdrawal was treated as a point extraction assigned to the model cell. This withdrawal, or volume extracted, was added to the surface water diversions for the respective irrigation entity. When water master records were not available to determine the amount of ground water pumped, estimates were made. For the three companies mentioned, the surface-water component is set to zero, since there is no surface-water supply.

The aggregation process resulted in 43 irrigation entities (Table 10). These 43 entities were assigned an identification number (for use by the GIS/Fortran Recharge Tool) and a descriptive name. Descriptive names were created by choosing the largest (by area) organized irrigation company in the entity, and adding on to that name the number of organized companies aggregated to create that entity. For example, aggregated entity IESW16, named "Egin 2", consists of two organized companies, Egin Bench Canals Inc. and St. Anthony Union Canal Company, of which Egin Bench Canals Inc. is the larger (by area), of the two companies. (Note that a mid-project recombination of some of the entities to correspond to new return-flow data resulted in some entities whose names may violate the "biggest company" naming convention.) Figure 28 shows the final set of irrigation entities. For a more detailed description of the aggregation of canal companies into irrigation entities, the reader is referred to ESPAM Design Document DDW-008.

Delineation of Ground Water Irrigation Polygons

This section describes the designation of portions of the study area into "Ground Water Irrigation Polygons" for the purpose of recharge calculation. The withdrawals associated with irrigation from ground water are a negative recharge and are calculated based on adjusted ET and precipitation. The ET adjustment factor is applied according to the geographic location of the irrigated land being calculated and the method used to apply irrigation water. ET adjustment factor and application method parameters for irrigation from ground water are carried as attributes of the ground water irrigation polygon map.

The goals in constructing the ground water irrigation polygon map were to adequately represent known differences between geographical areas and management practice and to minimize the number of unique ground water polygons (to reduce data management concerns and recharge tool run times). Because these ground water irrigation polygons are only used for assigning ET adjustment and application method parameters for recharge calculation, no requirement was made that polygons be contiguous areas. Similarly, the ground water irrigation polygons assigned for recharge calculation are not based on current ground water management areas or measurement districts, nor is it contemplated that these polygons would form the basis for any administrative boundaries or decisions.

Because both ET adjustment factor and percent sprinkler application are driven largely by cost of water, and because the primary cost of ground water is the energy cost for lifting water out of the ground, depth-to-water was used as the basis for delineation of the polygons. Relative to the range of depths on the plain, water level changes since 1980 are minor, so a single water table map was deemed adequate for the delineation. Figure 29 shows the depth-to-water map used for the analysis, digitized from a paper map created by Lindholm and others (1988).

Pumping lift was hypothesized to influence the cost of water and crop production and consequently the intensity of management. Regional variations in cropping patterns and climate throughout the Snake Plain were also considered to be factors in management intensity. Intensively managed crops are expected to approach the ideal values of crop coefficients. Poorly managed crops are expected to exhibit less evapotranspiration. Depth to water (pumping lift) provided a basis for dividing the Snake River Plain into GIS polygons. These polygons were then subdivided based on location within the plain. That is, if a single polygon represented a depth to water of 100 to 200 feet, this polygon would be divided into two units if this depth range existed in both the southwest and northeast portions of the plain. The final GIS polygons are presented in Figure 30. The central portion of the plain is absent of irrigation which is identified as polygon IEGW600 in Figure 30.

The Mud Lake area and the US Bureau of Reclamation project known as the "A & B Irrigation District" were the first large-scale applications of ground water on the plain (Goodell, 1988). These developments pre-dated the widespread use of sprinklers, while most other ground water development post-dated the use of sprinklers. Field observations show that the Mud Lake area still has a different mix of application method relative to other ground-water areas. The same is true of the A & B irrigation district (Temple, 2002). For this reason, these two areas were partitioned into their own, unique ground water irrigation polygons. Figure 30 shows the ground water irrigated polygons.

Method of Irrigation Application

An analysis was done to identify what percentage of irrigated areas has been irrigated by sprinkler versus furrow irrigation throughout the simulation period. Because actual evapotranspiration may be affected by the type of application system used (as well as other factors), and because changes in application system type (e.g. gravity to sprinkler) have occurred during the period of the study, a method for identifying application method and describing changes was required. Identification of the method of irrigation application on each parcel of land allows application of ET adjustment factors for deviations from predicted ET which are associated with sprinkler or furrow irrigation.

Previous modeling efforts have not included an ET adjustment factor, so there has not been a need to identify application method. Neither Garabedian (1992) nor IDWR (1997) explicitly referred to consideration of application method in irrigation calculations. Goodell (1988) used application method to derive discharge pressure parameters for pumpage calculations, but not for recharge or ET calculations. IDWR (1997) adjusted for non-irrigated inclusions based on a distinction between ground water and surface water, but examination of maps indicates that it is likely the difference is actually driven by application method, and water source was used as a surrogate.

Available data included Geographic Information Systems (GIS) electronic maps that delineate the irrigated lands in the study area in 1982 and 1992 as sprinkler or gravity irrigated (IDWR 1982, 1992). The Natural Resource Conservation Service National Resource Inventory (NRI) includes a report of a statistical sample indicating percent of irrigated acres using pressurized (sprinkler) systems by 8-digit Hydrologic Unit Code area or by Major Land Resource Area (MLRA) (NRCS, 1997). NRCS also classifies drip irrigation as a pressurized system but this is such a minor practice within the current calibration period that it is neglected here.

Since the 1982 and 1992 GIS maps represent the most certain data, and the data with the best spatial resolution, these maps were used as the primary data source. The NRI data are statistically-based, and quantify percentages, so they were used to establish overall percentages for 1987 and 1997.

Initial tables of sprinkler percentage for each irrigation entity or polygon were constructed for 1982 and 1992, using GIS and the 1982 and 1992 maps. From the irrigation entity and water source maps (Figures 27, 28 and 30), all ground-water-irrigated and mixed-source lands in each ground water polygon, and all surface-water-irrigated and mixed-source lands in each surface-water entity were identified using GIS software. These maps were intersected with the application method maps to produce maps of irrigated lands with appropriate water source, by application method, by ground water polygon or irrigation entity. The total area of each method, within each entity, was used to calculate a sprinkler percentage for each entity or polygon. This process was done for both 1982 and 1992. The result was a table of values, having a unique sprinkler percentage for each irrigation entity or polygon, for the break-point years 1982 and 1992.

The NRI data were used as a secondary source, to determine sprinkler percentages for 1980, 1987, 1997 and 2000. Sprinkler percentages for other years were linearly interpolated between these values. Table 11 lists the percentage of area under sprinkler application for each ground-water and surface-water entity for each of the years for which data were available.

The complete table used in model calibration includes values for each stress period and is presented in Appendix B, Table B-5. Figures 31 and 32 show the spatial distribution of the sprinkler fraction for the years 1980 and 2000 by surface water irrigation entity and by ground water polygon, respectively.

Surface Water Irrigation

Net recharge incidental to surface irrigation occurs when more irrigation water is applied and remains on the field than the crop demands. As noted in Equation 8, field delivery is the volume of water diverted minus canal leakage and irrigation return flows. Net recharge to the aquifer is estimated as the field delivery plus precipitation, less adjusted ET (Eq. 9). Precipitation and adjusted ET have been discussed in previous sections. The following sections discuss estimation of irrigation diversions, return flows conveyance loss and the estimation of net recharge due to surface water irrigation.

Irrigation Diversions

In order to effectively and accurately estimate percolation to the aquifer due to surface water irrigation, irrigation diversions from the river must be estimated with the highest possible degree of accuracy. Irrigation return flows to the river and evapotranspiration are also components of calculating percolation from surface water irrigation.

For Snake River diversions, two sources of data were considered for use in estimating surface water irrigation diversions. The first source is irrigation diversion and return flow 'raw' daily data from the water districts, and the second source is 'processed' monthly data that is used in the IDWR Reach Gain/Loss Program. For consistency with the IDWR Reach Gain/Loss Program estimates of reach gains that were used for model calibration, the 'processed' monthly data were used to estimate irrigation diversions.

The diversion data which are used as input to the IDWR Reach Gain/Loss Program were assigned to appropriate canal companies. The diversion data for each canal company were aggregated into the appropriate surface irrigation entity by use of a Microsoft EXCEL spreadsheet, described below. More information about the estimation of Snake River surface irrigation diversions is available in ESPAM Design Document DDW-012.

Data for surface water diversions from sources other than the Snake River were primarily available from watermaster records. The actual data were obtained from various sources, including electronic files from Idaho Department of Water Resources (2001), paper and microfiche watermaster records (IDWR, 2002b), and other sources. In the case of watermaster reports, data were generally available as annual summaries. Monthly fractions were determined by hand calculation from a sample of microfiche or paper copies of daily watermaster records, and applied to annual data. The irrigation entities which use some non-Snake River diversions are IESW005, IESW007, IESW008, IESW025, IESW029, IESW037, IESW051, IESW052 and IESW054 (see Table 10). A complete description of the non-Snake River diversion data is available in ESPAM Design Document DDW-024.

Using both the Snake River and non-Snake River diversions and the aggregated surface water irrigation entities, a spreadsheet was created in Microsoft Excel to estimate surface water irrigation diversions for each surface water irrigation entity. This spreadsheet was also used to perform the calculations to estimate irrigation return flows to the Snake River, using monthly diversion data and return flow percentages (see section on Irrigation Return Flows).

The spreadsheet contains separate worksheets for each irrigation entity. Each worksheet contains the diversion data and return flow factors for all of the irrigation companies and private irrigators which comprise the associated irrigation entity.

Irrigation return flow factors (discussed in the following section) are applied to the respective diversion data on each worksheet of the spreadsheet file. The monthly diversions and returns for each canal company and private irrigator are summed to yield the monthly diversions and returns for the irrigation entity. Table B-6 lists the diversion volume for each irrigation entity for each stress period.

Irrigation Return Flows

Forty-six irrigation returns were measured as part of this study. The sites were selected and measured in a joint effort between Idaho Power and the U.S. Geological Survey, with oversight from the ESHM Committee. Irrigation return flow locations on the Snake River below American Falls Reservoir were suggested by IDWR to match the sites used in a study conducted in 1985-86. For the upper Snake River, candidate sites were identified from a video taken during a helicopter flight over the Snake River above American Falls and the Henrys Fork.

The site selection was verified through field work. Each selected site was assigned a standard eight digit USGS gage identification number. Pressure transducers with data loggers were installed at each site and irrigation return flow data were collected for the 2002 and 2003 irrigation seasons. The reader should note that both 2002 and 2003 were extraordinarily dry years, so it is unknown whether the measured return flows from these two seasons are representative of other years. However, very little measured return flow data exist for the ESRP. Table 12 lists the site name, location (lat/long) and USGS identification number for each measured site. Maps of site locations above and below American Falls are included in Figures 33 and 34, respectively.

Each return flow was assigned to an appropriate irrigation entity as defined in ESPAM Design Document DDW-008. The assignment was accomplished using the map of irrigation entities and return flow locations from Figures 33 and 34. The assignment was made based on location, land elevations and canal locations. Some of the returns on the Henrys Fork serviced more than one irrigation entity. The number of return sites per entity ranged from as many as ten for IESW032 (Twin Falls Southside) to one site shared by three irrigation entities on the Henrys Fork. Several entities were grouped together for the purpose of return flow calculation rather than try to parse the amount diverted from a single diversion between two or more entities. This procedure resulted in aggregating the returns and diversions into ten unique groups that were used to calculate the return flow lag factors. Table 13 lists the grouping of irrigation entities used to estimate return flow percentages. Diversions were summed for each of the return flow groups. Using measured return flows and an estimate of the volume of un-measured return flows for each group, a total percentage of irrigation return flow was estimated. This percentage was used to reduce the total diversion by the fraction of return flow to estimate how much water to apply to lands irrigated with surface water. Figure 35 shows the net irrigation diversions (minus return flows) and return flows for each year.

It should be noted that the Milner-Gooding Canal is used to deliver surface irrigation water to the Big Wood River. Irrigation water for surface irrigation entity IESW007 (American Falls Reservoir District No. 2) is supplied from both the Big Wood River and the Snake River. In order to not double-count this water that is delivered from the Snake River to the Big Wood River, the volume of water delivered to the Big Wood River was reflected as an irrigation return flow for IESW007. In this manner, this water was counted twice as a diversion for IESW007 (once in the Snake River diversion data and once in the Big Wood River diversion data) and debited once from IESW007 as an irrigation return flow. Since conveyance loss is estimated as a percentage of the diversion, the conveyance loss for the Milner-Gooding Canal would reflect this additional water being transported to the Big Wood River, but reflecting this volume of water as an irrigation return flow avoided double-counting the water as a diversion. The inclusion of this transported water in irrigation returns will serve to somewhat dampen the variability but increase the magnitude of the graph of returns shown in Figure 35.

Irrigation diversions and return flows are also used for the estimation of river gains and losses, which are discussed in a later section. In addition to the return percentage, the measured return flow data were also used to calculate the lag time of return flows in support of the estimation of river gains and losses. Examination of typical hydrographs of surface water returns versus diversion records indicates that there is a time lag between the timing of the diversions and the timing of the returns. A typical return flow hydrograph shows an increase as the irrigation season progresses. The diversions will remain constant or actually decrease during this same time period. The increase is likely due to increased returns as the fields and canals become saturated.

This phenomenon was dealt with by applying the concept of lag factors. Lag factors are the portion of the diverted water which returns to the river in each month following diversion. The lag factors are a time series of ratios. For example, a typical lag factor series might be (.01, .03, .07, .02, .01). Applied to a single month's diversion, this would mean that 1% of the diverted water returns in the first month, 3% in the second month, 7% in the third month, etc. By applying the lag factor series to the monthly diversions, the net diversion and return flow for each model stress period can be calculated. The sum of the lagged factors equals the total return percentage used in calculating net diversions.

Up to twelve lag factors could be used but more than five were never needed to obtain a "best fit." The lags were estimated using an Excel spreadsheet. Measured return flow hydrographs were compared with predicted return flow hydrographs. The return flow lag factors used to generate the predicted return flow hydrographs were adjusted until a reasonable match was obtained between predicted and measured hydrographs. This process was repeated for each of the ten groups of irrigation entities. Table 14 shows the final return flow lag factors for each of the ten groups of irrigation entities. ESPAM Design Document DDW-005 describes the estimation of return flow lag factors in detail. ESPAM Design Document DDF-007-2002 summarizes the measured return flow data for the 2002 season.

Irrigation entities for which there were no measured return flows were correlated with one of the ten groups of entities based on a) magnitude of diversions, b) method of irrigation application, c) regional similarity and d) similar crop mix. The return flow lag factors for the correlated entity were applied to the entity for which there were no measured return flows. These lag factors were entered into the input data sets for the IDWR Reach Gain/Loss Program which is used to estimate monthly Snake River gains and losses.

During model calibration, comparison of net model recharge with measured hydrographs indicated that there was too much water being applied to the model in the latter ten years of the calibration period. After much discussion, the ESHM Committee agreed that applying an increase in irrigation returns would serve the purpose of reducing the net recharge. This adjustment was made to help balance the water budget and did not imply any knowledge of the trends of irrigation return flows over time. Irrigation return flows have largely been un-measured on the ESRP despite the fact that return flows are such an important element of the water budget. The current study was limited to using measurements from the 2001 irrigation season and some limited measurements which were made in the 1985-1986 seasons. Efforts to measure return flows on the ESRP should be continued into the future so that the return flows can be better characterized and the new information can be incorporated in future modeling and calibration efforts. Table B-7 lists the return flow volume for each irrigation entity for each model stress period.

Conveyance Loss

Some of the water lost from irrigation is seepage from canals and ditches. This water is not available for irrigation and therefore neither available for crop evapotranspiration (ET) nor for recharge associated with irrigated agricultural fields. However, the leakage is still a component of recharge associated with irrigation activity. Seepage from canals can be an important source of aquifer recharge. Long canals in porous soils can lose 40% or more of the water diverted from the source (Chavez-Morales, 1985). In Idaho's climate, virtually all of this loss is associated with leakage to the aquifer (Dreher and Tuthill, 1999). Canal leakage can be represented by explicitly identifying leakage rates and locations. Or, a simplified approach can be taken by assuming that canal leakage is spatially distributed across the irrigated lands served by the canal.

Most canal systems have a large main canal or canals, supplying secondary laterals. These in turn supply individual farm ditches. Because size, construction, and maintenance of laterals and farm ditches are highly variable, estimating leakage on these secondary conveyances is difficult. Alternate wetting and drying can damage the "skin of sediment and biological slime" that helps seal canals. Smaller channels have more frequent drying cycles, and have more wetted perimeter relative to total flow capacity, so losses in these ditches are often higher than in main canals (Hubble, 1991). These laterals and farm ditches are widely distributed across irrigated areas. For these reasons, the simplified approach often closely reflects reality.

In prior Eastern Snake Plain models, a mixed approach has been taken. Garabedian (1992) treated three canals - Aberdeen-Springfield (95,000 AF/year), Milner-Gooding (97,000 AF/year), and Reservation (11,000 AF/year) - as leaky. IDWR (1997) treated only the Milner-Gooding Canal as leaky and attributed 146,000 AF of annual leakage to that canal. In both models, all other canal leakage was assumed to have spatial distribution similar to the spatial distribution of irrigated lands.

In the ESPAM model, Northside, Milner-Gooding and Aberdeen-Springfield canals are represented as leaky. These are high-volume canals with significant leakage along reaches that do not correspond with the irrigated places of use. Figure 22 shows a map of the canals which are represented as leaky in the ESPAM model. Some of the canal reaches shown in Figure 22 are sub-reaches of the three canals mentioned above.

Seepage is a function of the hydraulic conductivity of the bed material, the wetted perimeter, and the head (depth of water) in the canal. Because wetted perimeter and head can vary with flow, there is conceptual justification for using a percentage of flow to describe leakage. This is sometimes done in irrigation system assessment (Hubble, 1991) and has been used in aquifer modeling (Booker and others, 1990). Canal leakage can also be represented as a specified rate (volume per time), which has also been used in ground-water modeling efforts (Garabedian, 1992).

Because both specified-rate and percentage-based leakage rates are supported in the literature and can be justified conceptually, either was a candidate for use in the ESPAM model. Since a diversion rate partially controls seepage (apparent from the Chavez-Morales (1985) data), and since a percentage calculation guarantees that there will never be leakage calculated in a period without diversions, a percentage-based method was selected for the ESPAM model. Canal leakage was applied to linear GIS features representing leaky sections of canal. The recharge tools accommodate multiple leaky canal sections per irrigation entity, each with a unique leakage rate. The leakage rate can also be varied with time. Locations and leakage rates were assigned based on interviews with canal company personnel and results of previous studies. Some laterals of the Northside Canal were added in response to comparisons between model-predicted hydrographs and observed hydrographs at some wells, during early stages of calibration. For the Northside and Milner-Gooding canals, a constant leakage rate was used throughout the study period. For the Aberdeen-Springfield canal, unique values were assigned to each stress period based on canal-company data (Howser, 2002).

Varying canal seepage within a season may allow a better fit to measured heads in wells. While it is acknowledged that intra-season variation in canal leakage may occur, and that these differences may propagate into aquifer heads, data were not available to adequately represent these conditions for the calibration period. Leakage rates were based on interviews with canal personnel and checked against values published by Garabedian (1992) and IDWR (1997). Because imprecision in calculating canal leakage affects only the spatial distribution and not the total amount of recharge, and because of the danger of introducing error by synthesizing data, canal leakage for the model calibration period was estimated as a constant percentage of diversion volume within each irrigation season. To allow for future testing of various scenarios, the GIS and Fortran components of the recharge tool allow unique canal leakage percentages to be applied to each stress period. The data available from the Aberdeen-Springfield Canal Company are annual volume totals, so the fractions calculated were based upon annual volumes. Table B-8 lists the canals, the assigned irrigation entities and the seepage percentages used during the simulation for each of the canals.

Net Recharge from Surface Irrigation

Net recharge due to surface irrigation is calculated in the GIS/Fortran Recharge Tool (Appendix C). The GIS component of the tool prepares text data files containing a) a mapping of surface water entities to model cells within each entity's service area, b) reduction factors for non-irrigated inclusions, c) ET and precipitation for each model cell for each stress period, d) ET adjustment factors, e) diversion data, return flow percentages, canal leakage percentages and sprinkler proportion for each model stress period for each surface water irrigation entity and f) off-site pumping volume delivered for irrigation.

For each model cell, for each stress period, the GIS/Fortran Recharge Tool calculates the net recharge due to surface water irrigation according to Equations 8 and 9. The net recharge from surface water irrigation is added to other estimated recharge and discharge (for example, ground-water withdrawals in the same model cell). Figure 35 shows the net recharge due to surface water irrigation for every year of the calibration period. Inspection of Figure 35 shows that there is approximately a 2 million-acre-ft variation in net recharge due to surface water irrigation between the highest and lowest years of the 22-year calibration period. This reflects the great variation in natural water supply. This also reflects the important role that incidental recharge to the aquifer from surface water irrigation plays in aquifer recharge.

Ground Water Irrigation

Net discharge from ground-water irrigation is estimated as consumptive use (ET) offset by available precipitation (Eq. 10). ET adjustment factors are applied to the estimated evapotranspiration based on source of irrigation water and method of application. No difference was found between ET for ground-water or surface-water irrigation. Sprinkler irrigation was determined to consume approximately 5% more water than furrow irrigation (see ESPAM Design Document DDW-021). Figure 35 shows the net extraction due to ground-water irrigation. As can be seen in Figure 35, the net impact of the approximately 1 million acres of ground-water irrigated land is a relatively constant 2 million AF annually. This reflects the relative constant rate of ET (see Figure 25). Much of the variation in net extraction due to ground-water irrigation (a variation of approximately 900,000 AF) is arguably driven by variation in precipitation (approximately 1,200,000 AF variation). Figure 36 shows the spatial distribution of the net extraction due to ground-water irrigation averaged for the 22-year model calibration period.

Tributary Underflow

Groundwater contributions from tributary basins, or tributary underflows, were estimated for the new model based on tributary underflow estimates published in

Garabedian (1992). The Garabedian estimates were adjusted in tributary basins where the ESPAM aquifer boundary differed from the Garabedian aquifer boundary. As part of the water budget balancing process, all of the tributary underflow estimates were scaled by a factor of .97 (a net 3% reduction). Table 5 lists the average annual tributary underflow values used for ESPAM.

Recognizing that tributary underflow varies seasonally and from year to year, the average annual ESPAM tributary underflow values were scaled using normalized annual values based on measured discharges at Silver Creek. Silver Creek was selected because a) it is almost entirely spring-fed and sits on bedrock, b) there is a long-term gage on Silver Creek and c) the flows in Silver Creek reflect spring discharge from a basin which is similar to many of the Snake Plain aquifer tributary basins from the standpoint of land use, precipitation, and elevation. It is believed that flow of Silver Creek is more seasonally variable than underflow in the tributary valley. Therefore, the variation of Silver Creek discharge was dampened by 1/3 to decrease the amplitude of variation. Table 15 lists the non-dampened and dampened normalized flows for Silver Creek for each year of the ESPAM model calibration period. The average annual tributary underflow discharge for each tributary basin was multiplied by the dampened Silver Creek normalized flow for each time period, yielding the contribution from each tributary to the ground water model for each stress period. While it is acknowledged that there will be intra-year variations in flow, lack of knowledge about the basin-to-basin differences in the timing of peak flow dictated shaping underflow on a year-by-year basis (Table 5). ESPAM Design Document DDW-004 describes the estimation of tributary underflow for the ESPAM model in more detail.

Recharge on Non-Irrigated Lands

This section discusses calculation of two spatially-distributed components of the aquifer water budget; recharge from precipitation on non-developed lands and spatially-distributed recharge and discharge from land uses that comprise a small fraction of the study area. These minor-use areas are dry farms, cities, and wetlands.

Precipitation on the plain is approximately 6.7 million AF per year, with 80% of this falling on non-developed lands. Garabedian (1992) estimates that precipitation on non-developed lands produces 700,000 AF of recharge per year, which equals approximately 30% of the magnitude of irrigation recharge. It is the component of recharge to which Garabedian assigns the most uncertainty. The other land uses, dry farms, cities, and wetlands, represent minor components of the water budget, with a combined net effect of about 160,000 AF per year (calculated from data reported by Goodell, 1988).

Recharge on Non-Developed Lands. A method was developed for estimating recharge from precipitation using GIS grid maps of monthly precipitation (Daly and others, 1998) and thickness and texture of soil coverage (Figure 23). The developed method is suggested by Rich (1951). Rich studied basins which, unlike the Eastern Snake Plain, had a component of surface discharge. His relationship actually described total basin yield, but it is simplified here to represent recharge, since runoff that does occur on the plain collects in depressions where it also recharges the aquifer. The equation is:

$$\text{Recharge} = K * (\text{Precipitation})^N \qquad \text{(Eq. 12)}$$

where K is an empirical slope parameter and N is an empirical exponent that introduces curvature into the relationship.

Rich applied this formula to annual precipitation. The formula presumes that with less precipitation, most of the precipitation is intercepted by various mechanisms (leaf interception, depression storage, soil moisture storage, evaporation, etc.) and that with increasing precipitation, more of the precipitation is available for infiltration. Parameters K and N can be adjusted to shape the calculated recharge curves. However, knowing the actual recharge from precipitation on non-irrigated arid lands is very difficult (Gee, 1988). Attempts to use a water balance to determine the non-irrigated recharge are frustrated by the fact that another large component of recharge, tributary basin underflow, is also poorly defined. Consequently, parameters K and N were initially calibrated to match previous results. ESPAM Design Document DDW-003 contains a detailed explanation of the estimation of recharge on non-irrigated lands.

Estimates of recharge depth from Equation 12 were performed for three soil classifications based largely on soil thickness. These calculations employed monthly estimates of precipitation. Precipitation during November through February was summed into the February value to represent snowmelt. These calculations were performed external to the GIS component of the recharge program but were input to the Fortran component of the recharge program as monthly recharge depths. A fourth pseudo soil classification was used to represent the minor land uses (cities, wetlands and dry farms).

Within the Fortran-Recharge Program, the recharge depths from non-developed land were multiplied by the non-irrigated land in each cell. Non-irrigated land was determined as the difference between the area of a cell and the irrigated area within the cell. Monthly non-irrigated recharge values were summed to estimate recharge in each stress period. Figure 37 illustrates the areal distribution of non-irrigated recharge averaged for the 22-year calibration period.

Recharge on Minor Land Use Types. Several minor land use types were identified and recharge on these areas was handled separately. The categories of minor land uses which were identified were: dry farm, water and wetlands and cities and industrial areas. Table 16 lists the minor land use types, the acres represented by these types and the recharge rate. On dry farms, the recharge rate was presumed to be zero. Discharge on wetlands was presumed to be three feet, less precipitation. Discharge for cities and industrial areas was presumed to be 1.2 feet/year. The discharge from wetlands and cities is represented in Figure 37 as negative recharge. These minor land uses are discussed further in Contor (2002).

Fixed Point Pumping

Fixed point pumping (or recharge) represents an impact that occurs at a single point and does not enter into any other recharge calculation. Negative values are applied directly as an extraction from the model cell that contains the point, and positive values are applied as a direct injection. Fixed point pumping was used to represent the following practices: a) pumping where the pumped water is added to a natural water body to augment the surface water supply and the same water is counted as a diversion from that surface water body, b) recharge corrections for deficit irrigation on the Richfield tract and c) recharge correction for wetlands. Table B-9 lists the model cells where fixed pumping is represented.

Irrigation Wells. In the ESPAM model, certain irrigation wells are treated as fixed-point pumping because the pumped water is delivered to a natural water body and is included in the water master reported diversion volume of water diverted for irrigation from the water body. One group includes wells known as "exchange wells," which pump water into the Teton River or the Snake River. Their volumes are included as diversions within the diversion data files from the IDWR planning model (see ESPAM Design Document DDW-012). The other group of fixed-point wells includes the wells that deliver water into Mud Lake or Camas Creek in Jefferson County, for diversion to irrigation entity IESW029. The volume of water pumped from these wells is included within the diversion volumes reported by Water District 31 (see ESPAM Design Document DDW-025).

The spatial location of the "exchange wells" class of fixed points was obtained from GPS data or public land survey legal descriptions supplied by Water District 01 (Madsen, 2000; Olenichak, 2003). Figure 38 shows the location of these exchange wells.

The GIS points for the Mud Lake fixed points and the offsite ground-water pumping wells were placed to represent groups of physical wells within small local areas. The actual locations of the physical wells were obtained from IDWR GPS data (1999) and aerial photography. Figure 39 shows the fixed points in the Mud Lake area, relative to the model grid, observation wells, and physical pumping wells.

Pumping volume for the "exchange wells" fixed points was obtained from Water District 01 annual reports (2003). These data are complete for the entire calibration period. The annual reports include monthly pumpage volume for each well that is active in a given year. The gross pumping volume for the "Mud Lake" fixed points was obtained from Water District 31 data, as described in ESPAM Design Document DDW-025. To apportion the Mud Lake volume to individual points, the number of wells per model cell was adjusted to better reflect field observations of relative production of individual well groups. The fraction of the total volume assigned to each point was proportioned to the adjusted number of wells, as shown in Table 17. Any uncertainty in apportionment represents imprecision in the spatial distribution of discharge, but not an uncertainty in the water budget.

Richfield Tract Recharge Adjustment. An adjustment was made on the Richfield tract to account for deficit irrigation conditions. Because most irrigated areas with limited surface-water supplies have supplemental wells, the recharge tools automatically impute ground-water pumping whenever surface-water supplies are inadequate to meet consumptive use demand. For some stress periods this is an inappropriate calculation for irrigation entity IESW007 (in the Richfield area), since deficit irrigation occurs without the opportunity for supplemental ground-water pumping. This is corrected by applying an offsetting volume to a deficit-irrigation class of fixed points, in those cells where deficit irrigation occurs without supplemental ground water. This correction is explained in further detail in ESPAM Design Document DDW-003.

Deficit irrigation correction volumes were determined by identifying cells without groundwater where net irrigation from surface-water irrigation was zero or negative. Using a spreadsheet, a correction volume was calculated to offset the indicated negative recharge.

Wetlands Correction. During model calibration, the need for a correction for wetlands became apparent. As described in ESPAM Design Document DDW-003, Recharge on Non-irrigated Lands, a correction was required for model cells that contained both wetlands and irrigated lands. The recharge tools apply the cell-average non-irrigated recharge rate to the non-irrigated lands within each model cell. When part of the cell is irrigated and part is wetlands, the cell-average rate is biased by the non-irrigated-recharge rate associated with the soil type on the irrigated lands. This bias was corrected by applying an offsetting volume to a wetlands class of fixed point pumping in those cells containing both irrigation and wetlands. Wetlands correction point volumes were determined by calculating the correct non-irrigated recharge in individual cells with both wetlands and irrigation, and comparing the volumes to the volumes calculated by the recharge tool.

Figure 40 illustrates fixed points used to represent the wetlands and deficit-irrigation correction points. Table 18 lists the total adjustment to recharge for each stress period for each category of fixed point well.

Off-Site Ground Water Pumping

Offsite ground water pumping refers to irrigation pumping that is conveyed to a distant location for application to irrigated lands. It must be accounted as a withdrawal from the model cell that contains the well and as applied irrigation water to the model cells that contain the irrigated lands. While physically this is the same process that is represented by fixed-point pumping for the exchange wells and Mud Lake wells described above, the accounting difference is that offsite-pumping volumes have not been included in a water-master reported diversion volume. They must be added to diversions within the recharge calculations. In this modeling effort, wells in Jefferson County that supply water to irrigation entity IESW044 are represented as offsite ground water pumping. While irrigation entities IESW001 (A & B Irrigation District) and IESW018 (Falls Irrigation District) also pump ground water into canals for conveyance to places of use, their wells are distributed approximately uniformly across the irrigated service area, similar to other ground-water irrigated areas within the study area. There is not a need to spatially separate the extraction and recharge associated with irrigation.

In the Fortran component of the recharge tool, the pumped volume from the offsite ground water pumping wells is removed from the cells in which the wells are located, and added to diversions for IESW044. The entire pumped volume is included in the irrigated-lands recharge calculation as a contribution towards recharge. Volume-for-volume, any over-estimate in pumping becomes an over-estimate in irrigated-lands recharge, and any under-estimate in pumping becomes an under-estimate in recharge. The inaccuracies balance, so that the only consequence of an inaccuracy in estimating pumping volume is an inaccuracy in spatial distribution of discharge and recharge. The region in which this practice occurs is distant from the Snake River so these potential inaccuracies have a low probability of impacting predictions near the river.

An initial pumping estimate of 4 AF/ac/yr comes from experience of the North Water Measurement District for water years 1997 through 1999. This appears reasonable considering ET, precipitation rates and irrigation and conveyance efficiency.

The lands in IESW044 are aggregated from three irrigation companies; Jefferson Irrigation, Monteview, and Producers Canal Companies. Three of the offsite points are associated with the Jefferson lands, three with the Monteview lands, and two with the Producers lands. Figure 41 shows the location of the off-site wells. Based on the original GIS shapefiles (see ESPAM Design Document DDW-008), the 2000 irrigated lands map was clipped to show irrigated lands in each of the three companies. The acreage of these lands was multiplied by four feet to determine a gross pumpage volume for each company, then divided by the number of represented off-site wells to obtain an annual volume per well. The annual volume was distributed among the months according to a crop-weighted average monthly ET from US Bureau of Reclamation (2003) Agrimet data for 2000.

To scale pumpage to reflect year-to-year differences in ET, an index was constructed for each year 1980 through 2000 using revised ET values (Allen, 2002) for Hamer, Idaho (the nearest weather station with a full record). The ET index is a factor that relates ET for each given year to the long-term average ET. It is multiplied by the derived average monthly pumpage to give a monthly pumpage adjusted for the individual year's climatic regime.

Because the Monteview AGRIMET station did not start operation until 1997, the Hamer NOAA station was used to calculate the index for years up through 2000. For each of those years, the index was simply the individual year's ETr divided by the average ETr. Because the revised ETr for the Hamer NOAA station did not include a value for 2001, the 2001 index was derived from Monteview AGRIMET data. The results are summarized in Table 19. ESPAM Design Document DDW-026 contains more details regarding the estimation of off-site ground-water pumping. Table 20 lists the represented pumping in each model stress period for the off-site wells.

Perched River Seepage

Perched seepage, or bed loss, represents seepage from a creek or river which is above the water table. The seepage rate is independent of the nearby aquifer water levels; that is, the reach is not hydraulically connected to the aquifer. All perched seepage is entered into the model as a line source. The estimated seepage is distributed among the model cells associated with each perched reach. This information is prepared as input to the Fortran recharge program, which applies the perched seepage in the estimation of net recharge.

Perched river seepage for rivers and creeks other than the Snake River was estimated from a water balance using gage and diversion data. The same data were often used for both diversion (see section on surface water diversions) and seepage calculations. Figure 21 shows the primary perched reaches. Some of the less significant represented perched reaches (for example, the Birch Creek hydropower discharge) were represented in the model but are not shown on Figure 21. Table 6 contains a complete listing of the represented perched reaches. Table B-2 lists the model cells associated with each of the perched reaches.

Data were not always available for every gage for every year. The following section summarizes how the seepage from each perched reach was estimated. For a complete description, the reader is referred to ESPAM Design Document DDW-024.

Camas Creek and Lone Tree. Flood-control diversion volumes (USGS, 2002) were applied as a line source at the Lone Tree spreading location. Camas Creek perched-river seepage (bed loss) was based on the difference in flow between two gaging stations at Camas Creek. The upper gaging station is Camas Creek at Red Road near Kilgore and the lower is Camas Creek near Camas. Corrections were made for diversions at Lone Tree and irrigation diversions between the two gages (Shenton, 2002).

The Red Road gage data series (the north end of the losing reach) was incomplete. Thus, the final perched seepage values used in model calibration were based on gage data for all periods where data were available and estimated seepage where Red Road gage data were not available.

Medicine Lodge Creek. Medicine Lodge Creek lies partially inside and partially outside the model study area. GIS analysis showed that 45% of District 32-c irrigated lands are within the study area. Medicine Lodge Creek sinks into the Snake River Plain south of the irrigated lands. Bed loss was calculated by subtracting the inside-study-area diversions from the gaged flow of Medicine Lodge near Small, Idaho. The gaging station for Medicine Lodge began to function during the summer of 1985; records were not kept prior to that date. For years after 1985, the "Big Lost River Below Mackay Reservoir" gaging station was compared with Medicine Lodge creek gage records using linear regression. This produced a reasonable relationship, which was applied to the years before 1985. For all years before 1985, the predicted Medicine Lodge gage record was used with actual diversions in calculating bed loss. Actual data were used to calculate bed loss for all years after 1985.

Birch Creek and Birch Creek Hydropower Plant. The bed loss and diversion calculations for Birch Creek are divided into two different time periods. Before 1987, water was delivered to Reno Ranch through a ditch with an estimated 50% bed loss. After 1987, water was diverted into a lined canal and pipeline and delivered to the Birch Creek hydroelectric plant before being used by the Reno Ranch (Sorenson Engineering, 2002).

Prior to 1987, Birch Creek was measured at the USGS gage station "Birch Creek at Eight-mile Canyon Road Near Reno Idaho." Water measured by this gage station was then diverted into the old Reno Ranch ditch during summer months. Excess water (and all water during winter months) was allowed to continue downstream and flow out onto the desert.

For months when the Eight-mile gage station was not active, gage records were predicted using regression based on Birch Creek diversions. Prior to 1987, half of the reported diversions were applied as diversions to irrigation entity IESW037. The Eight-mile gage record, minus diversions applied to IESW037, was applied as perched river seepage (bed loss) in the natural channel of Birch Creek within the study area. This actually applied the 50% ditch loss from the old ditch to the natural channel of Birch Creek, but since the old ditch is outside the model study area, seepage from the ditch actually enters the model domain as sub-surface flow in the model cells near the creek channel.

During the summer of 1987, the Birch Creek hydroelectric plant began to operate and the Eight-mile gage was discontinued. The entire flow of Birch Creek is delivered to the plant through a lined canal and pipe system. Outflow from the plant is applied to irrigation of the Reno Ranch or delivered to a channel where it infiltrates into the subsurface. Discharge records were obtained from the Birch Creek hydroelectric plant for use in calculating bed loss (Sorenson Engineering, 2002), in combination with watermaster diversion records.

<u>Camas National Wildlife Refuge and Mud Lake</u>. For the wildlife refuge, surface-water delivery volumes are recorded by the watermaster. These volumes are applied to a GIS line feature along the axis of the wetland.

<u>Camas Creek inflows to Mud Lake</u>. In some years, particularly during the winter, Camas Creek supplies water to Mud Lake. In the perched river seepage data set, Camas

Creek inflows are applied as perched river seepage (recharge to the aquifer) to a GIS line feature that occupies the same model cells as the lake. Summertime values are obtained from watermaster records (Shenton, 2002). Wintertime inflows are not recorded directly, but are computed from a mass-balance calculation of October and May lake contents, winter-time pumping to the lake, and estimates of winter-time ET and precipitation, using watermaster-supplied data.

Mud Lake Flood Control. In high water years, water is pumped from Mud Lake to the desert south of the farm lands as a flood control measure. Data are obtained from watermaster records. No irrigation diversions are associated with this perched river seepage site.

Little Lost River and Little Lost River Flood Control. Because the Little Lost River infiltrates to the aquifer a short distance beyond the irrigated lands, perched river seepage is calculated as the difference between flow at the Little Lost River gage (very near the model boundary) and diversion volume.

When annual diversion volumes were interpolated to monthly values based on percentages from 2001 daily records, many negative bed loss values were generated. To correct this condition, annual diversion volumes were distributed temporally according to summer gaging station temporal patterns. This gave a more reasonable distribution without causing negative bed loss values.

The gaging station at "Little Lost near Howe" was decommissioned in 1991. A number of prediction options were explored to estimate gaging records for the last years of the model calibration period. A linear regression based on precipitation at the Howe gage was the selected method.

Using the predicted yearly gage station record for years after 1991, yearly diversions were subtracted to give a total bed loss for each year. Annual values were interpolated to monthly results using percentages from the pre-1991 data. To smooth the time series, months were grouped together and averaged. The groups were April-Oct, Nov-Feb, and March.

In 1985, a flood-control spreading area was developed up-river of Little Lost River diversions. During winter months water is diverted to the spreading area to prevent icing and local flooding. Another line source was developed to show this location as a point of recharge during winter months. Prior to 1985, wintertime bed loss is applied to the channel of the Little Lost River below the gage. For 1985 and later years, it is applied to the spreading area. Summertime bed loss is always applied to the river channel.

Big Lost River. The entire irrigated area of the Big Lost Valley that is included within the model area is bounded between two gages on the Big Lost River. The river flows through irrigated lands throughout this area, and there is a fairly dense network of diversion canals and laterals throughout the irrigated area. The gage data were complete for the entire calibration period. Therefore, the recharge associated with surface water irrigation, canal leakage and perched river seepage was all lumped into the surface-water irrigation calculation. For summer months, the entire difference between the upstream gage (Mackay Dam) and the downstream gage (Near Arco) was applied as a diversion to irrigation entity IESW005. In the winter months, the entire difference was applied as bed loss (perched river seepage) to the line feature representing the riverbed, illustrated in Figure 21. This resulted in some wintertime negative values, which could be consistent with the processes of periodically gaining reaches and of lagged return flows. These are both physical possibilities, so the negative values were retained in the data. Three gages below Arco and records of diversions to a flood-control spreading ground at the Idaho National Laboratory were used to spatially distribute any water discharging past the Near Arco gage to the spreading ground and lower reaches of the river.

Big Wood River and Little Wood River. Most of the Big Wood River was represented with no perched seepage because the bed loss calculated from gage data oscillated about zero, with a very small magnitude relative to stream discharge. Upstream and downstream gage data (adjusting for diversions and returns) were used to calculate bed loss in the Little Wood River, the lower reach of the Big Wood River, and the reach of the Big Wood River identified in Table 6 as the "Below Magic Reservoir" reach, just below the reservoir.

Twin Falls Canal and Lake Murtaugh. Because nearly all of the Twin Falls Canal Company lands lie outside the study area, the diversions applied to irrigation entity IESW041 were discounted substantially. However, the leaky portion of the canal within the study area and a part of Lake Murtaugh within the study area contribute recharge to the aquifer based on total diversions. Because of the large volume of recharge relative to the small fraction of diversions applied to the model, these leaky features were not treated with the leaky canal function of the GIS/Fortran Recharge Tool. Instead, recharge for these locations was calculated in a spreadsheet using the full diversion volume, and applied in recharge calculations as perched river seepage to the location illustrated in Figure 21. Leakage calculations relied upon data from Twin Falls Canal Company (circa 1955).

Table 6 lists the average perched seepage for each reach. Both average stress period seepage and average annual seepage are listed in Table 6.

Steady-State Model Water Budget

During compilation of water level data, it became apparent that there was an 18.5-year period (May 1, 1982 to October 31, 2000) during the 22-year model calibration period where aquifer water levels across the eastern Snake River Plain started and ended at approximately the same levels. This would indicate that during that period, there was no net change in aquifer storage or, stated otherwise, that on the average during that period the inflows were equal to the outflows. This period was selected as the steady state period for the ESPAM model. To generate the recharge for the steady state model, each component of recharge was averaged for that period. Figure 42 shows a bar graph of the elements of the steady state recharge. River gains in Figure 42 represent the net of Snake River and Henrys Fork gains and losses above Minidoka and spring discharges in the Milner to King Hill reach. Figure 43 shows a map of the areal distribution of steady state recharge.

Transient Model Water Budget

All of the components of recharge described above were estimated for each of the 44 transient model stress periods and were processed through the GIS/Fortran Recharge Tool. The output of the Fortran component of the recharge tool is the MODFLOW-formatted well file or recharge array which contains the net recharge or discharge for every model cell for every stress period. Figure 44 shows a graph of the annual net recharge for the 22-year period, graphed along with precipitation for the same period. There are several striking features to note in Figure 44. The amount of net aquifer recharge is highly correlated to the amount of precipitation. Precipitation contributes to net aquifer recharge in three ways: precipitation is the basis for the water supply for surface water irrigation, high summer precipitation reduces the requirement for ground-water pumping and precipitation contributes directly to aquifer recharge via recharge on non-irrigated lands. Additionally, in a high precipitation year, carryover water will be left in the reservoirs for use in the following season, helping to sustain the supply of water available for aquifer recharge in the following year. Another striking feature from Figure 44 is that there is a 4 million acre-foot variation in estimated recharge to the aquifer, ranging from a high in 1984 of approximately 6.3 million AF to a low in 1989 of approximately 2.2 million AF. These dramatic variations in net aquifer recharge will cause dramatic variations in aquifer water levels.

Figures 45 and 46 show the spatial distribution of recharge for the irrigation season and the non-irrigation season, respectively, for 1980-1981. Comparison of Figures 45 and 46 shows that irrigated agriculture plays a significant role in net aquifer recharge.

Model Calibration

The ESPAM model was calibrated using automated parameter estimation tools. The goal of model calibration was to adjust model parameters (transmissivity, storativity, riverbed conductance and drain conductance and elevation) until model-predicted values of aquifer water levels and discharges to the river matched observed values. The calibration was done in two steps. An initial steady state calibration was done to establish initial aquifer transmissivity and riverbed and drain conductance. After the initial steady state calibration, a coupled steady state and transient calibration was done.

During the coupled steady state and transient calibration, the parameter estimation software would adjust aquifer storage and drain elevation during the transient portion, followed by a check of the steady state model fit. This forced the transient calibration to not only provide a 'best fit' to the transient data but to also honor the steady state observations. Changes to the transmissivity field and riverbed and drain conductance were allowed during the coupled steady state/transient calibration.

The following sections describe the parameter estimation tools used for ESPAM model calibration, the collection of aquifer observation data used during model calibration and the initial steady state and final coupled calibrations. Final model parameters and a comparison between model-predicted values and observed values are presented in the section describing the coupled steady state and transient calibration.

Parameter Estimation Tools

PEST, a nonlinear, least-squares inverse modeling program developed by Doherty (2003) was used to calibrate the model. (PEST is available for download on the web at *www.sspa.com/pest*.) During calibration, PEST runs the MODFLOW model thousands of times, comparing model-predicted results with observations. After each model run, the objective function is analyzed to determine whether the model run was an improvement over the previous run. After each model run, PEST evaluates each adjusted parameter to determine the next best adjustment to that parameter. PEST then prepares the input data set for the next model run with the adjusted parameters, runs the model and re-evaluates the output. The goal is a weighted, least-squares optimization of the fit between the model-predicted values and the observations.

A key to success at using parameter estimation tools is to have a greater number of observations than parameters being estimated. With previous parameter estimation packages (including previous versions of PEST), this was accomplished by establishing zones of transmissivity and storativity. The parameter estimation software would be tasked to calibrate a single parameter value for each zone, thus greatly reducing the number of parameters being estimated for the entire model. The delineation of the zones was subjective and the calibrated model had abrupt changes in parameter values at zone boundaries.

PEST allows an option of using "pilot points" where parameter values are estimated at user-specified points. PEST interpolates model parameter values between the pilot points using kriging or some other spatial interpolation scheme. For example, during ESPAM model calibration using PEST, transmissivity was estimated at 169 pilot points. The transmissivity at these 169 points was interpolated to the entire grid of 11,000 active model cells. Similarly, storativity, which has a much lower degree of variation than transmissivity, was estimated at 28 pilot points and interpolated to the whole grid. Doherty (2003) provides a more rigorous description of pilot points and how the process works. Additionally, PEST was instructed to calibrate riverbed conductance at the five reaches of the upper Snake River and drain conductance and elevation at the six spring reaches in the lower Snake River. At each calibration run, PEST minimized the difference between observed and model-predicted aquifer water levels and river gains.

River Gain/Loss Calibration Targets

For the upper Snake River, the river gain/loss calibration targets were estimated using the IDWR Reach Gain/Loss Program. The Reach Gain/Loss Program uses gaged reach inflows and outflows, measured diversions and estimated irrigation returns and reservoir storage and evaporation to calculate a water balance for the reach. The residual of the water balance is the estimated river reach gain from or loss to the aquifer. More information on the IDWR Reach Gain/Loss Program can be obtained directly from IDWR. Inputs to the Reach Gain/Loss Program include measured diversions, gaged river flows, reservoir stage and irrigation return flow lag factors (described above). For the purposes of the ESPAM modeling, the newly calculated return flow lag factors were entered into the Reach Gain/Loss Program input files.

Figures 47 through 51 show the estimated monthly reach gain for the five reaches of the upper Snake River (Ashton to Rexburg, Heise to Shelley, Shelley to Near Blackfoot, Near Blackfoot to Neeley and Neeley to Minidoka). As can be seen in Figures 47-51, there is a lot of noise in the monthly data. Prior to use as calibration targets, the monthly reach gains/losses were filtered to eliminate some of the noise (see transient calibration section).

The streamflow gages on the Snake River are maintained by the USGS and are assigned a rating of "excellent," "good" or "fair," with associated uncertainty bands of ± 5%, ± 10% and ± 15%, respectively. Each of the upstream gages for the five reaches of interest is rated "good." Given the "good" rating, the uncertainty on the inflows for each reach is approximately ± 10%. In general, assuming that there is no systematic error introduced at a gage, the ± 10% uncertainty is for an instantaneous measurement.

Assuming no systematic error, the uncertainty in the river discharge should be reduced as single day measurements are aggregated into weekly or monthly measurements.

The uncertainty in the estimated river gain or loss is driven by a) uncertainty in both the upstream and downstream gages, b) uncertainty in measured diversions, c) uncertainty in estimated irrigation return flows and d) uncertainty in reservoir storage and evaporative losses. The estimated reach gain or loss cannot be more accurate than the least accurate component. In order to provide a sense of the magnitude of the estimated river gain or loss relative to gage uncertainty, Figures 47 through 51 also show an uncertainty band of ± 5% of the upstream gage. This is not a statement of the true uncertainty of the estimated reach gain or loss but is provided as a guideline for the magnitude of the gain or loss relative to a conservative uncertainty band on the gaged inflow.

If the estimated reach gain or loss is approximately the same magnitude as the ± 5% band, then there is low confidence that the reach is gaining or losing. Figure 51 shows that the magnitude of the Neeley to Minidoka estimated reach gain is almost always within this ± 5% band; hence, there is significant uncertainty that this reach is gaining or losing. In contrast, Figure 50 shows that the magnitude of the Near Blackfoot to Neeley estimated reach gain is significantly greater than the ± 5% band; hence there is more confidence that this reach is gaining. The estimation of river gain and loss calibration targets is further discussed in ESPAM Design Document DDM-017.

Spring Discharge Calibration Targets

Spring discharge calibration targets proved to be something of a challenge for the ESPAM project. Very few of the springs in the Thousand Springs region are measured with any regularity or accuracy. For many of the springs in the region, it is difficult to discern the discharge point of the spring. Many of the springs have complex plumbing which routes the collected water to various users, making measurement difficult.

The USGS estimates the total annual spring discharge from the regional eastern Snake River Plain aquifer (excluding spring discharge from the Twin Falls area on the south side of the river) based on a regression equation developed by Kjelstrom (1995b). The regression equation uses measured flow at several index springs. However, the Kjelstrom method addresses neither seasonal nor spatial variation in spring discharge. Table 21 lists the annual estimated reach gain from the north side in the Milner to King Hill reach for the calibration period.

In order to compensate for this lack of data, the ESPAM modeling team and the ESHM committee members agreed to try to spatially distribute the total reach gains as predicted by the Kjelstrom method according the magnitude of the springs recorded by Covington and Weaver (1990). For each of the spring sub-reaches shown in Figure 19, the relative magnitude of spring discharge in the sub-reach to spring discharge in the whole reach was estimated. Table 22 lists the relative magnitude of the six spring sub-reaches from Milner to King Hill and the percent of the total reach gain that each represents. Temporal discretization was done using the seasonal variation in measured springs such as Blue Lakes, Crystal and Box Canyon, which were deemed representative of the springs in the whole reach. This was the method initially used to generate spring calibration targets in the Thousand Springs reach. This method was successful for generating average spring reach calibration targets for steady state calibration. During transient model calibration, however, it became apparent that springs varied markedly in their temporal discharge patterns. Thus the initial method of generating spring targets was unsuccessful for use in the transient calibration.

The second approach, which ultimately was successful for transient calibration, was to use actual spring measurements for the springs for which measurements exist. Initially, the springs for which long-term measurements existed were: Devils Washbowl, Devils Corral, Blue Lakes, Crystal Springs, Clear Lakes, Briggs Springs and Box Canyon Springs. The two springs with the greatest magnitude of discharge, Thousand Springs Power Plant and Malad Gorge Power Plant, did not have discharge measurement records.

At the request of the modeling team, Idaho Power used power generation records at the two plants to estimate spring discharge for Malad and Thousand Springs. Although, not obtained through direct measurement, these turned out to be reasonable proxies for measurements of the springs at Malad and Thousand Springs. Once those hydrographs were obtained, transient model calibration was successful. Figure 52 shows the location of the individual springs used as calibration targets. Hydrographs of the measured (and estimated) springs will be presented in figures in the discussion of transient model calibration. Table 23 lists the model cells representing the springs used as transient calibration targets. Table 24 lists the number of observations and the date range of the observations for each of the calibration target springs. In addition to using monthly spring measurements, the mean discharge and standard deviation of each spring were also used as calibration targets. The annual Kjelstrom estimate of total spring discharge for the entire Milner to King Hill reach as well as the estimated sub-reaches were used to help evaluate the model fit. The estimation of spring discharge calibration targets is further discussed in ESPAM Design Documents DDM-018 and DDM-008.

Aquifer Water Level Calibration Targets

Aquifer water level calibration targets were obtained from the IDWR data base of Idaho aquifer water level measurements using the program WellLog. The WellLog data base includes measurements from the USGS, IDWR, Idaho Power and private consulting firms contracted by the agencies to conduct water level measurements. More information about WellLog can be obtained in the WellLog user's manual (IDWR, 1997c).

Several synoptic measurements (mass measurements) of aquifer water levels were done in 1980-1981 as part of the USGS Regional Aquifer-Systems Analysis effort on the eastern Snake River Plain. This entails measuring as many wells as possible throughout the study area in a short period of time in order to estimate a regional potentiometric surface. As part of the current study, three additional synoptic measurements were done; in Spring, 2001, Fall, 2001 and Spring, 2002. This provided mass measurements at the beginning and ending of the model calibration period.

WellLog was queried for all depth to water measurements within the study area within the calibration period. Depth to water measurements which were documented to be in aquifers other than the regional aquifer, such as locally perched zones, were excluded. Similarly, depth to water measurements which appeared flawed (perhaps an error in recording or a measurement taken shortly after a well was pumped) were discarded. If neighboring water level measurements corroborated a seemingly spurious measurement, the measurement was retained.

Wellhead elevations were estimated using USGS 10 meter digital elevation maps (DEMs) intersected with the IDTM position of each well. This was done using GIS software. An analysis of the accuracy of this technique was done by comparing the elevation determined using 10 meter DEMs versus surveyed elevations where they existed. It was found that, on the average, the elevation determined from the DEMs was within 1.21 ft of the surveyed elevation. This was considered acceptable accuracy by the ESHM committee members. More detail on the use of DEMs for estimating wellhead elevation can be found in ESPAM Design Document DDM-011.

Using the estimated wellhead elevations and the measured depth to water, water table elevations were calculated for each measurement. Figure 9 illustrates water table contours from the Fall 2001 mass measurement. More detail on the collection of aquifer water level data can be found in ESPAM Design Document DDW-014.

Initial Steady State Calibration

Steady-State Calibration Data

Although true steady state conditions rarely exist in natural aquifers, most ground water modeling efforts include a steady state analysis because the transmissivity distribution tends to be more sensitive to steady state water levels than transient water levels. As previously stated, the net change in aquifer storage, as indicated by water levels between May 1, 1982 and October 31, 2000 was small, so the period was selected as the steady state period. At steady state, the recharge and discharge for an aquifer system are balanced and no water is entering or leaving aquifer storage.

Steady state calibration water level targets were generated by averaging water level measurements for this period. Wells with only one observation during this time period were not used as targets. A total of 1009 steady state aquifer water level observations were used. Figure 53 shows the locations of the wells used as observations for steady state calibration. Figure 53 also shows the location of the river and spring reaches. The reader will note in Figure 53 that many of the wells used for steady state calibration targets are located reasonably close to the river and spring reaches. This helps to control the certainty of the calibrated parameters in these areas of high interest. In areas with few observation wells, the calibration parameters are less certain.

Steady state river gain targets were estimated by averaging the transient river gains for each of the five sub-reaches for the steady state period. Similarly, steady state spring calibration targets were estimated by averaging the transient spring reach targets for the steady state period. Table 25 lists the steady state river and spring calibration targets.

Steady-State Calibration Procedure

During steady state calibration, the model parameters of aquifer transmissivity and riverbed and drain conductance were estimated. The steady state calibration was accomplished using 1020 observations and 180 adjustable parameters. The observations include 1009 aquifer water level observations, five river reach gain/loss observations, and six spring reach observations. The adjustable parameters include 169 pilot points used to adjust the transmissivity distribution, five river parameters to adjust riverbed conductance for the five river reaches, and six drain parameters to adjust drain conductance for the six spring reaches. Figure 54 shows the location of the pilot points used for calibration of aquifer transmissivity.

The steady state calibration was accomplished by minimizing the difference between model-predicted steady state aquifer water levels and Snake River gains and losses and the averaged observed water levels and averaged estimated Snake River gains and losses and spring discharges. The steady state calibration was done using PEST parameter estimation tools. During the steady state calibration, model-predicted aquifer water levels, which are generated for the center of each model cell, were interpolated to the actual location of each observation well prior to comparison.

The same steady state calibration targets and calibration procedure were used during the initial steady state calibration and during the coupled steady state/transient calibration. The ending steady state heads and aquifer transmissivity and riverbed conductance became the starting values for the coupled steady state/transient calibration. The product of the initial steady state calibration is an intermediate product. The coupled steady state/transient calibration yielded both calibrated steady state and transient versions of the ESPAM model.

Coupled Steady State/Transient Calibration

Transient Calibration Data

The transient calibration data include aquifer water level observations, monthly Snake River gains and losses, and spring discharge observations. Transient calibrations are undertaken primarily to determine specific yield. Specific yield is a function of change in aquifer water level; hence transient model water level targets are changes in water levels, not the absolute measured water levels. Modeled aquifer water levels were also converted to changes in water levels for comparison with the targets. For the ESPAM calibration, three different types of transient aquifer water level data were used as calibration targets: 1) seasonal wells - wells with long time series consisting of frequent observations (9548 total observations in 39 wells over a maximum of 17 years), 2) mass measurement wells - water level observations collected between spring 2001 and spring 2002 as part of this project (1766 total observations in 601 wells), and 3) trend wells - wells with regular spring-time observations (1403 observations in 173 wells). Figure 55 shows the locations of the transient aquifer water level observation wells.

As during the steady state calibration, model-predicted aquifer water levels are interpolated from the center of the model cell to the actual location of the observation wells. For the transient part of the calibration, a similar interpolation was also done in time. The model-predicted water levels are generated at every model time step (in the case of the ESPAM calibration, every 18.2 or 18.3 days). During calibration, the PEST software interpolated model-predicted water levels to times which match the actual dates of aquifer water level observations.

The monthly gains and losses for the five river reaches above Milner Dam which were computed using the IDWR Reach Gain/Loss Program proved to contain significant measurement noise, so the data were filtered in a computer program called TSPROC and then used as calibration targets. TSPROC uses a Butterworth filter to remove excessive noise in time series data sets. Doherty and Johnston (2003) explain TSPROC in greater detail. Model-predicted river gains were filtered using TSPROC and matched with the filtered observations.

Measured spring data from Devils Washbowl, Devils Coral, Blue Lakes, Crystal Springs, Clear Lakes, Briggs Springs and Box Canyon Springs were used as calibration targets, as were the spring discharge estimates for Thousand Springs and Malad which were estimated from power records. Model-predicted spring discharge at the model cells noted in Table 23 were interpolated in time and then compared with the measured spring discharges. Despite the fact that these individual springs were explicitly modeled, the ESPAM model is a regional model and is not intended for predictions of impacts to individual springs. A regional model is limited to replicating broad-scale heterogeneity in the physical system and cannot replicate localized heterogeneities.

Coupled Steady State/Transient Calibration Procedure

The coupled steady state/transient calibration was done using PEST parameter estimation software. During the transient part of the calibration, aquifer specific yield was calibrated at 28 pilot points (see Figure 54), spring (drain) elevation was estimated at the model cells representing the springs used as calibration targets and spring (drain) conductance was estimated at the six spring reaches and the nine drains used as calibration targets. The steady state portion of the calibration was as described above. The ending heads from steady state were used as starting heads for the transient calibration. During the coupled steady state/transient component of each calibration model run, PEST was allowed to modify aquifer transmissivity and river and drain conductance as well as establish aquifer specific yield and spring elevations. After each pair of steady state and transient model runs, the model-predicted aquifer water levels and river and spring discharges were compared with the thousands of calibration target values. The coupling of the steady state and transient models during transient model calibration forced the calibrated transient model to match both the steady state and transient calibration targets, ensuring that there was minimal degradation in the match to the steady state data caused by the transient calibration.

The objective of the transient part of the model calibration was to minimize the difference between observed river gains and losses, spring discharges and water level changes between May 1, 1985 and April 30, 2002. The transient model required a warm-up period of about five years because observations during the initial 1980-1985 period are partly dependent on events that occurred years prior to 1980. By using the ending steady state heads as the transient starting heads, the impacts of recharge and discharge in the years prior to 1980 were approximated. When the model was allowed to run with estimated recharge and discharge data from 1980 to 1984, by 1985 the model was responding appropriately.

The coupled steady state/transient calibration utilizes about 16,600 observations and 225 adjustable parameters. The observations include 12,700 aquifer water level change observations, 1300 Snake River gain/loss observations, 1500 spring discharge observations and the previously mentioned steady state observations. The adjustable parameters include 169 pilot points to adjust the transmissivity distribution, 28 pilot points to adjust the specific yield distribution, 5 river parameters to adjust riverbed conductance for the five river reaches, and 9 drain conductance parameters and 9 drain elevation parameters at model cells with spring records.

When the data entry errors in the calibration targets were discovered in ESPAM Version 1.0, the coupled steady state/transient calibration was re-run using the corrected reach aggregations and upper Snake River calibration targets. Keeping all initial estimates of calibration parameters and the overall calibration methodology the same as were used for Version 1.0, making only the changes required for correcting the data entry errors in the previous calibration, the PEST calibration was re-run to generate ESPAM Version 1.1. The statistics and parameters discussed below are for ESPAM Version 1.1. These data entry errors, however, did not significantly affect results of the model simulation.

Steady State Calibration Model Fit

Model residuals (the difference between model-predicted and observed values) are generated by the PEST software, providing an indication of how well the model-predicted values match the observed values. Model statistics for the steady state calibration indicate an overall correlation coefficient between measured and modeled aquifer water level observations of 0.9942. The standard error for the aquifer water level estimates is 17.76 ft indicating that about 95 percent of the modeled aquifer water levels are within about 35.4 ft of observed values, which represents less than 2% of the average saturated thickness of the aquifer. Figure 56 shows a scatter plot of model-predicted versus observed aquifer water levels. Figure 56 shows an excellent match between the predicted and observed aquifer water levels. A regression line for the data indicates a slope of .9943 and an intercept of 24.906. With a perfect match, each point in Figure 56 would fall on a line with a slope of 1 and an intercept of 0. Relative to the range of values on either axis, 24.906 is very nearly zero. Figure 57 shows a map with water level contours for both the model-predicted and observed aquifer potentiometric surface. Figure 57 also shows an excellent fit between the model and the steady state observations.

Steady state model-predicted versus observed discharge to river and springs is shown in a scatter plot in Figure 58. Figure 58 shows an excellent fit between model-predicted and observed discharges to the river, with an R^2 value of .9963. The regression line which fits the data in Figure 58 has a slope of 1.006 and a y-intercept of 407,156. Table 25 lists the model-predicted and observed steady state river and spring discharges.

Transient Calibration Model Fit

Comparison of Simulated and Observed Transient Heads

One of the measures of a transient calibration is how well the model simulates measured aquifer water levels over time. Figures 59 through 63 show transient model-predicted versus observed water levels. On Figures 59 through 63, the transient comparisons are sited on maps of the study area with pointers to the location of each hydrograph. In each of these figures, the pink line represents the model-predicted values.

Wells with multiple measurements each year for a long period were selected to calibrate the ESPAM's model ability to replicate the seasonal changes in aquifer water level. Figures 59 and 60 show eight selected wells with seasonal fits. The ability of the model to replicate seasonal aquifer water level changes is a function of aquifer storativity and transmissivity as well as the model recharge and discharge. Figures 59 and 60 show that the ESPAM model does a very good job of matching seasonal aquifer water level data.

Wells with a spring observation for each of many years were selected to test the ESPAM model's ability to replicate the long-term trend of aquifer water levels for the calibration period. Figures 61 and 62 show model-predicted versus observed aquifer water level trend data. Similar to the seasonal data, a model's ability to match trend data is a function of aquifer storativity, transmissivity and model recharge and discharge. Figures 61 and 62 show that the fit to trend data was very good.

Figure 63 shows the model's fit to the mass measurement data which was collected for three periods at the end of the calibration period. Figure 63 also shows a reasonable fit to the mass measurement data.

Comparison of Simulated and Observed River Reach Gains

Figures 64 through 68 show the filtered modeled gains in the upper Snake River versus the filtered observed gains. Figures 69 through 73 show the same data, without the filtering. Figures 64 through 68 and 69 through 73 represent reach gains in the Ashton to Rexburg, Heise to Shelley, Shelley to Near Blackfoot, Near Blackfoot to Neeley and Neeley to Minidoka reaches, respectively. The pink line in Figures 64 through 68 represents the model-predicted values. The observation data shown in Figures 64 through 68 is the filtered data shown in Figures 47 through 51, as previously discussed. In each river reach, no attempt was made to match the first five years of data due to the transient model warm-up period. As can be seen in Figures 64 through 68, the model does a reasonable job of predicting reach gains in each reach of the upper Snake River. For the Neeley to Minidoka reach, the measured data shows that the reach gain is somewhat erratic, year to year, but is a slight gain on the average. The model predicts an effective constant modest gain for Neeley to Minidoka. Inspection of Figure 51, the raw monthly reach gain observation data versus gage uncertainty for the Neeley to Minidoka reach, shows that this reach effectively, on the average, has a slight gain. Hence, the model-predicted value was considered reasonable.

Figures 69 through 73, the comparison of unfiltered model-predicted versus measured river gains, show the seasonal variation of both the measured and predicted river gains. The model generally under-predicts the month to month variation of the measured data; however, inspection of the unfiltered measured reach gains shows a significant amount of noise in the data, reflecting uncertainty in instantaneous river gage measurements.

Comparison of Simulated and Observed Spring Discharges

Figures 74 through 82 show the model-predicted versus observed spring discharges for the following springs: Devils Washbowl, Devils Corral, Blue Lakes, Crystal, Clear Lakes, Briggs, Box Canyon, Thousand Springs and Malad. As with previous transient hydrographs, the pink line represents the model-predicted values in Figures 74 through 82. As can be seen in Figures 74 through 82, the model does an excellent job of predicting the magnitude of the spring discharge for each spring. The model underestimates the seasonal amplitude of spring discharge for Crystal, Briggs, Box Canyon, Thousand Springs and Malad. The measured seasonal amplitude for these springs is approximately 20% and the model-predicted seasonal amplitude is approximately 9%.

Calibrated Model Parameters

Aquifer Transmissivity

Simulation results indicate a wide range in transmissivity from about 125 to 4.74 x 10^7 ft^2/day (Figure 83). Riverbed and drain conductance ranges from 10.3 to 1.57x 10^7 ft/day/ft. Final values for riverbed and drain conductance can be found in Tables 3 and 4, respectively. Figure 84 shows the ratio of the final ESPAM model transmissivity to the preliminary steady state transmissivity. As can be seen in Figure 84, the preliminary steady state transmissivities were scaled by as much as an order of magnitude during the coupled steady state/transient calibration. This represents the amount of change required in the initial steady state transmissivity field in order to accommodate the transient data.

The map of the calibrated model transmissivity (Figure 83) shows that estimated transmissivity values tend to be lower along the margins of the plain and higher towards the center. Two major exceptions to this generalization include the Mud Lake barrier and the Great Rift. The Mud Lake barrier extends east to west across the aquifer from the Bitterroot Mountains to just south of the confluence of the Henrys Fork and the South Fork of the Snake River. The Great Rift extends north to south across the plain from the Big Lost River Valley to just west of American Falls Reservoir. The transmissivity of both of these features is lower and impedes ground water flow as evidenced by the more tightly spaced equipotential lines in these areas. These features in the calibrated transmissivity distribution match our current understanding of the aquifer.

Aquifer Storage

The specific yield distribution ranges from 5.2×10^{-3} to 0.280 (Figure 85). Model statistics indicate an overall correlation coefficient between measured and modeled transient observations of 1.000. The standard error for the seasonal aquifer water level observations is 1.840, for the mass measurement observations the standard error is 5.174, for the trend observation it is 5.834.

The transient component of a model calibration is primarily used to calibrate aquifer storage (storativity or specific yield). In the case of the ESPAM model, the confined representation of the physically unconfined system uses aquifer storativity (rather than the unconfined parameter of specific yield). However, unlike a truly confined system, the storativity values expected for the ESPAM model would be in the range of .001 to .3, a range much more typical of specific yield.

During the coupled steady state/transient calibration, specific yield was calibrated at 28 pilot points (Figure 54) and interpolated to every model cell. Aquifer storage has a much lower degree of spatial variation, so fewer pilot points are required for calibration. Figure 85 shows the distribution of specific yield for the ESPAM model.

Drain Elevation

After the coupled steady state/transient calibration, drain elevations, which were modified as part of the calibration, were assessed relative to the ending steady state heads. It was noted that some of the ending drain elevations were within a few feet of the ending steady state heads. The ESHMC discussed the fact that the ending drain elevations were high relative to the ending steady state aquifer levels, with the potential result that drains would shut off with minor declines in aquifer water level. It was agreed that the true elevations of the drains are unknown but that an absolute discontinuation of major portions of spring discharge due to a minor change in aquifer water level would be unreasonable.

As previously noted, Equation 7 is the governing equation for aquifer discharge through a drain. Inspection of Equation 7 shows that discharge is directly proportional to the conductance of the drain as well as to the elevation differential between the aquifer level and the drain elevation. The ESHMC discussed the fact that drain elevations could be changed with a corresponding change in drain conductance to alleviate this concern without changing the calibration or any major functionality of the model. To achieve this modification, all drain elevations were checked against the ending aquifer water levels in the same model cell. Any drain elevation which was within 30 feet of the ending steady state aquifer water levels was adjusted to be 30 feet below. A corresponding adjustment was made to the drain conductance in that model cell to keep the drain discharge the same. Table 4 lists the final values for drain conductance and drain elevation for each model cell representing a drain.

This modification was deemed a reasonable representation of the physical system of springs. In the ESPAM model, all model cells, including drain cells, are 1-mile square. A model cell representing a drain should not be considered to represent an individual spring but rather the collective spring discharge along a 1-mile segment of the canyon wall. In the physical system, springs at high elevations will shut off with significant water level declines. This will still be represented in the model as a decline in the spring discharge represented in a model cell. However, it was deemed that the total discharge of a 1-mile segment was more likely to be reduced than to be eliminated by a realistic change in aquifer water level. Clearly, really significant changes (30 ft or more) in aquifer water levels from the steady state ending heads would result in the wholesale discontinuation of spring discharge in a model cell.

Model Limitations

As with any model of a natural system, the ESPAM model has a degree of limitation and uncertainty. Simplifying assumptions must be made to model complex, natural systems. Components of the aquifer water budget which have the least certainty are irrigation return flows, recharge on non-irrigated lands and tributary underflow. As discussed in the Water Budget section, these elements were estimated based on the collective professional judgement of the modeling team and the ESHMC using existing published material. As previously discussed, there is a shortage of data on spring discharges. The ESPAM model calibration would have been enhanced by the existence of additional measured or estimated spring discharge data.

The ESPAM model is a regional ground-water model. For this reason, the model is best used for broad-scale predictions. As previously noted, the user should avoid the temptation to model localized impacts, such as impacts to a specific spring.

A primary objective of the model development and calibration was the characterization of the interaction between the aquifer and the river. Although thousands of aquifer water level observations were used during the model calibration the model was optimized for prediction of impacts to the river due to water use on the plain. The model can be used to provide a general sense of ground-water to ground-water impacts, however, the model is best used for prediction of impacts to surface water resources due to ground-water use.

Despite these noted limitations, the ESPAM model is the most thoroughly calibrated model in existence on the eastern Snake River Plain Aquifer. The extensive use of model calibration tools and the prevalence of available data yielded an excellent model calibration.

Related Reports

To be supplied.
A brief summary of the design documents and a table of which documents were created.

Summary and Conclusions

To be supplied.
Including recommendations for future work.

References

Allen, R.A. and C.E. Brockway. 1983. Estimating Consumptive Irrigation Requirements for Crops In Idaho. Idaho Water and Energy Resources Research Institute.

Allen, R.A. 2002. Draft revision of Estimating Consumptive Irrigation Requirements for Crops In Idaho, preliminary electronic data. University of Idaho.

Allen, R.A., M. Tasumi and R. Trezza. 2002. Crop-year 2000 SEBAL (METRIC) Estimates of Evapotranspriation, Snake River Plain, Idaho. Electronic data. University of Idaho.

Allen, R.A. 2003. Personal communication.

Allen, R.G., M. Tasumi and A. Morse. 2005. Satellite-based Evapotranspiration by METRIC and LANDSAT for Western States Water Management. U.S. Bureau of Reclamation Evapotranspiration Workshop, February 8-10, Ft. Collins, Colorado.

Anderson, M.P. and W. W. Woessner. 1992. "Applied groundwater modeling." Academic Press, San Diego, CA., 381p.

Anderson, S. R., 1991, Stratigraphy of the unsaturated zone and uppermost part of the Snake River Plain aquifer at the Idaho Chemical Processing Plant and Test Reactors Area, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4010, 71 p.

Booker, J., R.A. Young, C. M. Zhang, and H.J. Morel-Seytoux. 1990. HELM: An Integrated Model Applied to the South Platte Stream-Aquifer System, in Conference Proceedings: Groundwater Engineering and Management Conference. Colorado Water Resources Research Institute and The Office of the State Engineer.

Chavez-Morales, J. 1985. An Optimization and Simulation Methodology for Irrigation Planning. University of California, Davis.

Contor, B.A. 2002. Non-irrigated recharge for minor land use types, memorandum to Eastern Snake Plain Aquifer Model Enhancement Project Technical Committee.

Cosgrove, D.M., G.S. Johnson, S. Laney, and J. Lindgren, 1999, Description of the IDWR/UI Snake River Plain Aquifer Model: Idaho Water Resources Research Institute, University of Idaho, Moscow, ID, 120 p.

Covington, H.R. and J.N. Weaver, 1990, Geologic map and profile of the north wall of the Snake River Canyon. U.S. Geological Survey Miscellaneous Investigation Series, Maps I-1947A through I-1947E.

Daly, C. and G. Taylor, 1998. PRISM Briefing Book and Questionnaire, A Description of the PRISM Model for Spatially Distributing Observed Precipitation. Natural Resources Conservation Service Water and Climate Center and Oregon Climate Service, Oregon State University. (http://www.ocs.orst.edu/prism/nrcs_brief.html)

Daly, C., G.H. Taylor, W.P. Gibson, T. Parzybok, G.L. Johnson, and P.A. Pasteris, 1998. Development of High-Quality Spatial Climate Datasets for the United States. Presented at First International Conference on Geospatial Information in Agriculture and Forestry, Lake Buena Vista, FL, June 1-3, 1998b.

de Sonneville, J.L.J., 1974, Development of a digital ground-water model with application to aquifers in Idaho: University of Idaho unpublished thesis, Moscow, ID, 227 p.

Doherty, J. 2004. PEST Model-Independent Parameter Estimation Users Manual, Watermark Numerical Computing, 336 Cliveden Avenue, Corinda 4075, Brisbane, Australia

Doherty, J. 2003. Ground water model calibration using pilot points and regularization, Ground Water, vol. 41, no. 2, 170-177.

Doherty, J., and J.M. Johnston, 2003. Methodologies For Calibration And Predictive Analysis Of A Watershed Model. J. American Water Resources Association, vol 39, no 2, p 251-265.

Dreher, K. J., and D.R. Tuthill. 1999. Report regarding evaluation of irrigation diversion rates. Idaho Department of Water Resources Adjudication Bureau, report to the Snake River Basin Adjudication District Court.

Frederick, D. B. and G. S. Johnson. 1996. Estimation of hydraulic properties and development of a layered conceptual model for the Snake River Plain aquifer at the Idaho National Engineering Laboratory, Idaho: Idaho Water Resources Research Institute, University of Idaho, Moscow, ID, 80 p.

Garabedian, S.P. 1992. Hydrology and digital simulation of the regional aquifer system, eastern Snake River Plain, Idaho. USGS Professional Paper 1408. F.

Gee, G.W. 1988. Groundwater recharge in arid regions: review and critique of estimation methods, Hydrological Processes vol. 2, 255-266.

Goodell, S.A. 1988. Water use on the Snake River Plain, Idaho and Eastern Oregon. USGS.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model-user guide to modularization concepts and the ground-water flow process. USGS Open-File Report 00-92.

Hill, M.C. 1990. Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.

Howser, S. 2002. General Manager, Aberdeen-Springfield Canal Company. Personal communication.

Hubble Engineering, Inc. and Associated Earth Sciences. 1991. Guidelines for the Evaluation of Irrigation Diversion Rates. Prepared for the State of Idaho Department of Water Resources.

Idaho Department of Agriculture. 1981 - 2002. Idaho Agricultural Statistics.

Idaho Department of Water Resources. 1980. RASA80LC. GIS shapefile and attribute tables of LANDSAT land cover classification.

Idaho Department of Water Resources. 1982. 1980 Inventory of Irrigated Cropland on the Snake River Plain. Idaho Image Analysis Facility.

Idaho Department of Water Resources. 1994. SRBAS91LU. GIS shapefile of land cover.

Idaho Department of Water Resources. 1997a. Upper Snake Basin Study.

Idaho Department of Water Resources. 1997b. SNAKLC92. GIS shapefile of land cover.

Idaho Department of Water Resources. 1997c. WellLog users manual.

Idaho Department of Water Resources. 1999. GIS point file, GPS locations of Mud Lake-area wells.

Idaho Department of Water Resources. 2002a. ESPAC2000. GIS shapefile of land cover.

Idaho Department of Water Resources. 2002b. Watermaster records available on microfiche and in paper files.

****Idaho Water Resources Board. 1996. *****

Johnson, G.S., D.M. Cosgrove, S. Laney, and J. Lindgren, 1999, Conversion of the IDWR/UI ground water flow model to MODFLOW: the Snake River Plain aquifer model. Idaho Water Resources Research Institute, University of Idaho, Moscow, ID, 42 p.

Kjelstrom, L.C.. 1995a. Streamflow gains and losses in the Snake River and ground-water budgets for the Snake River Plain, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-C, 47p.

Kjelstrom, L.C.. 1995b. Methods to estimate annual mean spring discharge to the Snake River between Milner Dam and King Hill, Idaho. U.S. Geological Survey Water Resources Investigations Report 95-4055.

Kuntz, M.A., H.R. Covington, and L.J. Schorr. 1992. An overview of basaltic volcanism of the eastern Snake River Plain, Idaho: in Regional Geology of eastern Idaho and Western Montana, eds. P.K. Link, M.A. Kuntz, and L.B. Platt, Geological Society America Memoir 179, pp. 227-267.

Lindholm, G.F., S.P. Garabedian, G.D. Newton, and R.L. Whitehead. 1988. Configuration of the Water Table and Depth to Water, Spring 1980, Water Level Fluctuations, and Water Movement in the Snake River Plain Regional Aquifer System, Idaho and Eastern Oregon. Map. USGS. Hydrologic Investigations Atlas HA-703.

Madsen, R. 2000. GIS point file, GPS location of Water District 01 measurement and diversion locations.

Mann, L., 1986. Hydraulic Properties Of Rock Units And Chemical Quality Of Water For INEL-1: A 10,365-Foot Deep Test Hole Drilled At The Idaho National Engineering Laboratory, Idaho. Idaho Falls, Idaho: U.S. Geological Survey

McDonald, M. G. and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A1.

Mehl, S.W. and M.C. Hill, MODFLOW-2000. 2001. the U.S. Geological Survey Modular Ground-water model—user guide to the Link-AMG (LMG) package for solving matrix equations using an algebraic multigrid solver. U.S. Geological Survey Open-File Report 01-177.

Morse, A., M. Tasumi, R.G. Allen., W.J. Kramber. 2000. Final Report. Application of the SEBAL (METRIC) Methodology for Estimating Consumptive Use of Water and Streamflow Depletion in the Bear River Basin of Idaho Through Remote Sensing. Idaho Department of Water Resources and University of Idaho.

Morse, A. 2001. IDWR GIS Supervisor. Personal communication.

Newton, G.D., 1978, Application of a simulation model to the Snake Plain aquifer: University of Idaho unpublished thesis, Moscow, Idaho.

Norquest, E. 2002. Unpublished GIS shapefiles of irrigated lands within service areas. IDWR Adjudication Bureau.

Olenichak, T. 2003. Water District 01. Personal communication.

Rich, L.R. 1951. Forest and Range Vegetation. Transactions - American Society of Civil Engineers. Proceedings - Separate, No. 90.

Robertson, J. B., 1974, Digital modeling of radioactive and chemical waste transport in the Snake River Plain aquifer at the National Reactor Testing Station, Idaho: U.S. Geological Survey Open-File Report 74-1089, 41 p.

Shenton, G. 2002. Watermaster, Water District 31. Personal communication and unpublished paper water district records.

Sorenson Engineering. 2002. Unpublished electronic spreadsheet of power-plant discharge volumes.

Spinazola, J.M., 1994, Geohydrology and simulation of flow and water levels in the Mud Lake area of the eastern Snake River Plain, eastern Idaho: U.S. Geological Survey Water-Resources Investigations Report 93-4227, Boise, ID, 78 p.

Temple, D. 2002. A & B Irrigation District. Personal communication.

Twin Falls Canal Company. Circa 1955. Unpublished seepage study.

United States Bureau of Reclamation. 2003. Agrimet: The Pacific Northwest Cooperative Agricultural Weather Network. Internet website http://mac1.pn.usbr.gov/agrimet/h2ouse.html

US Department of Agriculture, National Agricultural Statistics Service (NASS), 1992 and 1997. US Census of Agriculture. Electronic data on compact disk.

US Department of Agriculture, National Agricultural Statistics Service (NASS), 2000. Published Estimates Data Base On Line. (http://www.nass.usda.gov:81/ipedb/front/html)

US Geological Survey. 2002. Gauge station data. http://nwis.waterdata.usgs.gov/usa/nwis/discharge

Water District 01. 2003. Annual Reports 1980 - 2001.

Welhan, J. and T. Funderberg, 1997, Stochastic modeling of hydraulic conductivity in the Snake River Plain aquifer: 1. Hydrogeologic constraints and conceptual approach: Proceedings of the 32nd Symposium on Engineering Geology and Geotechnical Engineering, Boise, ID, March 26-28, 1997, pp. 75-91.

Whitehead, R.L., 1986. Geohydrologic Framework of the Snake River Plain, Idaho and Eastern Oregon. Atlas HA-681.

Wright, J.L. 1993. Nongrowing Season ET from Irrigated Fields, in Management of Irrigation and Drainage Systems. Conference proceedings, Irrigation and Drainage Division, American Society of Civil Engineers.

Appendix 1—Eastern Snake Hydrologic Modeling Committee Process

Appendix 2—Specified Flux Bounary Model Cell Associations

Appendix 3—Description of the GIS/Fortran Recharge Tool