ENHANCED SNAKE PLAIN
AQUIFER MODEL
VERSION 2.1

Final Report

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Idaho Department of Water Resources

with guidance from the

Eastern Snake Hydrologic Modeling Committee

Abstract

The development of groundwater and surface-water irrigation on the eastern Snake Plain has necessitated conjunctive management of the groundwater and surface-water resources. To facilitate this management approach, the Idaho Department of Water Resources (IDWR) has placed a strong emphasis on the development, use and refinement of scientific tools which help quantify the impacts of changing water use practices on groundwater and surface-water supplies on the eastern Snake Plain. Recognizing the importance of the groundwater model as a water management tool, the IDWR, the State Legislature and the water user community embarked on a model reformulation/development process that produced the Enhanced Snake Plain Aquifer Model Version 1.1 (ESPAM1.1). Subsequently, IDWR, other government agencies and the water user community continued with data gathering and model improvement, resulting in development of the Enhanced Snake Plain Aquifer Model Version 2.1, or ESPAM2.1.

Development of ESPAM 1.1 was funded as a joint effort between the State of Idaho, Idaho Power, the U.S. Bureau of Reclamation, and the U.S. Geological Survey. Model development was overseen by the Eastern Snake Hydrologic Modeling Committee (ESHMC), a collection of scientists and engineers representing the above-identified agencies, other government agencies, and private water-user groups. The actual modeling was accomplished by the Idaho Water Resources Research Institute (IWRRI) at the University of Idaho. Major design alternatives were presented to ESHMC members for discussion and guidance. To provide transparency, the model development was accomplished in an open environment, with acceptance of design input from all committee members.

The development of ESPAM2.1 was funded by the Idaho State Legislature with in-kind contributions from the water-user community and other government agencies. IDWR managed the project and calibrated the model, with data and technical work provided by IWRRI and members of the ESHMC.

The ESPAM2.1 technical effort was initiated in 2005 and included data collection for a 6.5-year period (Spring 2002 through Fall 2008). In combination with the ESPAM1.1 data (Spring 1980 through Spring 2002), these data support a 28.5-year simulation period (Spring 1980 through Fall 2008). The ESPAM2.1 technical effort involved incorporating the ESPAM1.1 model grid, revising some boundary conditions, and performing an exhaustive calibration of the new model. The 28.5-year simulation period is broken into 342 one-month stress periods. The calibration was accomplished using version 12.0 of PEST (Doherty, 2004), a non-linear parameter estimation program for data interpretation, model calibration and predictive analysis. ESPAM2.1 was calibrated to over 43,000 observed aquifer water levels, over 2,000 river gain and loss estimates, and over 2,000 transient spring discharge measurements collected from 14 different spring complexes. The resulting model, ESPAM2.1, is a single layer, time-constant transmissivity[1] model with 104 rows and 209 columns. Each model grid cell is 1 mile x 1 mile. The model contains 11,236 active cells.

This report documents the design and calibration of the ESPAM2.1. As design decisions were made during the life of the project, slide presentations, e-mails, web site postings, and memoranda were used to apprise the ESHMC of decisions and progress. Many of these were formalized into Design Documents, containing greater detail than this report. This report summarizes the accounting of recharge and discharge for the 28.5-year simulation period, the technical tools used to develop the model, the observations used for model calibration, and comparison of the model-predicted aquifer water levels, spring discharges and river gains with observed data. The report cites the various Design Documents for the reader who is interested in more detail. This report also discusses model limitations and recommendations for future work.

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[1] The storage coefficients are typical of unconfined conditions, but the mathematical representation is identical to a confined representation.

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IDWR would like to express appreciation to the members of the Eastern Snake Hydrologic Modeling Committee (ESHMC) for their participation and input throughout the model development process, and to members of the water user community who funded the participation of technical experts on the ESHMC. Members who frequently attended committee meetings during the development of ESPAM2.1 include:

ESHMC Member	**Current Affiliation**
Rick Allen	University of Idaho
Hal Anderson	Idaho Water Engineering, LLC
Dave Blew	Idaho Power Company
Jon Bowling	Idaho Power Company
Jim Brannon	Brannon Developments
Chuck Brendecke	AMEC
Chuck Brockway	Brockway Engineering, PLLC
Dave Colvin	Leonard Rice Engineers, Inc.
Bryce Contor	Rocky Mountain Environmental Associates, Inc.
David Hoekema	University of Idaho
Gary Johnson	Idaho Water Resources Research Institute
Jennifer Johnson	U.S. Bureau of Reclamation
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I. INTRODUCTION

I. A. BACKGROUND AND OBJECTIVES

This report documents the design, development, and calibration of the Enhanced Snake Plain Aquifer Model Version 2.1 (ESPAM2.1). ESPAM2.1 was designed to be used by the Idaho Department of Water Resources as an administrative and planning tool to evaluate the interaction between groundwater and surface-water resources and to support water management decisions. It is also intended for use by other agencies and stakeholders for the analysis of aquifer conditions and the interaction between surface-water and groundwater resources.

The ESPAM2.1 development project was initiated and funded by the State of Idaho, with in-kind contributions from the water-user community and other government agencies. Technical oversight and input from representatives of water user groups and government agencies were incorporated into model development to create an unbiased representation of the complex aquifer system and the best possible technical tool for management of groundwater resources on the eastern Snake Plain. The process established for allowing oversight and technical input from interested parties is described in section I. C.

The objective of the ESPAM2.1 project was to improve upon and update EPSAM1.1 by incorporating the following design features: a) lengthen simulation period to incorporate an additional 6.5 years of aquifer stresses and observed responses, b) refine time discretization to monthly stress periods, c) refine representation of interactions between the aquifer, springs, and Snake River downstream of Kimberly, d) incorporate time-variable representation of irrigated land area, and e) incorporate available METRIC ET data.

I. B. PROJECT SCOPE

The scope of this project was limited to the refinement and re-calibration of the ESPAM1.1 groundwater model used for water management on the eastern Snake 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 Plain, and refinement and calibration of a numerical model to represent the ESPA. The scope of the project was limited to model refinement and calibration and did not entail generation of new water management scenarios.

I. C. THE ROLE OF THE EASTERN SNAKE HYDROLOGIC MODELING COMMITTEE

ESPAM2.1 was created with extensive review and input from the Eastern Snake Hydrologic Modeling Committee (ESHMC). The ESHMC is comprised of professionals working on eastern Snake Plain water issues. Regular members include agency representatives (Idaho Department of Water Resources, U.S. Bureau of Reclamation (USBR), U.S. Fish and Wildlife Service, U.S. Geological Survey (USGS)), industry representatives (Idaho Power), researchers (University of Idaho, Idaho Water Resources Research Institute), and private consultants (AMEC; Brockway Engineering, PLLC; HDR, Inc.; Leonard Rice Engineers, Inc.; Principia Mathematica, Inc.; Rocky Mountain Environmental Associates, Inc.; Spronk Water Engineers, Inc.; and others) representing water users on the eastern Snake Plain. The ESHMC was formed in 1998 and followed the previous Idaho Technical Committee on Hydrology (ITCH), which had a similar function. The ESHMC was originally formed to allow researchers and water users a forum for discussing water issues and research on the eastern Snake Plain, and is chaired by the Idaho Department of Water Resources (IDWR). For both ESPAM1.1 and ESPAM2.1, model design, construction, and calibration were overseen by the ESHMC in a collaborative process. IDWR's goal was to provide insight and input into the model design so that all parties could attest to the facts that a) the model was created with as little bias as possible and b) the model was as accurate a representation of the physical system as possible, given the available data. It was understood that not every decision would attain complete agreement from all members of the ESHMC.

The process of regular meetings and input from the ESHMC was expanded in the ESPAM2.1 effort to include provision of data, methodology, technical work, and software tools by ESHMC members. IDWR managed the project and performed the model calibration, with continued provision of data and technical work by IWRRI. IDWR held meetings about every other month (or more when necessary) to present project status and proposed design choices to the ESHMC. The design choices were documented in memoranda, e-mails, and slide presentations at ESHMC meetings. During the design reviews, ESHMC members received presentations of various design options. These options would often be discussed at length. Once either consensus (but not necessarily unanimous agreement) was reached or there was no further discussion, the design decision was documented in a final Design Document. Many fundamental design decisions were modified specifically in response to ESHMC guidance. Realizing that the group was being presented with an extraordinary volume of information and detail during the design reviews, the ESHMC members were encouraged to provide written comments on specific design issues as well as oral comments during meetings.

If, in the course of model development or calibration, the technical team determined that a design decision needed to be changed or required more extensive committee review, changes and rationale were communicated to the ESHMC. At every juncture, the ESHMC committee members were kept apprised of model design options and decisions. Recognizing that multiple (often disparate) viewpoints were represented at ESHMC meetings, it was understood that not all design decisions could be made with unanimous agreement. All major design decisions, however, were discussed at length, and consensus on the design approach was reached among the majority of the present parties. Throughout this report, major design decisions made by the ESHMC members are noted. The authors recognize that this is an extraordinary approach for groundwater model documentation; however, the authors feel that the method of model development, including and soliciting input from interested parties from the very beginning of model design, was a unique approach aimed at gaining consensus on a potentially contentious model.

I. D. ESPAM VERSIONS

The first modeling effort overseen by the ESHMC commenced in the year 2000, and this effort originally resulted in the Enhanced Snake Plain Aquifer Model Version 1.0 (ESPAM1.0) This was almost immediately updated to Version 1.1 (ESPAM1.1), which was used by the IDWR between 2005 and early 2012. In July 2012, the ESHMC determined that the calibration of Version 2.0 (ESPAM2.0) was complete.

During the preparation of this final project report, data calculation mistakes were discovered in the original model calibration (ESPAM2.0), requiring re-calibration. The mistakes involved the calculation of water-budget parameters in the Mud Lake area. These mistakes were corrected and some less significant revisions to water-budget input data were made to incorporate newly available data. Sukow (2012) documents the changes to the water budget. The model was re-calibrated in November 2012, resulting in the release of ESPAM2.1. This report describes the development and calibration of Version 2.1 (ESPAM2.1).

It is anticipated that the next five to ten years will see an evolutionary progression through Version 2.2, 2.3, etc. as moderate revisions are made to the ESPAM. When a significant change to the model conceptual design is implemented, it will be released as ESPAM3.0. This will likely include significant conceptual model changes or broadening of scope and purpose (e.g., multiple aquifer layers, changes in modeling software or algorithms, internal incorporation of surface-water processes in the modeling, linkage to surface-water models).

I. E. STUDY AREA DESCRIPTION

The Snake 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 groundwater hydrology. The eastern Snake Plain is the focus of this report and encompasses an area of about 11,000 square miles extending from Ashton, Idaho, in the northeast to King Hill, Idaho, in the southwest (Figure 1). Elevation of the eastern plain varies from about 2,600 feet above sea level in the southwest to over 6,000 feet in the northeast. The model boundary was originally defined by the U.S. Geological Survey (USGS) Regional Aquifer System Analysis (RASA) program (Lindholm, 1993) and was later modified for ESPAM1.1. Further minor modifications to the model boundary were made for ESPAM2.1. The model boundary shown in Figure 1 is the modified boundary used for ESPAM2.1.

Population within the plain is generally sparse; most inhabitants reside along the eastern and southern margins 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 outcrops that include the Craters of the Moon National Monument.

The Snake Plain has an arid to semi-arid temperate climate. Precipitation ranges from about 8 to 14 inches per year and irrigation is required for agricultural production. Snowfall in the surrounding mountains is a significant source of water supply for agricultural production on the plain. 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 portion of the plain.

Irrigation on the eastern Snake Plain began in the late 1800s using water from the Snake River and its tributaries. Garabedian (1992) describes changes in surface-water and groundwater irrigated areas on the eastern Snake Plain that are shown graphically in Figure 2. Acreage irrigated by surface water has been declining since the mid-1940s. Since the onset of groundwater irrigation in the 1950s, the number of acres irrigated by groundwater increased steadily until the early 1980s.

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 latter part of the 20th century have dramatically affected water administration and management on the Snake Plain. Idaho initiated a basin-wide adjudication of water rights 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 issuance of permits to divert water for new consumptive uses has been in effect for the Snake River Basin since 1992. The moratorium includes both surface-water and groundwater sources within the basin (Idaho Water Resource Board, 1996). Idaho Department of Water Resources (IDWR) adopted conjunctive management rules in 1994, essentially linking administration of groundwater and surface-water rights.

Three Water Measurement Districts were established within the ESPA in 1996 to measure and report groundwater diversions outside of organized Water Districts. Those Water Measurement District have since been replaced by five Water Districts created and/or expanded between 2002 and 2007, following the issuance of Partial Decrees in the Snake River Basin Adjudication. Water Districts oversee distribution of water, in addition to measuring and recording diversions.

Managed recharge of the Snake Plain aquifer has also been supported by the Idaho legislature. Estimates of managed recharge, which has occurred at various locations through existing irrigation facilities, are listed in Table 1.

II. MODEL HISTORY

Numerical groundwater flow models of the ESPA 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 used administratively was developed by the University of Idaho for IDWR and the U.S. Bureau of Reclamation (deSonneville, 1974). The original IDWR/UI 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 Groundwater Flow Model Code. The application of this code to the ESPA will be referred to as the IDWR/UI Groundwater 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 Groundwater Flow Model was re-calibrated to 1980-1981 conditions. This re-calibration was able to capitalize on the extensive data collection effort by the USGS in support of the RASA study of the Snake Plain during that period. In the early 1980s, the USGS also created a model of the ESPA for scientific investigations (Garabedian, 1992).

In 1999, the IDWR/UI Groundwater Flow Model was converted to one of the most widely used and accepted groundwater modeling codes, MODFLOW (McDonald and Harbaugh, 1988). Model representation of physical properties such as aquifer transmissivity, storage, and streambed conductance were preserved in this conversion. The 1999 MODFLOW application to the ESPA was 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) MODFLOW capabilities are continuously increasing, e) MODFLOW has a significant capability for treating more advanced features such as three-dimensional flow and variable grid spacing, f) the MODFLOW code is well documented, and g) the MODFLOW software is public domain.

In addition to conversion of the IDWR/UI Groundwater Flow Model to the MODFLOW code, the model was modified to improve the 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).

The onset of drought conditions in 2000 and potential for rising conflict between surface-water and groundwater users on the eastern Snake Plain caused multiple legal actions to be initiated accelerating the conjunctive administration of surface-water and groundwater resources. It was widely agreed that the Snake River Plain Aquifer Model (SRPAM1.1), the predecessor to ESPAM1.1, was not sufficiently documented to support conjunctive management decisions. As a result, IDWR embarked upon a full reformulation and re-calibration of the groundwater model in 2000. This effort resulted in the development of ESPAM1.1. ESPAM2.1, which is documented in this report, is a refinement and upgrade of ESPAM1.1.

III. HYDROGEOLOGY

III. A. GEOLOGIC FRAMEWORK

The surface of the Snake 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 subsurface geology is composed of a series of relatively thin basalt flows and interbedded sediments. Individual flow units 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 flow units 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 Plain is estimated to exceed several thousand feet in places (Whitehead, 1986). More detailed descriptions of the geology of the eastern Snake Plain are provided by Anderson (1991), Whitehead (1986), and Kuntz and others (1992).

The eastern Snake 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).

III. B. SURFACE-WATER HYDROLOGY

The headwaters of the Snake River (locally referred to as the South Fork) are in Yellowstone Park in Wyoming. The Henrys Fork, which originates in the Island Park area near the Idaho-Montana border, joins the Snake River north of Idaho Falls (Figure 3). On average, the Henrys Fork contributes approximately a third of the flow at the confluence.

From the confluence of the South Fork of the Snake River and the Henrys Fork, the Snake River flows along the southern margin of the eastern Snake Plain. Tributaries to the Snake River are located on the north, east, and south sides of the basin (Figure 3). Some northern tributaries such as the Big and Little Lost Rivers flow onto the Snake Plain and seep into and recharge the ESPA, but their surface channels do not reach the Snake River. The Big and Little Wood Rivers also drain the northern margin of the basin and join to form the Malad River, which flows into the Snake River north of Hagerman. Other major tributaries include the Blackfoot River, the Portneuf River, and the Raft River, all entering from the south side of the basin.

The Snake River is intensively managed for irrigation and hydropower generation. Reservoirs have been constructed on the Snake River and its tributaries for the purposes of irrigation, flood control, hydropower generation, and recreation. An extensive network of irrigation canals and laterals deliver surface water for irrigation. In 1980, the USGS reported 2.1 million acres of surface and groundwater irrigated land (Garabedian, 1992) within the RASA aquifer boundary. Data compiled for the 2006 irrigation season indicate that there were approximately 0.9 million acres irrigated by surface water and approximately 1.1 million acres irrigated by groundwater[2], for a total of approximately 2.0 million irrigated acres within the ESPAM2.1 boundary[3].

Irrigation diversions consume a large proportion of the flow of the Snake River and its tributaries during irrigation season. Surface water diversions peaked in the early 1970s and dropped dramatically in the drought year of 1977. Even though subsequent water years included years with above average runoff, surface water diversions did not return to pre-1977 volumes (IDWR, 1997a). ESPAM2.1 data indicate that surface water diversions from the Snake River and tributaries within the model boundary ranged from approximately 6.3 to 8.5 million acre-feet per year between water years 1981 and 2008. Annual surface water diversion volumes generally exhibited a declining trend over the model simulation period.

Surface water diversions both deplete and affect the timing of flows in the river, with some of the water returning to the river as either surface or groundwater return flows. Due to the hydraulic connection between groundwater and surface water, ground water pumping reduces

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[2] Precise determination of the number of acres irrigated by groundwater and surface water is complicated by the delineation of irrigation district and canal company service areas, and the existence of supplemental irrigation wells. Approximately 0.3 million irrigated acres are designated as mixed source lands in ESPAM2.1.

[3] The RASA boundary included irrigated areas in the vicinity of Twin Falls that are outside the ESPAM2.1 boundary, while the ESPAM2.1 boundary includes irrigated areas in the Big Lost River Valley and Rexburg Bench that were outside of the RASA boundary.

discharge to the Snake River and increases river losses to the aquifer. The interconnection between surface and groundwater will be discussed in later sections of this report.

In average and wet years, spring snowmelt exceeds system storage capacity and irrigation demands, and water is spilled past Milner Dam. Between 1980 and 2008, annual discharge past Milner Dam (Figures 3 and 4) averaged 2.1 MAF. A gradual increase in river flow below Milner Dam is due to tributary inflow and aquifer discharge to the river, primarily from springs on the north wall of the Snake River canyon. Annual discharge of the Snake River at King Hill, located at the boundary between the eastern and western plain, averaged 7.4 MAF between 1980 and 2008 (Figures 3 and 5).

III. C. GROUNDWATER HYDROLOGY

The ESPA underlies the eastern Snake Plain. This highly productive aquifer is composed of fractured basalts and interbedded sediments. Although the collective thickness of the basalt flows may be in excess of several thousand feet in places, the active portion of the aquifer is often thought to be limited to the upper several hundred feet of saturated thickness. Robertson (1974), in reference to the National Reactor Testing Station (now the Idaho National Laboratory), 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 to 800 feet thick. Model studies by the U.S. Geological Survey (Garabedian, 1992) represented 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; Cosgrove and others, 1999) represent the aquifer as a single layer ranging from 200 to 1,700 feet thick.

Most of the groundwater flow in the aquifer is through highly-permeable rubble zones located at the tops of the numerous individual basalt flows which compose the ESPA. Contours of the potentiometric surface indicate that groundwater flow direction generally is parallel to the axis of the plain (Figure 6). 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) reported that the median specific capacity on a county basis for 176 wells across the eastern plain ranged from 4 to 950 gallons per minute per foot of drawdown, with the largest values occurring 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. In the RASA model developed by Garabedian (1992), transmissivity ranged from $4x10^3$ to $1x10^7$ ft^2/day. In the SRPAM, transmissivity ranged from $2x10^4$ to $5x10^6$ ft^2/day. In the ESPAM1.1, transmissivity ranged from $1x10^2$ to $5x10^7$ ft^2/day. These ranges of values are consistent with published values for fractured basalt (Freeze and Cherry, 1979).

The ESPA is generally considered an unconfined aquifer; however, the aquifer responds as a confined system in some locations. The layered basalts and interbedded sediments may produce conditions that appear locally confined, at least when subjected to short duration stress as was demonstrated on site at the Idaho National Laboratory (Frederick and Johnson, 1996). In the Mud Lake area, low permeability lakebed sediments create local confining layers (Spinazola, 1993).

Aquifer storage in the ESPA is reasonably high due to the highly fractured nature of the system. In the RASA model (Garabedian,1992), specific yield ranged from 0.05 to 0.2 (unitless). Specific yield values used in the SRPAM are higher, ranging from 0.08 to 0.26. In ESPAM1.1, specific yield values ranged from 0.005 to 0.28. In ESPAM2.1, specific yield values range from 0.01 to 0.3. The specific yield values used by Garabedian, the SRPAM, ESPAM1.1, and ESPAM2.1 are consistent with published estimates for unconfined systems, although many of the SRPAM, ESPAM1.1, and ESPAM2.1 values are near the upper limits of published values (Freeze and Cherry, 1979). In some areas, the higher specific yield values occur in areas of interbedded sediments.

The Snake 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 directly to the Snake River, to springs along the Snake River and through groundwater pumping. Figure 7 shows a conceptual model of recharge and discharge to the ESPA. The relative magnitudes of the recharge and discharge components were evaluated by the USGS (Garabedian, 1992) and, more recently, by IWRRI and IDWR during development of ESPAM1.1 and ESPAM2.1. The average annual aquifer water budget, based on the calibrated ESPAM2.1, is shown in Figure 8.

Incidental aquifer recharge from irrigation is a significant component of the water budget and has varied as irrigation practices have evolved. Garabedian (1992) estimated that surface-water irrigation contributed more than 50 percent of the total recharge to the aquifer in 1980. Historically, aquifer water levels and corresponding discharges to the Snake River increased in the first half of the 1900s in response to the onset of surface-water irrigation. This is particularly apparent in the historic discharge in the Milner-to-King Hill reach shown in Figure 9. Aquifer water levels peaked around 1950 and have been declining since that time. The declines are attributed to the onset of groundwater irrigation, more efficient surface-water irrigation practices such as conversion to sprinkler irrigation and canal lining, and the recent droughts. Historic discharge in the Near Blackfoot-to-Neeley reach shows a less dramatic response to changes in irrigation practices; however, the reach does exhibit more dramatic seasonal variation since the 1970s.

The effects of weather variation and irrigation recharge are also apparent in the short-term variation of spring discharge. Maximum discharge occurs around October, near the end of the irrigation season. According to Kjelstrom (1955a), 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.

ESPA groundwater eventually discharges to the Snake River, either via springs or directly into the river as base flow. Groundwater 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. Much of the ESPA discharge occurs in two Snake River reaches: Milner-to-King Hill, and Near Blackfoot-to-Neeley. These reaches are defined by gaging stations shown in Figure 1. Significant discharge in the Kimberly-to-King Hill reach occurs where the Snake River bisects nearly the entire sequence of the ESPA basalts along the western margin of the aquifer between Kimberly and King Hill. Aquifer discharge has varied in response to changes in precipitation, irrigated acreage, and irrigation practices. Overall, discharge in the Milner-to-King Hill reach appears to have been impacted more than in the Near Blackfoot-to-Neeley reach (Figure 9); although, the Near Blackfoot-to-Neeley reach shows more seasonal variation since approximately 1970.

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 location, 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 (Garbedian, 1992). Between Roberts and Shelley, and between approximately Minidoka and Milner Dam, the Snake River is not believed to be hydraulically connected to the regional aquifer system.

Aquifer water levels have generally declined over the past several decades in response to changes in irrigation practices and variations in weather. Figure 10 shows the ESPA water level changes for the period from spring 1980 to spring 2001. The green areas represent areas of water level increases, while the red areas represent areas of aquifer water level decreases. The points in the figure represent the well locations used as control points for the analysis of water level changes. The largest water level declines appear in the southwestern part of the plain, particularly in the Oakley Fan area. Figure 11 shows the water level changes on the plain for the period of spring 2002 to spring 2008. Declines in aquifer water levels are more dispersed across the plain for this time period. Figure 12 shows water level changes for the period of spring 1980 to spring 2008. During this period, water levels across the plain generally declined between 5 and 20 feet, with declines as great as 80 feet in the Oakley fan area. This change in water level corresponds approximately to the change in aquifer storage shown in Figure 8 (water years 1981 through 2008).

IV. MODEL DESCRIPTION

IV. A. 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. ESPAM1.1 and ESPAM2.1 have been constructed using storage coefficients typical of unconfined aquifers. However, the mathematical representation uses time-constant transmissivity, mathematically equivalent to a confined representation of the ESPA. The generally considerable saturated thickness of the ESPA (Whitehead, 1986) supports a time-constant representation of transmissivity, because drawdown is generally expected to be less than 10% of total saturated thickness (Anderson and Woessner, 1992). The time-constant transmissivity representation of the ESPA allows a more stable numerical simulation of the aquifer during automated model calibration. ESPAM1.1 Design Document DDM-019 discusses the time-constant transmissivity representation of the ESPAM. The thickness of the aquifer is discussed further in section IV. B. Model Extent.

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

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

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)

W is the rate of aquifer recharge (1/day); W>0 represents recharge to the aquifer, W<0 represents well pumping or other flux out of the aquifer

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

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(K_{yy}\frac{\partial h}{\partial y}\right)+W=S_s\ \frac{\partial h}{dt} \qquad \text{(Equation 2)}$$

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)

W is the rate of aquifer recharge (1/day); W>0 represents recharge to the aquifer, W<0 represents well pumping or other flux out of the aquifer

S_s is the specific storage (1/ft)

t is the time (days)

The ESPAM2.1 is a transient, two-dimensional, isotropic representation of the ESPA. The isotropic representation means that hydraulic conductivity in the horizontal plane is independent of direction (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 $\frac{b}{T}$, where b is saturated thickness (ft) and T is aquifer transmissivity (ft^2/day), yields the following:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + W\frac{b}{T} = 0 \qquad \text{(Equation 3)}$$

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + W\frac{b}{T} = \frac{S}{T}\frac{\partial h}{dt} \qquad \text{(Equation 4)}$$

where:

T is aquifer transmissivity (ft^2/day)

h is aquifer head (ft)

W is the rate of aquifer recharge (1/day); W>0 represents recharge to the aquifer, W<0 represents well pumping or other flux out of the aquifer

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:

$$Q = -KA\frac{dh}{dl} \qquad \text{(Equation 5)}$$

where:

Q is discharge (ft^3/day)

K is hydraulic conductivity (ft/day)

A is cross-sectional area (ft^2)

$\frac{dh}{dl}$ is hydraulic gradient (dimensionless)

In a numerical model, for river, drain, and general head boundary cells, the hydraulic conductivity term represents the conductivity of the river-bed or drain sediments which controls the flow between the river, drain, or general head boundary and the aquifer. The gradient $\frac{dh}{dl}$ represents the head differential between river stage (or drain elevation) and the aquifer.

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

ESPAM2.1 was constructed using MODFLOW 2000, a finite-difference code widely used for groundwater modeling which was created by the U.S. Geological Survey (McDonald and Harbaugh, 1988, Harbaugh and others, 2000). ESPAM2.1 was constructed using the Pre-Conjugate Gradient (PCG) solver (Hill, 1990) with the head closure criterion set to 1.5×10^{-4} feet and the residual criterion for convergence set to 2000 ft^3/day for model calibration. The parameter estimation code, PEST version 12.0 (Doherty, 2004) was used to assist with model calibration. MODFLOW 2000 was selected because it is considered an industry standard for finite difference groundwater 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.

IV. B. MODEL EXTENT

Figures 13a through 13d show the ESPAM boundaries (ESPAM1.1 and 2.1), the RASA boundary, and the SRPAM boundary. Both versions of ESPAM were developed for the conjunctive management of groundwater and surface-water resources and model extent was evaluated based on inclusion of irrigated areas. During development of ESPAM1.1, modifications were made to expand the model boundary to include irrigated acreage in the Kilgore, Rexburg Bench, American Falls, and Oakley Fan areas, and the ESPAM boundaries were extended up the Big Lost River drainage to Mackay Dam to simplify the estimate of tributary underflow in that drainage.

The Twin Falls tract is within the RASA boundary but not the SRPAM boundary and was excluded from the ESPAM models. The Snake River is deeply incised between Kimberly and King Hill, and it is believed that there is little communication between the aquifers on the north and south sides of the Snake River.

In the King Hill area, the RASA boundary extends further to the west than the SRPAM boundary (Figure 13b). The ESPAM boundaries follow the RASA boundary in this area, allowing inclusion of the King Hill gage on the Snake River. The ESPAM2.1 boundary is similar to the ESPAM1.1 boundary, but is refined slightly in the Hagerman (Ralston, 2008), Big Lost, Lincoln Fork/Ross Fork Creek, and Pocatello areas. More detailed information on the delineation of ESPAM boundaries is available in ESPAM1.1 Design Document DDM-002 and ESPAM2 Design Document DDM-002.

In addition to the areal extent of the study area, an analysis was done during development of ESPAM1.1 to delineate the bottom of the ESPA in order to estimate saturated thickness. Whitehead (1986) published basalt thickness maps for the eastern Snake Plain based on a limited number of borehole logs and geophysical surveys. During development of ESPAM1.1, the ESHMC agreed that a delineation of the bottom of the ESPA, which is based on Whitehead’s work with an assumption of a minimum aquifer thickness at the aquifer margins of 200 ft, is a reasonable approach. Figure 14 shows the Kriged surface of the bottom of the aquifer assumed for the ESPAM1.1 study. Because very few data points were available, Whitehead (1986) made assumptions at some locations (Figure 14) to delineate the bottom of the aquifer. Figure 15 shows the locations at the aquifer margin where the aquifer thickness is set to 200 ft. More details about the determination of the bottom of the aquifer can be obtained in ESPAM1.1 Design Document DDM-012. The ESPAM1.1 delineation of the aquifer bottom was carried forward to ESPAM2.1.

IV. C. DISCRETIZATION

Finite difference modeling consists of breaking a large physical area into small volumes, which are called model cells, and simultaneously solving the governing equations for each model cell. Additionally, if the model is transient, the total simulation time is also broken down into smaller time steps and the problem is solved at the end of each time step. In the case of groundwater modeling, the problem is 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.

In MODFLOW, 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.

IV. C1. Spatial Discretization

The spatial discretization of the model study area is the subdivision of the ESPA system into 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 is considered an active cell, for which aquifer head is computed using the model. Any cell outside of the model boundary is considered an inactive model cell and not part of the calculation of aquifer head.

IV. C1. a. 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 NAD 1983 (IDTM83) coordinates x=2,378,350.35 meters east and y=1,332,998.93 meters north. This is in the SE-NW-SW quarter of Section 3, Township 3 South, Range 8, East Boise Meridian in the Public Land Survey system. For more information on IDTM83 coordinates, the reader is encouraged to contact IDWR.

The model grid is rotated 31.4° counter-clockwise relative from an east-west orientation. The rotation is selected to minimize the number of inactive model cells. Figure 16 shows the model grid, the origin, and the orientation. The model grid is comprised of 1 mile x 1 mile square cells (5,280 ft x 5,280 ft). There are 11,236 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 Plain aquifer. Figure 17 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 ESPAM1.1 Design Document DDM-015.

IV. C1. b. Model Layers

ESPAM 1.1 and ESPAM2.1 are single-layer models of the ESPA. It is generally agreed that the ESPA resides in a single large stratigraphic unit, consistent with a single layer model (Whitehead, 1986), however there are localized lenses of sediments in some locations on the plain (the Egin-Henrys Fork area, the Rigby Fan, and the Burley-Rupert area), which may support locally elevated water levels. When ESPAM1.1 was being designed, it was agreed among the ESHMC that the option of adding a top layer to represent localized 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 ESHMC members agreed that a single layer model was sufficient. More information on the choice of using a single layer representation is available in ESPAM1.1 Design Document DDM-003. This decision was carried forward to ESPAM2.1.

IV. C2. Temporal Discretization

ESPAM2.1 is a transient model. Therefore, 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 based upon input from the ESHMC.

The criteria used to select the model calibration period included a) the period should represent 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 groundwater model to adequately predict long-term aquifer trends, and d) the period should include current and historic land use and irrigation practices. The ESHMC selected a model simulation period of 28.5 years, from May 1980 through October 2008. The starting date coincides with an extensive data collection effort on the eastern Snake Plain, conducted by the USGS as part of the RASA project. The end date coincides with a mass-measurement of aquifer water levels in the fall of 2008. The period of May 1980 through October 2008 includes the wettest year on record (1997), early drought years (1987-1990) and recent drought periods (2000-2004 and 2007-2008). 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 (described below).

In a MODFLOW model, a stress period is the length of time during which aquifer recharge and discharge (aquifer stresses) are held constant. For ESPAM2.1, one-month stress periods have been selected. Actual days per month (28 to 31) are used. Table 2 lists the months represented by each of the 342 transient stress periods.

In groundwater modeling using MODFLOW, stress periods are subdivided into time steps, and the groundwater flow equations are solved for every time step. Even though a constant stress is applied during a given stress period, aquifer water levels and river gains respond and change throughout the stress period. By further discretizing stress periods using time steps, the model predicts 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. In ESPAM2.1, two time steps of equal length are used for each model stress period. The net result is that aquifer water levels and river gains are estimated by the model approximately every 15.2 days during the 28.5-year simulation period.

IV. D. HYDROLOGIC BOUNDARY CONDITIONS

The assignment of hydrologic boundary conditions is a critical element of the conceptual design of any groundwater flow model. ESPAM2.1 employs several types of numerical boundary conditions. No-flow boundaries are used around most of the perimeter of the model, simulating the physical contact between the aquifer and the less permeable geologic formations. Specified flux boundaries are used to represent tributary underflow, seepage from non-Snake River reaches, recharge from precipitation on non-irrigated lands, irrigation conveyance loss and net recharge/discharge from surface and groundwater 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 reaches of the Snake River and springs immediately tributary to the Snake River.

The primary purpose of the model is to represent the exchange of water between the Snake River and the aquifer, and aquifer discharge to springs that are in close proximity and tributary to the Snake River. These fluxes are represented as head-dependent boundaries. Monitoring data representing these fluxes were used as calibration targets. All other fluxes into or out of the aquifer were represented as specified-flux boundaries.

Data describing the boundaries (fluxes, heads, and conductance parameters) are discussed in the Water Budget and Calibration sections in this report.

IV. D1. MODFLOW Representation of Head-Dependent Boundaries

Head-dependent boundaries represent flux between a surface-water body and an aquifer. Head-dependent boundaries are typically used to represent surface-water bodies which are hydraulically connected to, and can either gain water from or lose water to an aquifer. Head-dependent boundaries include river and general head boundaries, at which the flux may be either recharge or discharge from the aquifer, and drain boundaries, at which the flux may only be discharge from the aquifer.

In ESPAM2.1, the flow between the aquifer and a hydraulically connected surface-water body (e.g., river) 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. The discharge to (or from) the river is calculated as:

$$Q_{riv} = C_{riv} \ \left(h_{riv} - \max\left(r_{bot}, h_{aq}\right)\right) \qquad \text{(Equation 6)}$$

where:

Q_{riv} is the discharge to (if negative) or recharge from (if positive) 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)

r_{bot} is the elevation of the bottom of the river sediments (ft)

Figure 18 is a conceptual diagram showing how river leakage is calculated in MODFLOW. As long as the aquifer head is above the river bottom, the discharge to or from the river is calculated using 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.

In ESPAM2.1, springs that discharge to the Snake River downstream of Milner Dam 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:

$$Q_{drn} = min\ (0, C_{drn}\ (el_{drn} - h_{aq})) \qquad \text{(Equation 7)}$$

where:

Q_{drn} is the discharge to the drain (ft^3/day) and is the minimum value between zero (0) and $C_{drn}\ (el_{drn} - h_{aq})$, negative values indicate flux out of the aquifer

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)

Base flow that discharges from the aquifer directly to the Snake River between Kimberly and King Hill is represented using the MODFLOW General Head Boundary Package in ESPAM2.1. The General Head Boundary Package is similar to the River Package allowing water to both enter and exit the aquifer through the boundary. The equation governing aquifer flux through the General Head Boundary is:

$$Q_{ghb} = C_{ghb}\ (el_{ghb} - h_{aq}) \qquad \text{(Equation 8)}$$

where:

Q_{ghb} is the discharge to the general head boundary (ft^3/day), negative values indicate flux out of the aquifer, positive values indicate flux into the aquifer

C_{ghb} is the general head boundary conductance (ft^2/day)

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

el_{ghb} is the general head boundary elevation (ft)

IV. D1. a. ESPAM2.1 Head-Dependent River Boundaries

Most of the Snake River above Milner Dam, including American Falls Reservoir, is represented by two hundred-forty one river cells (Figure 19). Since riverbed conductance is a lumped parameter (i.e., it represents multiple physical attributes) and impossible to measure, it was estimated during model calibration. River cells were aggregated into five reaches for calibration (Figure 19).

Water balance calculations performed using the IDWR Reach Gain and Loss program indicate that there is virtually no leakage in the reach between Minidoka and Milner, so the reach is not represented in ESPAM2.1. The model cells used in the MODFLOW River Package, the river bottom elevation, and the assigned riverbed conductance values are listed in Table 3. Because river stage varies with each stress period, stage elevation is not included in Table 3.

The parameters in Equation 6 include river bed conductance (C_{riv}), aquifer head (h_{aq}), river stage (h_{riv}), and river bottom elevation (r_{bot}). As previously mentioned, C_{riv} is estimated during model calibration and is discussed more completely in the Model Calibration section. Aquifer heads for variable h_{aq} are calculated by the model code. River stage (h_{riv}) and (r_{bot}) are supplied as input data. For most river cells, river bottom elevations have been retained from ESPAM1.1 and were calculated from a Digital Elevation Model representation of land surface, minus a 30-foot estimated thickness of riverbed sediments, as described in ESPAM1.1 Design Document

DDM-010. River bottom elevations were modified for ESPAM2.1 at cells representing American Falls Reservoir. Taylor and Moore (2009) described the calculation of h_{riv} and r_{bot} as well as the locations of river cells for ESPAM2.1 in Design Document DDM-V2-03.

The use of one-month stress periods in ESPAM2.1, necessitates the representation of river stage (h_{riv}) as time-variable. Stage values are estimated by applying the monthly average stage at USGS river gages and interpolating between gages.

One-month stress periods also require time-variable values for American Falls Reservoir stage. The assignment of river cells to represent the reservoir (Figure 19) is based on aerial images of the reservoir when it was full. When the reservoir is full its "footprint" (aerial extent) is larger than when it is empty. The representation of wet or dry reservoir bottom is accomplished by manipulating the input data to Equation 6, as shown in Equation 9:

$$Q = C_{riv}[max(Res_{stage}, Res_{bed}) - max(h_{aq}, Res_{bed})] \qquad \text{(Equation 9)}$$

where:

Q is the discharge to or from the reservoir (ft^3/day)

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

Res_{stage} is the head in the reservoir (ft), varies by stress period

Res_{bed} is the elevation of the reservoir bed (ft), varies by reservoir cell and stress period, set to land surface elevation for some stress periods and to 30 feet below land surface for other stress periods based on reservoir stage.

h_{aq} is the head in the aquifer (ft), calculated by MODFLOW at each time step

The value $max(Res_{stage}, Res_{bed})$ is the greater of the reservoir stage and the reservoir bed elevation. The value $max(h_{aq}, Res_{bed})$ is the greater of the head in the aquifer and the reservoir bed elevation.

This change for the reservoir cells requires no modification to MODFLOW code. The values of $\left(max\left(Res_{stage}, Res_{bed}\right)\right)$ are presented to MODFLOW as value h_{riv} in Equation 6. The values of Res_{bed} at each cell are presented as R_{bot} in Equation 6, while h_{aq} is calculated by MODFLOW as before. ESPAM2 Design Document DDM-V2-03 discusses the following flux calculations:

1. Reservoir stage is above land surface and aquifer head is above reservoir stage: Res_{bed} is set to 30 feet below land surface. Flux is at the rate C_{riv} * (Res_{stage} - h_{aq}). The head difference is negative and flow is into the reservoir.
2. Reservoir stage is above land surface and aquifer head is below reservoir stage: Res_{bed} is set to 30 feet below land surface. If h_{aq}>Res_{bed}, flux is at the rate C_{riv} * (Res_{stage} - h_{aq}). In this case the head difference is positive and flow is out of the reservoir. If h_{aq} < Res_{bed}, the reservoir is perched above the aquifer and reservoir seepage occurs at the rate C_{riv} * (Res_{stage} – Res_{bed}).
3. Reservoir is dry within model cell and aquifer head is above the elevation of the reservoir bottom: Res_{bed} is set equal to land surface. Flux is at the rate C_{riv} * (Res_{stage} - h_{aq}). The head difference is negative and flow is into the reservoir. It is identical to the flow that the Drain Package (see discussion below) would produce for a spring with controlling elevation equal to the level of the reservoir bottom.
4. Reservoir is dry within model cell and aquifer head is below the elevation of the reservoir bottom: Res_{bed} is set equal to land surface. Flux is at the rate C_{riv} * (Res_{bed} - Res_{bed}), or zero. This is identical to a drain that has gone dry because aquifer head has dropped below the controlling elevation.

The estimation of parameters C_{riv} for the various reaches and the river gain and loss observations used for calibration targets are discussed in the Model Calibration section of this report.

IV. D1. b. ESPAM2.1 Head-Dependent Spring Representation

Springs in ESPAM2.1 are modeled using the MODFLOW Drain Package. Ninety drains are specified within 54 model cells located in the Thousand Springs area (Figure 20). Equation 7 governs the model representation of discharge to each drain. Unlike the river cells representing the Snake River above Minidoka, the drain cells are not contiguous. Drain cells (Table 4) were selected based on maps published by the USGS (Covington and Weaver, 1990). The Covington and Weaver maps were also used to establish drain elevations, though in some cases, elevations were adjusted as new information became available.

Without modification, MODFLOW will accommodate multiple drains per model cell. The ESHMC chose to include two drains if the cell contained more than one spring at different elevations. Two drains at different elevations, each with a different conductance, may result in a piecewise linear head/discharge relationship if one of the drains alternates between wet and dry. If the drains do not alternate between wet and dry during the model simulation, the head/discharge relationship remains linear.

For ESPAM1.1, the ESHMC agreed that drain cells should be aggregated into reaches. This 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. A significant part of the effort in developing ESPAM2.1 involved explicitly representing individual springs or small groups of springs located within one or two model cells. To provide additional calibration targets for ESPAM2.1, the drain cells were also aggregated into three “spring” reaches (Kimberly to Buhl, Buhl to Lower Salmon Falls, and Lower Salmon Falls to King Hill) based on the existence of gages on the Snake River. The drain cells are color-coded in Figure 20 according to spring reaches. Information regarding the representation of springs in ESPAM2.1 is found in file “ModSpgs_Drain_Max2_per_Cell_27Apr2011.xls” and in meeting notes and presentations in meeting folders on the IDWR website.

For ESPAM2.1, springs are divided into three categories, Group A, B, and C springs, based on the availability and quality of measured flux data. Group A springs are monitored by IDWR or the USGS and there is a high level of confidence in the data. The Group A springs include Devil's Washbowl Spring, Devil's Corral Spring, Briggs Spring, and Box Canyon Springs.

Group B springs are sites where water users report flow data to a Watermaster or IDWR. The data must be sufficient to compute the total monthly discharge from a spring or spring complex, and may be reported by more than one water user. Quantifying total monthly discharge for Group B springs can be complex because the data may include reuse water, multiple diversions, and irrigation return flows. In addition, portions of the spring discharge may not be diverted or measured during certain times of the year. IDWR and the ESHMC developed and/or reviewed data for ten Group B springs for ESPAM2.1, including Crystal Springs, Niagara Springs, the Blue Lakes Spring complex, Clear Lakes, Sand Springs, the Thousand Springs Power Plant complex, the National Fish Hatchery complex, the Rangen Hatchery complex, Three Springs/Weatherby Springs/Hoagland Tunnel and Spring Creek Spring, and the Malad River reach gains below the Gooding gage.

Group C springs are sites for which available discharge data were not sufficient to develop a transient data series or the data have not yet been compiled and presented to the ESHMC. The locations of these springs were identified by Covington and Weaver (1990). The flow data reported by Covington and Weaver (1990) were obtained by estimates or reconnaissance-level measurements taken during the period from the 1940s to the late 1980s. Unlike the Group A and B sites, flow data for each of these sites are limited to a single value reported by Covington and Weaver (1990). This value is converted to a ratio, which compares the spring discharge to the largest Group C spring in the same reach (i.e., Kimberly to Buhl, Buhl to Lower Salmon Falls, and Lower Salmon Falls to King Hill). These ratios are used during model calibration, along with reach gain, Group A and B spring discharge data, and base flow data, to apportion discharge between the Group C springs.

IV. D1. c. ESPAM 2.1 Head-Dependent Base Flow Representation

Comparison of spring flow data and Snake River reach gains between Kimberly and King Hill indicates that some water discharges directly from the ESPA to the Snake River without emerging as spring flow. This discharge is referred to as base flow and is represented in ESPAM2.1 using the MODFLOW General Head Boundary Package. Base flow discharge estimates are available for the three gaged reaches of the Snake River and for three shorter reaches where the USGS has performed miscellaneous river and spring flow measurements. The conductance of each general head boundary reach was adjusted by PEST and is further discussed in section VI. Model Calibration. The general head boundary cells used to simulate base flow in ESPAM 2.1 are presented in Figure 21 and Table 5.

IV. D2. Specified Flux Boundaries

In MODFLOW, specified flux boundaries represent any flow to or from the aquifer that occurs at a rate independent of head differential. Specified flux boundaries are commonly used to represent areal recharge, discharge from well pumping, and underflow from tributary basins outside the model boundary. In the ESPAM2.1, all flux into or out of the aquifer, except for gains and losses to the Snake River, American Falls Reservoir, and springs near the Snake River, is represented by specified flux boundaries using the MODFLOW Well Package. This is even true for some seepage sources (for example Mud Lake or the Aberdeen-Springfield Canal) which may in fact be hydraulically connected to the aquifer. The rationale is that the purpose of the model is to represent interchange between the aquifer and the Snake River and its nearby tributary springs.

Specified flux boundaries in ESPAM2.1 are used to represent recharge from precipitation on non-irrigated lands, tributary basin underflow, seepage from water bodies other than the Snake River, seepage from irrigation canals, incidental recharge on surface water irrigated lands, net groundwater pumping for irrigation, wetlands ET, and municipal pumping. Specified flux boundaries are described in the Model Water Budget section.

IV. E. INITIAL CONDITIONS

Estimates of aquifer water levels or starting heads for each model cell at the beginning of a simulation form the initial conditions. Of primary concern are the starting heads on May 1, 1980, the beginning of the model simulation period. For the ESPAM 2.1 transient simulation, the starting heads were computed using a steady state simulation with average water budget values from May 1999 – April 2000. This one-year period was selected because the calculated net recharge to the ESPA was similar to the average annual recharge estimated by Kjelstrom (1995) for water years 1976 through 1979, and it produced initial heads that were generally similar to observed May 1980 water levels. The ESHMC members originally suggested the water budget from the earlier years of 1981 to 1984 be used to generate the initial head; however this produced initial heads that were considerably higher than observed May 1980 water levels.

V. MODEL WATER BUDGET

The water budget is one of the most important elements of a groundwater model. The water budget comprises an accounting of all recharge and discharge to the aquifer for each model stress period. While all fluxes into and out of the aquifer are part of the physical water budget, in this report, the head-dependent fluxes to and from the Snake River (river reach gains and losses) and discharge from tributary springs are referred to as "calibration targets." All other flows, represented as specified fluxes, are referred to as components of the “model water budget”.

Figure 8 shows the average annual aquifer water budget for water years 1981 through 2008. Water use on the eastern Snake Plain is dominated by irrigated agriculture. The major sources of recharge to the aquifer are incidental recharge from surface-water irrigation, tributary underflow, conveyance losses from canals, seepage from rivers, and recharge from precipitation on non-irrigated lands. The major sources of discharge from the aquifer are spring discharges, net gains to the Snake River, and pumping from wells. There is considerable natural variation in the 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.

The model water budget is processed by the MKMOD program, which is described in Appendix B. The MKMOD code was written by Willem Schreuder (a member of the ESHMC) and reviewed and tested by IDWR staff and other members of the ESHMC. The MKMOD code compiles water budget input data, calculates the specified flux to be applied to each model cell, and writes a well file for input into MODFLOW. The MKMOD program replaces the readinp.for program used to compile water budget data and calculate specified flux for ESPAM1.1. The ESPAM2 Recharge Tools (Appendix C) are used to format water budget data for input into the MKMOD program. The ESPAM2 Recharge Tools replace the GIS Recharge Tool (espam.exe) program used to format water budget data for input into the readinp.for program for ESPAM1.1. Water budget data required as input into the MKMOD program include:

irrigated land area and water source;
diversions from surface water;
diversions from offsite wells;
canal seepage;
precipitation on irrigated lands;
crop evapotranspiration;
irrigation return flow to Snake River;
recharge on non-irrigated lands;
wetlands evapotranspiration;
tributary underflow;
non-Snake River perched seepage;
extraction from municipal and industrial wells.

Methodology used to develop water budget input data are described in the following sections of this report.

V. A. LAND USE/LAND COVER

One of the first steps in developing a water budget for a study area is to evaluate land use/land cover (referred to hereafter as "land use"). Recharge to the aquifer varies greatly among different land uses. For example, on surface water irrigated lands, the amount of water applied exceeds consumptive use, so there is generally net recharge to the aquifer. On the other hand, there is a net extraction from the aquifer to meet consumptive use on groundwater irrigated lands. Dry rangeland may produce very small amounts of recharge, while phreatic wetlands may seasonally discharge significant amounts of groundwater through evapotranspiration.

Multiple sources of imagery from 1980, 1986, 1992, 2000, 2002, and 2006 were processed to develop irrigated lands datasets for the ESPAM2.1 model. These data are described more fully in Design Document DDM V2-04. In summary, the 1980 land use data (RASA80LC, IDWR, 1980) is a digital classification of Landsat Multispectral Scanner (MSS) data produced by the IDWR Idaho Image Analysis Facility using the VICAR Image Processing System (IDWR, 1982). The 1986 land use data are a digital classification of Landsat MSS data completed by IDWR. The 1992 land use data (SNAKLC92, IDWR, 1997b) were developed from interpretation of 1987 aerial photographs and extensive field work. The 2000 land use data (ESPAC2000, IDWR, 2002a) was developed by IDWR for ESPAM1.1, using digital classification of multiple Landsat images, with a frequency of every 16 to 32 days throughout the growing season. The 2002 and 2006 land use data are high quality data generated by IDWR based on USDA Common Land Unit polygons. For 2002 and 2006, comparisons with aerial photography obtained from the USDA National Agriculture Imagery Program (NAIP) were used to further refine the land unit polygons. Digital analysis of Normalized Difference Vegetative Indices from Landsat data was to determine the irrigation status of parcels. This was followed with significant efforts to refine the irrigation status classifications based on visual comparisons with multiple Landsat images collected during each irrigation season, and with aerial photography obtained from the USDA National Agriculture Imagery Program (NAIP). Figures 22a through 22f show the irrigated lands data compiled from the review and interpretation of the imagery described above.

Irrigated lands and wetlands, which both show high vegetation density, were not differentiated in some of the land use data. Similarly, due to cost and time constraints, not all of the data were constructed to reliably differentiate between irrigated agriculture and semi-irrigated suburban areas. Consequently, all data are masked with a common map of urban and wetland areas to remove these areas from the irrigated lands datasets. This map is based on a 1991 digital analysis of Landsat data (SRBAS91LU, IDWR, 1994), as described in ESPAM1.1 design document DDW-015.

V. A1. Reduction for Non-Irrigated Inclusions

Some portions of the irrigated lands mapped in Figures 22a through 22d are actually non-irrigated areas such as roads, homes, rock piles, and canal banks. In both ESPAM1.1 and ESPAM2.1, the impact of non-irrigated inclusions on the water budget was addressed by applying a reduction factor to the irrigated area. In both ESPAM1.1 and ESPAM2.1, the recharge-calculation methodology allowed a unique reduction factor for each stress period and application method (gravity or sprinkler irrigation), but the available data only allowed calculation of a single unique factor for each irrigated lands dataset. In ESPAM1.1, a single reduction factor of 12% was applied for all stress periods.

Six different irrigated lands datasets representing the 1980, 1986, 1992, 2000, 2002, and 2006 irrigation seasons were prepared for ESPAM2.1. Using hand-drawn polygons of actual irrigated acres in a sampling of model cells, unique reduction factors were calculated for each dataset. The inability to reliably distinguish application method (other than center pivots) in aerial photographs resulted in a decision to apply identical reductions for sprinkler and gravity irrigated parcels. ESPAM2 Design Document DDM-V2-04 describes this process in more detail, and the reduction factors applied are listed by year in Table 6.

V. A2. Source of Irrigation Water

Within an irrigated tract, the source of irrigation water is used to assign parcels to groundwater or surface-water irrigation entities and to apply diverted volumes of water to the appropriate spatial locations. The water source also determines the selection of ET adjustment factors and application method (sprinkler or gravity), both of which impact recharge and discharge calculations. This is important for matching observed water-level fluctuations in wells; in areas dominated by surface-water irrigation, water levels respond to surface-water irrigation by rising during the irrigation season and declining during the non-irrigation season. Aquifer response to groundwater irrigation is the opposite. Finally, the source of irrigation water by parcel may be required for model scenarios; for example, a hypothetical scenario might represent curtailment of a specific source of irrigation water.

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% groundwater irrigated. However, some irrigated lands are designated as mixed source; they have both groundwater and surface-water rights. This occurs where surface-water sources may be inadequate, and supplemental groundwater sources have been developed. The following sections describe the method used in ESPAM1.1 to determine the source of irrigation water.

ESPAM1.1 relied primarily upon the Snake River Basin Adjudication database and IDWR water right database records. The two databases were not identical, because the adjudication process had not been completed. The adjudication database contained claims, recommendations, partial decrees, and water rights perfected before the statutory requirement to obtain a state permit. In addition, the source of water for parcels in the Northside Canal Company service area was confirmed and refined with information provided by the company.

Adjudication claims are a representation of water use in a defined location. The Idaho Department of Water Resources investigates claims and develops findings or recommendations to the Idaho State Court overseeing the adjudication process. The determination of the adjudicated water right by the court is called a partial decree.

When ESPAM1.1 was under development, recommendations existed for about 2/3 of the claims on the eastern Snake Plain. Partial decrees existed for a much smaller portion of the plain, and for those that did exist, not all the data were available for electronic querying. Consequently, the ESPAM1.1 determination of the source of irrigation water relied upon recommendations first, then claims if no recommendations were available, and finally upon water rights if no claims were available. This work is described in ESPAM1.1 design document DDW-017.

It was anticipated that continued progress in the Snake River Basin Adjudication would allow a similar analysis for ESPAM2.1, with more recommendations and partial decrees represented in the database and therefore, more precise results. However, as the Adjudication progressed, most water rights for canal companies and irrigation districts were recommended on a "Large Place of Use" basis, which described the general service area rather than the actual physical locations of where surface water is applied. The fine-scale resolution in the ESPAM1.1 data would have been lost if the large place of use data were relied upon. In addition, all parcels where only ground water is used within canal companies or irrigation districts would have become mixed-source parcels. Therefore, the ESPAM1.1 data were carried forward to ESPAM2.1.

ESPAM1.1 and ESPAM2.1 model data also include an adjustment in the Monteview/Mud Lake area based on Watermaster reports. Lands in the Jefferson Irrigation District and in the service areas of the Producers Canal Company and the Monteview Canal Company are entirely irrigated by groundwater pumped at distant locations and conveyed to the place of use in canals. Similarly, lands within the service areas of the Level Canal Company and Mud Lake Water Users Company, as well as some nearby lands irrigated with private water rights, receive groundwater pumped from distant locations, but it is comingled with surface water. To allow the water budget algorithms to appropriately represent canal seepage and percolation at the place of use, these lands that rely on distant pumping are designated surface water only in the dataset. Additional discussion of the treatment of these canal companies and irrigation districts is presented in section V. B2. c.

Figure 23 is a map of all irrigated lands on the eastern Snake Plain showing the source based on water rights data and compiled by 40-acre quarter-quarter sections using GIS. Parcels that have both surface water and groundwater rights are called mixed-source lands.

The fraction of supply from each source was identified in ESPAM1.1 to refine spatial distribution, although the fraction on mixed-source lands was uniform across each irrigation entity. In response, the ESHMC requested more spatial resolution in ESPAM2.1. IWRRI first assigned the mixed-source fraction according to the proximity of the place of use to irrigation wells, but with the subsequent decision to implement the On-Farm algorithm, the source fraction for many entities was modified to avoid improper calculation of deficit irrigation. Consequently, some entities have a uniform representation of source fraction, and some entities have groundwater fractions representative of the most extreme water-short months of the calibration period. ESPAM2 Design Document DDM-V2-04 describes the source of irrigation water and the source fraction on mixed-source lands in more detail.

V. B. ESTIMATION OF RECHARGE/DISCHARGE

The following sections describe the compilation of water budget components used as input data to ESPAM2.1. The components include canal seepage, incidental recharge on surface water irrigated lands, net discharge on groundwater irrigated lands, recharge on non-irrigated lands, tributary basin underflow, non-Snake River seepage, wetlands evapotranspiration, and municipal well pumping. Estimation of intermediate variables and calculations are discussed where applicable. More detailed information on the estimation of particular components is provided in the ESPAM2 Design Documents.

V. B1. Net Recharge on Surface-water Irrigated Lands

Net recharge on surface-water irrigated lands is calculated from diversions, canal seepage rates, evapotranspiration, precipitation, and infiltration and runoff (return flow) rates. Estimation of these intermediate parameters and the calculation of net recharge are described in this section.

V. B1. a. 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 boundary. Many of these irrigation companies share common acreage. In order to treat all surface-water irrigated areas in a consistent manner and to correctly map diversions to irrigated lands, surface-water irrigation companies were aggregated into a smaller number of “irrigation entities”. The entities were chosen to maintain a level of resolution consistent with available diversion and return flow data.

The aggregation process involved identifying the point of diversion from the river and the likely or actual corresponding return flow locations; determining the predominant irrigation practice, conveyance, and soil type; and identifying water right priorities, the common drainage area, and the previous aggregation in the earlier SRPAM model. Adjacent irrigation companies were aggregated into an irrigation entity if they had similar characteristics.

Most parcels with private surface-water rights within the model boundary were aggregated with an adjacent irrigation company. Parcels with private rights in Basin 31 (Camas and Beaver Creek), Basin 32 (Birch Creek and Medicine Lodge Creek), and Basin 33 (Little Lost River) are an exception, because they have unique practices or water sources. Entity IESW000 includes isolated irrigation parcels across the eastern Snake Plain where the water source is neither regulated nor reported by a Watermaster. Diversion volumes for IESW000 were estimated based upon computed ET and assumed rates of irrigation efficiency. In ESPAM2.1, IESW000 also includes a small portion of the Twin Falls Canal Company service area and small portions of service areas in the Ashton region which lie within the model boundary. These areas were formerly represented as entities IESW031 and IESW041 in ESPAM1.1.

There were 43 discrete irrigation entities in ESPAM1.1. ESPAM2.1 refinements resulted in 38 surface-water irrigation entities, shown on Figure 24 and listed in Table 7. Entity names are based on canal company, irrigation district, or a nearby town or geographic region. The aggregation of canal companies into irrigation entities is discussed in ESPAM1.1 Design Document DDW-008 and ESPAM2 Design Document DDW-V2-07**.**

V. B1. b. Irrigation Diversions.

In order to effectively and accurately estimate aquifer recharge from surface water irrigation, diversions from the river must be accurately estimated. Two sources of data were used to estimate Snake River diversions. Monthly diversion data processed by the IDWR reach gain/loss program were used for most diversions from the Snake River, Henrys Fork, Big Wood River, Little Wood River, and Teton River. These monthly diversion data were compiled by IDWR from water district records. Water district records were used directly to obtain data for diversions not included in the IDWR reach gain/loss program.

Diversion data input to the IDWR reach gain/loss program are assigned to appropriate canal companies and aggregated into the appropriate surface-water irrigation entity. Watermaster records are kept in IDWR electronic files (IDWR, 2001), paper and microfiche (IDWR, 2002b), and various other sources. Watermaster data are generally available as annual summaries, and monthly fractions were determined by hand calculation for most entities.

Entity diversions from sources other than the Henrys Fork, Snake River, or Teton River are referred to as “non-Snake River diversions.” Complete descriptions of the non-Snake River diversions are available in ESPAM1.1 Design Document DDW-024 and ESPAM2 Design Document DDW-V2-07.

Diversions for IESW005 (Big Lost River) and IESW059 (Gooding-Richfield area) are estimated on a mass balance basis, because IWRRI determined that available diversion records were not adequate. In IESW005, water district records after 1996 include both surface and groundwater diversions, but the annual summary reports do not consistently parse the volumes for all years of interest. For IESW059, it has been determined in consultation with the Watermaster that not all the necessary returns, diversions, and cross-connections were represented in the IDWR reach gain/loss program.

The mass balance approach for entities IESW005 and IESW059 involves adding up surface inflows to the entity and subtracting surface outflows. The net loss is attributed to either delivery to croplands or seepage into the stream bed. In the winter, there are no diversions, and the entire loss is attributed to stream bed seepage. This seepage is represented in the water budget as non-Snake River seepage. Winter stream bed seepage rates are used to estimate summer seepage, which is also applied to the water budget as non-Snake-River seepage. The remainder of the net loss is assigned to diversions. This method preserves the mass balance of net recharge for each irrigation entity, but may result in distortion of the spatial distribution of the recharge within the entity.

For 1980 through 1996, IESW005 diversions were obtained from Water District 34 records. For 1997 through 2008, IESW005 diversions were calculated using a regression based on comparing pre-1997 diversion data with the difference between inflow (measured at the Big Lost River below Mackay Reservoir gage and estimated at Antelope Creek) and outflow (measured at the gage below Arco).

In IESW059, the inflows include gaged flows from the Big Wood River, Little Wood River, Milner Gooding Canal, and the X-Waste Canal (which delivers Northside Canal Company tailwater into IESW059). Inflows also include estimates of the surface water contributions from Thorn Creek and Dry Creek. The IESW059 outflow is measured at the Malad River gage below Gooding. It should be noted that the Milner-Gooding Canal delivers Snake River water into the Big Wood River for re-diversion into other canals. In ESPAM2.1, the flow in the Milner-Gooding Canal at Shoshone is treated as an outflow from IESW058 (American Falls Reservoir District #2) and an inflow to IESW059, to preserve the mass balance.

Snake River and non-Snake River diversions were assigned to the appropriate surface water entity and summed to calculate total monthly diversions for each entity. Table A-1 lists the diversion volume for each irrigation entity for each stress period. More information about the estimation of Snake River irrigation diversions is provided in ESPAM1.1 Design Document DDW-012 and ESPAM2 Design Document DDW-V2-07.

V. B1. c. Conveyance Loss

There are approximately 900,000 acres of land irrigated by water delivered through canals and laterals across the eastern Snake Plain. Seepage or conveyance losses from major canals are represented as specified flux boundaries at the locations shown in Figure 25. A list of major canals with common name and model name is provided in Table 8. Table A-2 (Appendix A) contains a list of the model cells associated with each canal. The estimated flux for each canal is evenly distributed across the model cells assigned to that canal.

Canal seepage is an important source of aquifer recharge. Long canals in porous soils can lose 40% or more of diversions (Chavez-Morales, 1985). In Idaho, virtually all of this loss is assumed to be seepage to the aquifer (Dreher and Tuthill, 1999). Canal seepage can be represented by identifying seepage rates and locations, or a simplified approach can be taken by assuming that canal seepage 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. Canal seepage is applied to model cells intersected by the main canals (Figure 25). The MKMOD program accommodates multiple leaky canal sections per irrigation entity, each with a unique seepage rate. The seepage rate can also be varied with stress period in the MKMOD program.

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 diversions to quantify seepage. This is sometimes done in irrigation system assessment (Hubble, 1991) and has been used in aquifer modeling (Booker and others, 1990). Since the diversion rate partially controls seepage (Chavez-Morales, 1985), and since a percentage calculation guarantees there will never be seepage calculated in a period without diversions, a percentage-based method has been selected for ESPAM2.1.

Canal seepage rates have been assigned based on interviews with canal company personnel and results of previous studies, including data provided by ESHMC members. Some laterals of the Northside Canal have been designated as leaky sections in response to comparisons between model-predicted water level responses and observed responses at some wells. Estimation of canal seepage is described further in ESPAM1.1 Design Document DDW-020 and ESPAM2 Design Document DDW-V2-01.

Seepage from secondary laterals and farm ditches is modeled as incidental On-Farm recharge as described in section V. B1. g., and is spatially distributed to model cells in which the irrigated lands are located. Because size, construction, and maintenance of laterals and ditches are highly variable, estimating seepage 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). Because laterals and farm ditches are widely distributed across irrigated areas, including seepage from these channels in the incidental On-Farm recharge often closely reflects the actual spatial distribution.

V. B1. d. Evapotranspiration

Evapotranspiration (ET), the sum of evaporation and plant transpiration, is one of the largest components of discharge on the eastern Snake Plain. ET is controlled by climate as well as crop and soil characteristics. Climate affects the evaporative power of the atmosphere, providing the energy available to drive ET and influencing the capacity of air to accept evapotranspired water. Soil and plant characteristics control the ability of crops to extract water from the soil and the transpiration response to evaporative power. Soil texture, surface wetness and condition, and shading by plants control the response of the soil to evaporative power. Although far more water evapotranspires during the growing season, there is still measurable ET during the non-growing season.

University of Idaho data published as ET_{Idaho} 2009 (Allen and Robison, 2009) are used for ESPAM2.1. These reports provide values of both reference ET and reference ET multiplied by the crop coefficient (K_c) for a given crop and season, including year-round estimates. Annual ET (pre-PEST and post-PEST calibration values) and precipitation data for 1980 – 2008 are shown on Figure 26. The data indicate that ET is approximately 3 times greater than precipitation on ESPA irrigated lands.

The average ET depth for each county is determined by taking the weighted average of the crop-specific ET from the nearest NOAA station or occasionally from AgriMet stations. Because the data for each county include values for all typically grown crops, missing values represent rarely-grown crops. To avoid calculating zero ET if an atypical crop is grown, missing values were supplied or estimated from nearby stations, since the variation in K_c between weather stations for any given crop is low (Allen, 2003). This substitution will affect only a few acres within any stress period and has a very low potential of introducing a significant error. The determination of average ET depth is performed for each model stress period.

V. B1. d(1). Crop Mix

Knowledge of the mix of crops grown is needed to estimate evapotranspiration. Differences in the crop mix can change average evapotranspiration on the plain by as much as ten percent. The final crop mix used for the ESPAM2.1 is based on data from several sources of crop statistics. The primary 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: (1) the Published Estimates Data Base Online (USDA, 2000), (2) the US Agricultural Census (USDA, 1992, 1997), and (3) the Idaho Agricultural Statistics (Idaho Department of Agriculture, 1981 - 2010) reports. All formats were used in ESPAM2.1.

The Published Estimates Data Base (PEDB) version available on-line provides county-wide acres planted and harvested, by crop. These reports do not include alfalfa hay for the earlier years of the study, so values from the US Agricultural Census (Ag Census) version of the NASS data are used for 1982 and 1987. The Idaho Agricultural Statistics (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 2008 and used to fill in gaps in the PEDB potato data. The Ag Census reports provide details of irrigated and non-irrigated acreage by county for 1982, 1987, 1992, and 1997. IWRRI interviewed county agents during the ESPAM1.1 effort, and many recommended using the NASS/IAS data.

About half of the counties in the study area have farmed land both inside and outside the ESPAM2.1 model boundary (Figure 27). It is possible that the crop mix outside the study area is different than 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 evapotranspiration for each. The analysis was performed for Bonneville and Cassia Counties. The result of the analysis was that the “irrigated only” crop report data provided a better representation of the study area than did county-wide data. As a result, the "irrigated only" (agricultural census or IAS) data are used whenever possible.

The crop mix compilation incorporates data from IAS reports (Idaho Department of Agriculture, 1981 - 2010) with some refinements. Each report gives acreage for the preceding two years. Final crop mix fractions by year and county are listed in Table A-3 in Appendix A. The crop evapotranspiration estimates compiled from crop mix data and reference evapotranspiration data indicated that year-to-year variation in total crop consumptive use is very small. A more detailed description of the crop mix evaluation is provided in the ESPAM1.1 Design Document DDW-001. ESPAM2.1 crop mix data rely on the updated versions of the same data sources.

V. B1. d(2). ET Adjustment Factors

ET adjustment factors account for deviations from a perfectly managed crop such as a) water shortage, b) crop disease, c) post-harvest watering, d) crop varieties with a longer growing season, e) more intense management, or f) local differences in crop mix[4] or reference ET. The ET adjustment factors may also reflect differences in ET due to source of irrigation water or method of application. ET adjustment factors may also incorporate direct evaporation and canal-bank ET, because most canal banks are within the buffers used in adjustment factor calculations.

For ESPAM2.1, ET adjustment factors were estimated on an irrigation entity basis by comparing calculated county-wide ET with ET estimated by a remote sensing analysis using the METRIC algorithm (Allen and others, 2002; Allen and others, 2005; Morse and others, 2000) for the 2000 and 2006 growing seasons. For each irrigation entity, a unique pair of ET adjustment factors was developed; one for sprinkler irrigated land and one for gravity irrigated land. Design Document DDW-V2-11 includes more detailed information on the calculation of ET adjustment factors for gravity and sprinkler irrigation. Sprinkler irrigation generally consumes approximately 5% more water than furrow irrigation (see ESPAM1.1 Design Document DDW-021).

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[4] i.e. the specific irrigation entity has different crop mix than the county it lies within, or than the nearest-neighbor ET_{Idaho} data point.

METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration) was developed by the U of I to compute and map ET. METRIC is a satellite-based energy balance model for computing ET as a residual of the energy balance at the earth's surface, where ET is calculated by deducting sensible heat flux conducted into the ground and sensible heat flux convected into the air from net radiation. . METRIC computes actual ET, without requiring determination of crop type, and it computes evaporation from bare soil. For a full growing season, METRIC ET is about 90-95% accurate compared to ET measured with a precision weighing lysimeter (Allen et al., 2007a).

METRIC is a modification and refinement of the Surface Energy Balance Algorithm for Land (Bastiaanssen et al., 1998). METRIC uses AgriMet weather data to internally calibrate the ET computation. Seasonal and monthly ET images are computed by processing Landsat images throughout a year and using AgriMet data to interpolate between image dates. AgriMet is the US Bureau of Reclamation's network of over 70 weather stations in the Northwest (Agrimet, 2012).

IDWR uses Landsat images to compute and map ET because Landsat is the only operational satellite with a thermal sensor that can map ET at the field level (Allen et al., 2007b). Other strengths of Landsat are its 16-day repetitive coverage and large archive of images that are available at no-cost. Monthly and seasonal METRIC ET data are being developed for all years having sufficient cloud-free Landsat imagery from the mid 1980s to the present.

V. B1. d(3). Method of Irrigation Application

On the eastern Snake Plain, sprinkler and flood or gravity irrigation are used to apply water for crops. An analysis was done to determine the fraction of area within each entity that was irrigated by sprinkler throughout the simulation period. The resulting sprinkler fractions allow application of ET adjustment factors for deviations from predicted ET within irrigation entities.

Two sources of data were available for determining the historic method of application. The first source was GIS maps that delineate irrigated lands as sprinkler or gravity irrigated in 1982 and

1992 (IDWR 1982, 1997b). These maps represent the most reliable data with the best spatial resolution and served as the primary source of data. The second source was the Natural Resource Conservation Service (NRCS) National Resource Inventory (NRI) reports published in 1987 and 1997. The NRI reports identify the percentage of irrigated area using pressurized systems within an 8-digit Hydrologic Unit Code or by Major Land Resource Area (MLRA) (NRCS, 1997) for the years 1980, 1987, 1997, and 2000. The NRCS also classifies drip irrigation as a pressurized system, but this is a minor practice within the ESPAM2.1 simulation period and was neglected.

Sprinkler percentage data from the IDWR GIS maps and the NRI reports were combined and intersected with maps of irrigated entities and groundwater polygons (discussed in section V. B2. a.). Table 9 lists sprinkler fractions by entity and polygon for 1980, 1982, 1987, 1992, 1997, 2000, and 2008. Data for intermediate years are interpolated as described in ESPAM2 Design Document DDW-V2-12. The sprinkler fraction used in model calibration are presented by irrigation entity and stress period in Appendix A, Table A-4.

Figure 28 shows the sprinkler fraction by surface water entity in 1980, at the beginning of the model simulation period, and in 2008, at the end of the period. Many gravity systems were converted to sprinkler systems during the simulation period, but gravity irrigation is still practiced in some areas.

V. B1. e. Precipitation

Precipitation for the model period is 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 datasets to generate gridded estimates of several spatial and temporal climatic parameters, including precipitation. For calibration of ESPAM2.1, Geographic Information System (GIS) processing was used to assign the average value of PRISM data pixels (approximately 4 km spacing) to model grid cells. Figure 29 shows two PRISM precipitation maps from the 28.5-year model period, one during the non-irrigation season (January 2008) and the other during the irrigation season (July 2008). For more detailed information on the estimation of precipitation and data processing, the reader is referred to ESPAM1.1 Design Document DDW-011 and ESPAM2 Design Document DDW-V2-10.

V. B1. f. Irrigation Return Flows

Some water diverted for irrigation returns to the Snake River in surface channels. In the MKMOD program, these irrigation return flows are called runoff and are represented as the portion of water delivered to farm headgates that is not consumed by ET and does not percolate into the ESPA (Equation 10).

$$Runoff = (1 - OFE) \times Dh \times (1\text{-}DPin) + Max\,(Peff + OFE \times Dh - ET \times A - Max(\Delta SM,0),\ 0) \times (1\text{-}DPex)$$

(Equation 10)

where:

Runoff = Return flow to Snake River (ft/month)

Peff = effective precipitation (ft/month)

OFE = maximum On-Farm efficiency (unitless)

Dh = farm headgate delivery (ft/month)

A = ET adjustment factor (unitless)

ΔSM = change in soil moisture (ft/month)

Dpin = portion of initial loss to deep percolation (unitless)

Dpex = portion of excess delivery to deep percolation (unitless)

Irrigation return flows calculated by MKMOD were calibrated to measured values where available. Prior to the development of ESPAM1.1, the importance of measuring return flows was recognized, and most of the earliest data were collected by the USGS. Between 2000 and 2005, Idaho Power performed an aerial reconnaissance of the Snake River and the Henry Fork and identified 46 potential return flow monitoring sites. Idaho Power began monitoring 44 sites in 2004 under a contract with IDWR.

In late-2004, a Memorandum of Agreement was signed with IDWR, and the USBR initiated monitoring 15 of the 44 sites. At the same time and as a result of an informal agreement, the Northside Canal Company (NSCC) began monitoring 8 of the 44 sites in their service area and sharing the data with IDWR. Also in 2004, the USDA Kimberly Agricultural Research Station began monitoring 7 of the 44 return flows to the Snake River from the Twin Falls Canal Company (TFCC) service area. TFCC has shared the data with IDWR. Finally, 7 of the initial 44 return flow measurement sites were discontinued because of low flows, access was restricted at 2 sites, and Idaho Power continued to measure 5 sites.

Return flow sites measured during the ESPAM2.1 simulation period are shown in Figure 30. Return-flow measurements are aggregated to compile calibration targets for irrigation entities, and are used to calculate Snake River reach gains. The sites were assigned to irrigation entities, and the name, river reach, and entity are listed in Table 10. Further detail on the return flow sites is provided in ESPAM2 Design Document DDW-V2-15. Table A-5 (Appendix A) lists the measured return-flow volume for each irrigation entity for each model stress period.

V. B1. g. Incidental recharge on surface water irrigated lands

Incidental recharge on surface water irrigated lands within each entity is calculated from diversions, canal seepage rates, evapotranspiration, precipitation, and infiltration and runoff rates. Canal seepage is deducted from diversions to calculate farm headgate delivery volumes within each surface water irrigation entity. The fate of water delivered to farm headgates is calculated using the On-Farm algorithm, which is described in detail in Appendix B.

Water delivered to farm headgates may be consumed by evapotranspiration, be discharged as surface runoff returning to the Snake River, percolate into the ESPA, or be stored temporarily in the soil moisture reservoir for later consumption by crops. The On-Farm algorithm (Equation 11) calculates recharge on surface water irrigated lands as described in Appendix B.

$$Rech = (1 - OFE) \times Dh \times DPin + Max\,(Peff + OFE \times Dh - ET \times A - Max(\Delta SM, 0),\ 0) \times DPex$$

(Equation 11)

where:

Rech = deep percolation to ESPA aquifer (ft/month)

Peff = effective precipitation (ft/month)

OFE = maximum On-Farm efficiency (unitless)

Dh = farm headgate delivery (ft/month)

A = ET adjustment factor (unitless)

ΔSM = change in soil moisture (ft/month)

Dpin = portion of initial loss to deep percolation (unitless)

Dpex = portion of excess delivery to deep percolation (unitless)

Based on discussion among the ESHMC members, the maximum On-Farm efficiency was set at 0.85 for sprinkler irrigation and 0.80 for gravity irrigation. This is assumed to be the maximum efficiency that may be achieved by water users under conditions of extreme water shortage. The modeled irrigation efficiency varies with irrigation entity and model stress period, and is usually less than the maximum On-Farm efficiency. If farm headgate deliveries and available soil moisture are not sufficient to meet the crop irrigation requirement at the maximum On-Farm efficiency, the On-Farm algorithm assumes that the crop irrigation requirement is not met and that deficit irrigation occurred. The MKMOD program records the volume of deficit irrigation assumed to occur for the given irrigation entity and stress period.

Dpin and Dpex apportion the water not consumed by evapotranspiration between deep percolation to the ESPA and return flow to the Snake River. For irrigation entities that do not have surface returns to the Snake River, Dpin and Dpex are set to one. For irrigation entities that do have surface returns to the Snake River, Dpin and Dpex were adjusted during calibration to approximate available return flow data. For irrigation entities with unknown return flow volumes, Dpin and Dpex were adjusted during calibration based on other model calibration targets.

Figure 31 shows the canal seepage and net recharge in ESPAM2.1 surface water entities calculated for the simulation period. These values include a small amount of canal seepage and On-Farm recharge from irrigation systems supplied by offsite irrigation wells. Figure 31 shows that there is approximately 1.9 million acre-feet of variation in net recharge due to surface-water irrigation between the highest and lowest years of the simulation period. This reflects the natural variation in water supply and the important role that surface-water irrigation plays in recharging the ESPA. The variation in net recharge from surface-water irrigation provides part of the explanation for the storage changes described in section III.

V. B2. Net Discharge on Groundwater Irrigated Lands

Groundwater irrigated lands may be supplied by wells located on or near the irrigated field, or by offsite wells located several miles from the irrigated field. In ESPAM2.1, most groundwater irrigated land is assumed to be supplied by wells located on or near the irrigated field, and the groundwater extraction is assumed to occur within the same model cell as the irrigated field. Offsite well have been identified in a few areas within the model boundary. These wells are referred to as offsite wells when water is pumped directly to a canal without being included in water district diversion volumes, and as exchange wells when water is delivered to a river or lake for re-diversion to a canal. Re-diversions of exchange well water are included in water district diversion volumes. In ESPAM2.1, groundwater extraction from an offsite or exchange well is represented in the model cell that contains the irrigation well, conveyance losses are represented in model cells that contain the associated canal, and incidental recharge resulting from irrigation inefficiency is represented in the cell that contains the irrigated field.

Although irrigation entities IESW001 (A & B Irrigation District) and IESW018 (Falls Irrigation District) pump groundwater into canals for conveyance to places of use, their wells and canals are distributed approximately uniformly across the irrigated service area. In ESPAM2.1, these irrigation districts are modeled as lands irrigated by onsite groundwater, because there is not a need to spatially separate the extraction and recharge associated with irrigation.

V. B2. a. Delineation of Groundwater Irrigation Polygons

Groundwater irrigated lands were aggregated into entities defined as "groundwater polygons," to avoid any organizational or jurisdictional connotation. The delineation of groundwater polygons is not based on groundwater management areas or measurement districts. Groundwater polygons were delineated to adequately represent differences between geographical areas, the depth to water beneath land surface, and management practices. Withdrawals associated with groundwater irrigation are calculated based on adjusted ET and precipitation. Like the surface water irrigation entities, the groundwater entities each have a unique ET adjustment factor and percentage of sprinkler irrigation.

Groundwater depth was the basis for delineation of most of the polygons, which are not necessarily contiguous. Figure 32 shows the depth to water in 1980 mapped by Lindholm and others (1988). Figure 33 shows depth to water mapped based spring 2008 synoptic water levels. Because water level changes since 1980 are minor relative to the range of depths on the plain, the aggregation of groundwater polygons performed for ESPAM1.1 based on the 1980 depth to water map was considered adequate for ESPAM2.1.

The Mud Lake area (IEGW506) and the U.S. Bureau of Reclamation project known as the “A & B Irrigation District” (IEGW501) were delineated as separate groundwater polygons based on unique percentages of sprinkler irrigation. These projects were the first large-scale groundwater resource development efforts on the plain (Goodell, 1988). Initially, nearly all croplands in these areas were gravity irrigated because sprinklers were not widely used at the time. Field observations show that at the beginning of the calibration period the Mud Lake area still had a large proportion of gravity-irrigated cropland relative to other groundwater irrigated areas. This is also true of the A & B Irrigation District (Temple, 2002).

Figure 34 shows nine of the ten groundwater polygons delineated on the eastern Snake Plain. One other polygon (IEGW600) is not shown on Figure 34, because it encompasses the remainder of the plain, which is nearly absent of irrigation. The ESPAM1.1 and ESPAM2.1 groundwater polygons are essentially the same. Figure 35 shows the sprinkler fraction by groundwater polygon for 1980 and 2008.

V. B2. b. Net Recharge on Lands Irrigated from Onsite Groundwater

In ESPAM2.1, most groundwater irrigated land is assumed to be supplied by wells located on or near the irrigated field, and the groundwater extraction is assumed to occur within the same model cell as the irrigated field. Net recharge on lands irrigated from onsite groundwater is calculated using the groundwater entity algorithm in the MKMOD program, as described in Equation 12 and Appendix B.

$$Rech = Peff - ET \times A \qquad \text{(Equation 12)}$$

where:

Rech = net recharge to ESPA aquifer, negative values represent extraction

Peff = effective precipitation

A = ET adjustment factor

An ET adjustment factor is calculated and applied to the estimated ET based on the groundwater polygon and method of application, as described in section V. B1. d(2). During most stress periods, net recharge is negative, representing net extraction from irrigation wells. During winter months, precipitation may exceed evapotranspiration, resulting in small volumes of positive net recharge in some stress periods. MKMOD assumes that groundwater pumping will fully supply the crop irrigation requirement, and no deficit irrigation will occur on lands irrigated from onsite wells.

Figure 36 shows the net extraction due to groundwater irrigation from onsite wells. Net extraction is equivalent to the crop irrigation requirement attributed to groundwater polygons. This value includes a relatively small volume of crop irrigation requirement on mixed source lands that may have been served by surface water during part of the simulation period. An equal and off-setting amount of On-Farm recharge is applied to these lands through overlapping surface-water entities, maintaining the appropriate amount of net recharge in the model.

As can be seen in Figure 36, an average of 2.2 million acre-feet annually was consumed on approximately 1.1 million acres of groundwater irrigated land during the simulation period. There is approximately 1.1 million acre-feet in variation in consumptive use between the highest and lowest years of the simulation period. This may reflect natural variation in evapotranspiration requirements and precipitation, as well as anthropogenic variation in evapotranspiration requirements resulting from changes in crop mix or irrigation practices. The annual ET and precipitation volumes (Figure 26) vary 0.9 million acre-feet and 1.7 million acre-feet, respectively, between the highest and lowest years.

V. B2. c. Net Recharge on Lands Irrigated from Offsite Groundwater

Where groundwater is pumped from offsite wells or exchange wells the lands are classified as surface-water irrigation entities, and canal seepage and incidental recharge are calculated as described in section V. B1. For offsite wells, the pumping volume is added to the entity diversions. For exchange wells, the pumping volume is already included in diversions recorded by the water district. MKMOD deducts the groundwater extraction from the model cell in which the offsite or exchange well is located (Figures 37, 38, and 39), and apportions the water to canal seepage, ET, On-Farm recharge, and return flow in model cells associated with the canal and irrigated land.

V. B2. c(1). Exchange Wells Represented in Fixed Point Data

Nineteen exchange wells, which pump water into the Teton or Snake River are represented in the ESPAM2.1 water budget (Figure 37). The locations were obtained from GPS data or public land survey legal descriptions supplied by Water District 01 (Madsen, 2000; Olenichak, 2003). Diversions from these exchange wells were obtained from the Water District 01 annual reports (Water District 01, 2003). Re-diversions of this water from the river are included in the diversion data obtained from the IDWR Reach Gain/Loss program.

The ESPAM2.1 water budget also represents six groups of exchange wells that deliver water into Mud Lake in Jefferson County for re-diversion to irrigation entity IESW029 (Figure 38). The points represent groups of exchange wells, and are based on IDWR GPS data (IDWR, 1999), aerial photography, and input from the Watermaster. The volume of water pumped from these wells is obtained from Water District 31 records. Re-diversion of this water from Mud Lake is also reported by Water District 31. Table 11 shows the apportionment of Mud Lake pumping to individual points.

Figures 40a through 40d show the exchange well pumping over the simulation period. Table 12 lists the discharge attributed to the Teton/Snake River and Mud Lake exchange wells during each model stress period. Table A-6 lists the model cells where exchange well pumping is represented. Further information on exchange wells is provided in ESPAM1.1 Design Document DDW-025 and ESPAM2 Design Document DDW-V2-08.

V. B2. c(2). Offsite Irrigation Wells

The offsite pumping dataset represents offsite irrigation wells for which diversion volumes are not included in water district records. Nine irrigation wells are represented in this dataset (Figure 39), including wells north of Mud Lake in Jefferson County that supply water to entity IESW044, and one well northwest of Rexburg supplies water to IESW016.

The IESW044 pumping estimates are calculated from crop irrigation requirement, anticipated canal seepage losses, and anticipated irrigation efficiency. The IESW016 well is supplemental to a large surface-water system, and discharges into the canal downstream of the Watermaster's point of measurement. The groundwater diversions are represented by applying pumping at the rate defined in the water right held by the Freemont Madison Irrigation District to the few stress periods in the record where surface-water diversion volumes are markedly below the typical value for the particular month.

The estimated volume from offsite pumping is extracted from the cells where the wells are located (See Figure A-9) and added to the corresponding surface water entity diversions as a contribution towards incidental recharge. Because offsite pumping is calculated from crop irrigation requirement and estimated losses, it may be overestimated. An overestimate of pumping causes an over-representation of groundwater depletions, but is offset by an over-representation of incidental recharge in the corresponding surface water entity.

Figure 41 shows the total offsite pumping over the simulation period. Table 13 lists the represented pumping in each model stress period for the offsite wells. Table A-7 lists the cells representing offsite pumping.

V. B3. Underflow from Tributary Basins

Tributary underflow represents the subsurface discharge of water from a tributary basin into the ESPA. Because tributary underflow is subsurface flow, it is difficult to estimate. Underflow from 24 tributary basins is a source of recharge to the ESPA and is represented as a specified flux occurring at the individual model cells highlighted in red on Figure 42. A list of the tributary basins and estimated underflow volumes are presented in Table 14. The estimated flux for each tributary is evenly distributed across the model cells assigned to that tributary in each stress period. Table A-8 (Appendix A) contains a list of the model cells associated with each tributary.

The volume of underflow from tributary basins varies seasonally and from year to year, but is difficult to estimate. The development of annual volumes of tributary underflow from each basin for ESPAM2.1 was based on ESPAM1.1 adjustments to average annual estimates published in

Garabedian (1992). In addition, the recent development of the average annual flux from the Portneuf River basin by the Idaho Geological Survey (Welhan, 2006) and IDWR (McVay, 2009) was utilized for ESPAM2.1. These average annual flows were scaled to developed year to year flow estimates for each tributary basin.

In order to scale the year to year discharge for each basin, annual discharges at Silver Creek (Table 15) were used as a proxy. Silver Creek was selected because a) it is almost entirely spring-fed and flows over bedrock, b) there are long-term gage data available, and c) Silver Creek flows reflect the discharge of many other eastern Snake Plain tributary basins from the standpoint of land use, precipitation, and elevation. The first step was to normalize Silver Creek flows by dividing them by the average annual flow of the model period (1980 – 2008). Table 15 shows the flux ratios that were developed for each year. The resulting normalized flux was adjusted to reduce year-to-year variation. This dampening was based on the premise that the elevation of the springs feeding Silver Creek are at the top of the aquifer, and therefore, are more sensitive to seasonal changes in elevation than bulk aquifer flow. The flux ratios were dampened by 2/3 to decrease the amplitude of the annual variation (Table 15). The average annual tributary underflow for each basin from Garabedian (1992) was then multiplied by the Silver Creek dampened, normalized flux ratio for each year.

While it is acknowledged that there are variations in seasonal flow, the lack of information about the basin-to-basin differences in the timing of peak flows dictated shaping underflow for the 24 tributary basins on an annual basis. Monthly flows in Table 14 were then developed by dividing the annual flows by the number of days per year and multiplying by the number of days per month.

Figure 43 shows the total estimated underflow per stress period for 1980-2008 prior to model calibration. Figures 44a through 44f show the volume of tributary underflow per stress period (month) for each individual basin prior to calibration. ESPAM1.1 Design Document DDW-004 and ESPAM2 Design Document DDW-V2-13 describe the estimation of tributary underflow in more detail.

V. B4. Recharge on Non-Irrigated Lands

Precipitation within the ESPAM2.1 model boundary averaged approximately 6.8 million acre-feet per year between 1971 and 2000, with over 70% of this falling on non-irrigated lands. Garabedian (1992) estimated that precipitation on non-irrigated lands produces approximately 700,000 acre-feet of recharge per year. It is the component of recharge to which Garabedian assigns the most uncertainty.

For ESPAM1.1, a method for estimating recharge was developed from previous work by Rich (1951) using GIS grid maps of monthly precipitation (Daly and others, 1998) and the thickness and texture of soil types (Figure 45). Rich (1951) showed that basins which, unlike the eastern Snake Plain, have a component of surface discharge that can be used to describe total basin yield. This component is simplified here to represent recharge, since runoff that does occur on the eastern Snake Plain collects in depressions where it also recharges the aquifer.

The equation is:

$$Recharge = K * (Precipitation)^N \qquad \text{(Equation 13)}$$

where:

K is an empirical slope parameter, and

N is an empirical exponent that introduces curvature into the relationship.

Rich (1951) applied this formula to annual precipitation assuming that with less precipitation, most is intercepted by various mechanisms (leaf interception, depression storage, soil moisture storage, evaporation, etc.) and that with increasing precipitation, more 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. ESPAM1.1 Design Document DDW-003 contains a detailed explanation of the estimation of recharge on non-irrigated lands.

The ESPAM1.1 method of estimating recharge on non-irrigated lands was retained for ESPAM2.1, although efforts are ongoing to develop an alternate calculation for future model versions. Estimates of recharge were performed for three soil classifications based largely on soil thickness using Equation 13. In ESPAM2.1, winter recharge was assigned to one-month stress periods by assuming that ¾ of the precipitation falling in December and January is not available for recharge until snowmelt in February. In December and January, non-irrigated recharge is calculated using ¼ of the recorded precipitation. The February non-irrigation recharge is calculated using ¾ of the precipitation recorded in December and January plus the precipitation recorded in February.

Recharge depths from Equation 13 were multiplied by the non-irrigated land in each cell within MKMOD. Figure 46 illustrates the areal distribution of non-irrigated recharge averaged annually for the 28.5-year simulation period, prior to model calibration. Figures 47a through 47d display the non-irrigated recharge per stress period (month) for 1980 through2008, prior to model calibration.

V. B5. Water and Wetlands

Net recharge (wintertime) and discharge (summertime) from wetlands and open water are represented in the fixed point dataset. Negative values are applied directly as an extraction from the model cell that contains the point representing the wetland, and positive values are applied as a direct injection.

The net flux from wetlands is calculated as the difference between precipitation and evapotranspiration. Most wetlands recharge the aquifer between late fall and early spring when evaporative demand is relatively low and discharge from the aquifer between late spring and early fall. Precipitation data were obtained from PRISM and ET values were obtained from ET_{Idaho} (Allen and Robison, 2007, 2009). ET_{Idaho} provides different ET rates for “wetlands – large stands” and “wetlands – narrow stands”. In ESPAM2.1 wetlands are classified as narrow or wide. The ET_{Idaho} rate for “narrow stands” is applied to narrow wetlands and the ET_{Idaho} rate for “large stands” is applied to wide wetlands. The unit discharge rate (precipitation less ET) is multiplied by the wetland area to obtain a volumetric rate. Figure 48 shows the points where wetlands recharge and/or discharge occurs. Figure 49 is a time series of the wetlands recharge/discharge over the model calibration period, showing a net loss to the ESPA resulting from wetlands ET.

Table A-6 lists the model cells where wetlands are represented. Table 12 lists the total volume of aquifer recharge or discharge attributed to wetlands for each stress period. Further information of estimation of wetlands ET is provided in ESPAM2 Design Document DDW-V2-08.

V. B6. Urban Pumping

Net groundwater extraction for cities and industrial areas is represented in the fixed point dataset. Negative values are applied directly as an extraction from the model cells that contain the points representing the municipal or industrial wells.

Net discharge for cities and industrial areas is presumed to be 1.2 feet/year (Goodell, 1988). The depths are assigned to the same geographic areas used in ESPAM1.1, as described in Contor (2002). Figure 50 shows the points where urban extraction occurs. Figure 51 shows the time series of the urban extraction over the model calibration period. Table A-6 lists the model cells where municipal or industrial pumping is represented. Table 12 lists the total volume of pumping attributed to municipal or industrial wells for each stress period.

V. B7. Non-Snake River Seepage

Surface water seepage from non-Snake River sources recharges the ESPA at the 14 locations shown on Figures 52a, b, and c. The sources of seepage include rivers, creeks, lakes, flood control sites, part of the Twin Falls Canal, and a wildlife refuge. These sources are modeled as hydraulically disconnected from the aquifer, and the seepage rate is independent of aquifer head. Table A-9 (Appendix A) lists the seepage sources and associated model cells. Table 16 lists the seepage sources and the estimated annual seepage. The estimated flux for each source is evenly distributed across the model cells assigned to that source per model stress period.

Seepage from sources other than the Snake River is estimated from a water balance using gage and diversion data. The estimated seepage is distributed evenly among the model cells associated with each perched source. Figure 52 shows the locations of perched seepage sources, and Table 16 lists the average seepage rate for each source. Figure 53 shows the total volume of seepage per stress period during the model calibration period, and Figures 54a through 54d show the seepage from the individual sources for each stress period. Finally, Table A-9 lists the model cells associated with each of the seepage sources.

V. B7. a. Estimating Seepage for Non-Snake River Sources

The following sections summarize how the seepage for each non-Snake River source was estimated. In general, seepage calculations were based on gage data. If gage data were not available at one source (e.g., river, stream), another gage with similar characteristics in terms of location and flow was chosen as a proxy. Linear regressions were developed between the proxy and the site of interest to develop the missing data . While it is difficult to find a gage with a full period of record and similar characteristics, the process of using linear regressions was found to be an appropriate way to estimate flow at a gage. For a complete description of the process, refer to ESPAM2 Design Document DDW-V2-03.

V. B7. a(1). Medicine Lodge Creek

Medicine Lodge Creek flows south from uplands along the Idaho-Montana border, between the Birch Creek and Beaver Creek drainages (Figure42), and enters the eastern Snake Plain north of the Mud Lake area (see Figure 52c). Medicine Lodge Creek discharge is measured at a gage near

Small (USGS 13116500), which is located a short distance outside the model boundary. Water is diverted for irrigation both upstream and downstream of the gage, and these diversions are recorded by Water District 32C. Based on GIS analysis, approximately 45% of Water District 32C irrigated lands are within the ESPAM2.1 model boundary and downstream of the gage.

Medicine Lodge Creek seeps into the ESPA south of the irrigated lands, and seepage volumes were calculated by subtracting 45% of the total Water District 32C diversions (Watermaster reported) from the of Medicine Lodge Creek flows measured at the gage near Small. Data collection at this gage began to function during the summer of 1985, and records were not kept prior to that date. Flow data from the Little Lost River below Wet Creek near Howe, Idaho gage (USGS 13118700) were compared to the Medicine Lodge Creek near Small gage records (post-1985) using a linear regression. This produced a good correlation and supports using the regression to extrapolate estimates of pre-1985 flows, which then can be applied to calculate seepage for those years.

<u>V. B7. a(2). Birch Creek and Birch Creek Hydropower Plant</u>. Birch Creek flows south (Figure 3) and is located between the Little Lost River and Medicine Lodge Creek drainages (Figures 42 and 52c). Anthropogenic changes in water distribution in 1987 significantly changed the distribution of seepage in the Birch Creek basin. Prior to July 1987, seepage is modeled at the location labeled Birch Creek in Figure 52C. Beginning in July 1987, seepage is modeled at the location labeled Birch Creek Hydropower in Figure 52C.

Prior to July 1987, flows were measured at the USGS gage station at Birch Creek at Eight-mile Canyon Road near Reno (USGS 13117030), above the Reno Ranch (IESW037) diversion. During the summer, water was diverted to the Reno Ranch through an unlined ditch. Any undiverted water (including winter streamflow) continued to flow south and seeped into the ESPA. Seepage estimates are derived by subtracting Watermaster reported diversions to the Reno Ranch from the Eight-mile Canyon Road gage flows. Missing data from the pre-1987 gage measurement dataset were estimated using a linear regression with the discharge measured at the Silver Creek gage near Picabo (USGS 13150430).

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 now delivered to the plant through a lined canal and pipe system. Outflow from the plant is used for irrigation at the Reno Ranch (IESW037) or delivered to a channel where it infiltrates into the subsurface. Discharge records obtained from the Birch Creek hydroelectric plant are used in calculating seepage (Sorenson Engineering, 2008) in combination with Watermaster reported diversions.

V. B7. a(3). Camas Creek

Camas Creek flows south from uplands along the Idaho-Montana border (Figure 3). Inside the ESPAM2.1 boundary, Camas Creek flows southwest towards Mud Lake (Figure 52c). Seepage into the ESPA was estimated by differencing flows measured at the Camas Creek at Red Road near Kilgore gage (USGS 13108900), which is near the model boundary, and flows measured at the Camas Creek at Camas gage (USGS 13112000), and accounting for diversions in this reach. Diversions were obtained from Water District 31 records. Seepage which occurs downstream of the Camas gage is included in the Mud Lake seepage (section V. B7. a(4)).

The Red Road gage is missing several years of data during the model calibration period; therefore, the Little Wood River gage above High Five Creek near Carey (USGS 13147900) was used to develop a regression and estimate flows. The Camas Creek at Camas gage is also missing data during the calibration period. Instead of performing a linear regression, monthly average values were used to replace the missing data.

V. B7. a(4). Camas National Wildlife Refuge and Mud Lake

Surface-water deliveries to the Camas National Wildlife Refuge are recorded by the Watermaster. These volumes are applied as recharge to the model cells in the footprint of the refuge (Figure 52c).

Mud Lake seepage is derived from the estimated difference between the inflows and outflows of Mud Lake. The inflows include Camas Creek at Camas gage measurements (USGS 13112000) and exchange well pumping. The outflows include diversions to IESW029, diversions to the Camas National Wildlife Refuge, diversions to the Basin 31 flood control area (Figure 52c), and seepage from Mud Lake. Storage in the lake is calculated from stage measurements made on the first day of each month at the gage located at Mud Lake near Terreton (USGS 13115000).

Precipitation and evapotranspiration from Mud Lake and the Camas National Wildlife Refuge wetlands are represented in the non-irrigated recharge and wetlands datasets, thus they are not included in the calculation of the seepage. Mud Lake seepage calculations are described by Contor (2009) and Sukow (2012).

V. B7. a(5). Lone Tree Flood Control

Diversions from Camas Creek into the Lone Tree flood control area have only occurred during a few months in the model calibration period. Diversion data were acquired from gage on Camas Creek above Lone Tree near Dubois (USGS 13109600), and calculated volumes were applied at the location shown in Figure 52c.

V. B7. a(6). Basin 31 Flood Control

In high water years, water is pumped from Mud Lake and delivered to the Basin 31 flood control area south of the farm lands. The volume of water delivered to the flood control area is obtained from Water District 31 records and applied as seepage at the location shown in Figure 52c. .

V. B7. a(7). Little Lost River and Little Lost River Flood Control

The Little Lost River flows southeast in the basin between the Big Lost River and Birch Creek drainages (Figures 3 and 42). Because the Little Lost River infiltrates into the ESPA a short distance beyond the irrigated lands, seepage is calculated as the difference between the flow in the Little Lost River near Howe gage (USGS 13119000), which is very near the model boundary, and the diversions from IESW008 and IESW053 (Figure 24). The seepage is applied to the location shown on Figure 52c.

Data from the Little Lost near Howe gage are not available for several years in the 1980s, and the gage was decommissioned in 1991. A linear regression based on flow at the Little Lost River below Wet Creek gage (USGS 13118700) was used to estimate the missing flow data. Monthly diversions from IESW008 and IESW053 were subtracted from actual or estimated flow data to calculate monthly seepage volumes.

In 1985, a flood-control spreading area was developed upstream of the Little Lost River diversions. During winter months, water is diverted into the spreading area to prevent icing and local flooding. For 1985 and later, the spreading area is modeled as a source of recharge during winter months. Prior to 1985, the channel of the Little Lost River below the gage is modeled as a source of recharge during winter. The river channel is always modeled as a source of seepage during the summer.

V. B7. a(8). Big Lost River

The Big Lost River basin is located between the Little Lost River and Little Wood River basins (Figures 42 and 52). The Big Lost River enters the model boundary at the Big Lost River below Mackay Reservoir near Mackay gage (USGS 13127000) and flows southeast through the Big Lost River valley, where irrigated lands are relatively close to the river (Figures 23 and 52c). The Big Lost River near Arco gage (USGS 13132500) is located downstream of the irrigated lands. Between the Mackay and Arco gages, there is significant inflow from Antelope Creek and significant seepage loss from the Big Lost River channel. In dry years, there is little or no streamflow at the Arco gage. In wetter years, water discharging past the Arco gage flows south and east into the desert, where it seeps into the ESPA. Seepage from the Big Lost River is calculated for four river reaches (Figure 52c) and a flood control site.

For the Big Lost River reach between the near Mackay and near Arco gages, the seepage is calculated using the gage data, estimated Antelope Creek inflows, and recorded or estimated diversions (section V. B1. b.). The gage data for the near Mackay and near Arco gages are complete for the entire model calibration period.

Three gages below Arco and records of diversions to a flood-control spreading ground at the Idaho National Laboratory are used to spatially distribute any water discharging past the Big Lost near Arco gage to the spreading ground and lower reaches of the river.

V. B7. a(9). Big Wood River and Little Wood River

Seepage from the Little Wood River between Carey and Richfield was estimated by differencing the flow at the Little Wood near Carey gage (USGS 13148500) and the flow at the Little Wood near Richfield gage (USGS 13151000), and adding inflows from Silver Creek gage near Picabo (USGS 13150430) and Fish Creek near Carey (USGS 13150000). Fish Creek flows were only available for months that pre-dated the model calibration period; therefore, average values were used. Since the upper gage is outside of the model boundary, the estimated seepage was reduced by 13%. Seepage was applied at the location shown in Figure 52b.

Seepage between the Little Wood River near Richfield gage (USGS 13151000) and the confluence with the Big Wood River, and seepage between the Big Wood River below Magic Reservoir gage (USGS 13142500) and the confluence with the Little Wood River, was calculated using gage, diversion, and return flow data, with the assistance of the Water District 37 Watermaster (Lakey, 2009). During the irrigation season, the losses are partitioned between diversions and seepage, with the seepage portion estimated based on losses in the winter months. Seepage from these reaches is applied at the location shown in Figure 52b.

V. B7. a(10). Twin Falls Canal and Lake Murtaugh

Nearly all of the Twin Falls Canal Company (TFCC) irrigated lands lie outside the model boundary, but seepage from the Milner-Picketts canal and Murtaugh Lake (Figure 52b) contributes significant recharge to the ESPA. Seepage is calculated based upon data supplied by TFCC (circa 1955) and applied to the locations shown in Figure 52b.

V. B7. a(11). Malad River

The Malad River is perched between the confluence of the Big Wood and Little Wood Rivers (Figure 52b) and the Malad River near Gooding gage (USGS 13152500), a distance of approximately five miles. Seepage in this reach was estimated by calculating the average seepage rate per mile on the Little Wood River between Shoshone and Gooding, and applying this rate to the Malad River reach. Flow from the Milner-Gooding canal into the Little Wood River, calculated from Water District 37 records, was added to the estimated seepage to maintain a mass balance with surface water entities IESW058 and IESW059 (section V. B1. b.).

V. B7. a(12). Beaver Creek

Seepage from Beaver Creek was calculated for two stream reaches (Figure 52c). The first reach is between the Beaver Creek at Spencer gage (USGS 13113000) and the Beaver Creek at Dubois gage (USGS 13113500). Both gage sites are missing data for some years in the model simulation period. A linear regression with flows recorded at the Little Wood River above High Five Creek near Carey gage (USGS 13147900) was used to estimate the missing data for both gage sites. Seepage in this reach was calculated using the gage data and agricultural diversions recorded by Water District 31 (Murdock, 2009).

The second reach is between the Dubois gage and the Beaver Creek near Camas gage (USGS 13114000). Data from the Beaver Creek near Camas gage are not available during model simulation period, but are available from before 1980. The pre-1980 data were used to estimate flows during the model simulation period by performing a linear regression with flows measured at the Little Wood River above High Five Creek near Carey gage (USGS 1314790). Seepage in this reach was calculated using the measured and estimated gage data and agricultural diversions recorded by Water District 31 (Murdock, 2009).

V. C. TRANSIENT MODEL WATER BUDGET

All of the water budget components discussed were estimated for each of the 342 transient model stress periods and processed using the MKMOD program (Appendix B). The output is a MODFLOW-formatted well file which comprises a separate cell-by-cell array of the net recharge to be applied as a specified flux in each stress period. The stress represented in the well file is described by Equation 14. For a given cell, many of the components may be equal to zero.

$$Stress = NIR - GWCIR + CS + SWIR + TRB + PCH - WET - OP - EP - MLP - UP \qquad \text{(Equation 14)}$$

where:

NIR = non-irrigated recharge (ft^3/month)

GWCIR = crop irrigation requirement attributed to groundwater polygons (ft^3/month)

CS = canal seepage (ft^3/month)

SWIR = incidental recharge in surface water entities (includes recharge of water delivered from offsite and exchange wells) (ft^3/month)

TRB = tributary underflow (ft^3/month)

PCH = perched river seepage (ft^3/month)

WET = evapotranspiration from wetlands (ft^3/month)

OP = extraction from offsite wells (ft^3/month)

EP = extraction from exchange wells (excluding Mud Lake wells) (ft^3/month)

MLP = extraction from Mud Lake exchange wells (ft^3/month)

UP = extraction from municipal and industrial wells (ft^3/month)

Figure 55 shows the average annual model water budget components estimated for ESPAM2.1 before (pre-PEST) and after (post-PEST) model calibration. A parameter estimation code, PEST version 12.0 (Doherty, 2004), was used to assist with model calibration and will be discussed later in this report. The model water budget includes some applied surface water and precipitation that fulfill a portion of the evapotranspiration on irrigated lands directly and are not part of the aquifer water budget (Figure 8).

Figure 56 shows a graph of the annual net recharge for the 28.5-year period, along with total precipitation for the eastern Snake Plain. There are several features to note in Figure 56. The amount of net aquifer recharge is highly correlated to precipitation in three ways: (1) precipitation is a source of runoff for surface water diversion, (2) precipitation during the summer reduces the requirement for groundwater pumping, and (3) precipitation contributes to the ESPA via recharge on non-irrigated lands. Additionally, in a high precipitation year, more carryover may be left in the reservoirs for use in the following season, helping to sustain the supply of water available for irrigation and aquifer recharge. A series of wet or dry years would be expected to have a cumulative effect, which would appear as marked changes in aquifer storage over multi-year periods.

Figures 57 and 58 show the spatial distribution of average annual net recharge (pre- and post-PEST, respectively) for the 1981 through 2008 water years. PEST adjustments are discussed in the Model Calibration section of this report. Figures 57 and 58 illustrate the significant influence of irrigated agriculture on net aquifer recharge. On an annual average, there is negative net recharge in groundwater irrigated areas and positive net recharge in surface-water irrigated areas (Figure 23). In non-irrigated areas, there is generally positive net recharge in areas with thin soils and lava rock, and little net recharge where there are thick soils (Figure 45).

VI. MODEL CALIBRATION

The goal of model calibration is to adjust model parameters (transmissivity, aquifer storage, riverbed conductance, drain conductance, and general head boundary conductance) and, in this instance, certain components of the water budget (non-irrigated recharge, incidental recharge on surface-water irrigated lands, ET, surface-water seepage from perched sources, tributary valley underflow and canal seepage) until model generated aquifer water levels and discharges match observed values. Adjustment of parameters and water budget components was constrained to reasonable ranges of values determined through discussion with the ESHMC.

This section describes the parameter estimation tool that was used to calibrate ESPAM2.1, discusses the calibration procedure, describes the calibration targets, compares model-generated output to field measurements, and presents the calibrated input parameters.

VI. A. PARAMETER ESTIMATION TOOLS

PEST version 12.0, a nonlinear, least-squares inverse modeling program developed by Doherty (2004) was used to calibrate the ESPAM2.1. During calibration, PEST runs MKMOD and then MODFLOW thousands of times, comparing model-generated values with field observations. The calibration is optimized by minimizing the weighted, sum of the squared residuals for the difference between model-generated values and field observations (phi). PEST is available for download at *www.pesthomepage.org/*. MKMOD (Appendix B) is available for download at *http://www.idwr.idaho.gov/Browse/WaterInfo/ESPAM/model_files/Version_2.1_Current/MKMOD/.* MODFLOW is available for download at *http://water.usgs.gov/software/lists/groundwater/*.

A key to success when 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 aquifer storage. 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 version 12.0 allows the 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. Doherty (2003) provides a more rigorous description of pilot points and how the process works. During ESPAM2.1 calibration, transmissivity was estimated at 201 pilot points and interpolated across the model domain, which comprises 11,236 active model cells. Similarly, aquifer storage, which has a much lower range of variation than transmissivity, was estimated at 28 pilot points and interpolated across the model grid. Kriging was used to interpolate transmissivity and aquifer storage between pilot points during calibration of ESPAM2.1.

During calibration of ESPAM2.1, PEST was also used to calibrate values of riverbed conductance, drain conductance, general head boundary conductance, and selected water budget components as described in section VI. B. During each calibration run, PEST minimized the weighted, sum of the squared residuals for the difference between observed and model-generated aquifer water levels, river gains, spring discharges, base flow, and irrigation return flows as described in section VI. C.

VI. B. CALIBRATION PROCEDURE

Each calibration iteration consists of running MKMOD, which calculates net recharge on a cell-by-cell basis and writes those values to a text file, called a well file, for input into MODFLOW; then running MODFLOW to calculate aquifer heads, river gains/losses, and spring discharges and base flow for the Magic Valley. Starting heads for each transient MODFLOW simulation are calculated by MODFLOW during an initial steady-state stress period. The well file for the initial steady-state stress period is generated by MKMOD using average water budget data from May 1999 to April 2000. This period was selected because it generates aquifer heads that are reasonably close to water levels observed in May 1980. For ESPAM2.1, the steady-state stress period is used only to generate starting heads for the transient simulation; there are no steady-state calibration targets. Because the starting heads are only roughly approximated, the model is given a five-year warm-up period to recover from inaccuracies in the starting head field. PEST is not instructed to match any observations collected prior to May 1985.

Between each calibration iteration, PEST adjusts parameters used by MKMOD to calculate the well file values, in addition to transmissivity, storage, and conductance parameters used by MODFLOW. The ESHMC decided to allow adjustment within the bounds of uncertainty on several of the components of recharge during model calibration. Components are adjusted by a scalar uniformly applied throughout all model stress periods, with unique scalars applied to each zone or entity. The adjustable components are presented in Table 17 along with the adjustable ranges and spatial granularity for each component.

VI. C. Calibration Targets

ESPAM2.1 has been calibrated using transient water level and flux targets. Transient water level data include water level elevations and relative water level change targets. Transient flow measurement targets include river gain/loss in five reaches, spring discharge at 14 spring cells, total spring discharge to the Snake River in four reaches, discharge from the aquifer directly into the Snake River (called base flow), and irrigation return flows for 10 surface-water irrigation entities. The number of observations and duration of the transient calibration targets vary. Observations prior to May 1, 1985 were not included as calibration targets because that they occurred during the model warm-up period. Model outputs were interpolated in time and then compared with the observed values.

VI. C1. Upper Snake River Gain/Loss Calibration Targets

For the five river reaches upstream of Minidoka, the river gain/loss calibration targets were estimated using the IDWR Reach Gain/Loss Program (Idaho Water Resource Board, 1972). The program uses gaged reach inflows and outflows, measured diversions, evaporation, changes in reservoir storage, and measured and estimated irrigation returns to calculate a water balance for each of the river reaches. The residual of the water balance is the calculated river reach gain from or loss to the aquifer. The calculation of reach gain targets is discussed in more detail in ESPAM2.1 Design Document DDW-V2-15.

Figures 59 through 63 show the calculated monthly gains for the five upper Snake River reaches (Ashton-to-Rexburg, Heise-to-Shelley, Shelley-to-Near Blackfoot, Near Blackfoot-to-Neeley and Neeley-to-Minidoka). Even though the values represent monthly averages, there is still a large amount of “noise” in the data.

Most of the gages on the upper Snake River are maintained by the USGS. USGS gages are assigned a rating of “excellent,” “good,” or “fair,” with associated uncertainty bands of ± 5%, ± 10% and ± 15%, respectively. All of the gages that are used to define the five ESPAM river reaches are rated “good”. 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 measured or estimated irrigation return flows, and d) uncertainty in reservoir storage and evaporative losses.

VI. C2. Magic Valley Calibration Targets

River gains in the Snake River between Kimberly and King Hill come from two sources: above ground springs, and subsurface discharge directly into the Snake River (i.e., base flow). The above ground springs are simulated using MODFLOW Drain Cells, and base flow is simulated using MODFLOW General Head Boundary Cells (Harbaugh and others, 2000). Calibration targets between Kimberly and King Hill include monthly river gains, monthly discharge at 14 spring cells or complexes, average discharge at 36 spring cells, and average base flow to the Snake River.

VI. C2. a. Magic Valley Reach Gain CalibrationTargets

For the Kimberly-to-King Hill, Kimberly-to-Buhl, Buhl-to-Lower Salmon Falls, and Lower Salmon Falls-to-King Hill reaches, the sum of the Drain Cell and General Head Boundary Cell discharge was matched with the monthly Snake River gains (Figures 64 through 67). Groundwater discharge from the south side of the Snake River was calculated and deducted from each of the measured reach gains as described in ESPAM2.1 Design Document DDW-V2-14.

VI. C2. b. Spring Discharge Calibration Targets

Spring discharge calibration targets have been a challenge for the ESPAM project. Although the ESHMC found sufficient data to develop 14 transient targets for above ground spring complexes, many of the springs in the Magic Valley are not measured with regularity or accuracy. Some springs have complex collection and distribution systems that deliver water to various users, making the measurement and quantification of the discharge difficult. Other springs discharge from the aquifer beneath a cover of talus or alluvial material or directly to the Snake River, and direct or accurate measurements are not always possible.

The ESPAM spring calibration targets have been categorized into three groups based on the nature of the available data: Group A springs are measured by the USGS or the IDWR; Group B springs are measured and reported by water users; and Group C springs are not routinely measured or data have not been compiled and presented to the ESHMC. Table 18 lists the Group A and B springs and Figure 68 shows the locations. Table 19 lists the model cells representing the springs used as transient calibration targets, the number of monthly observations, and the date range of observations for each of the Group A and B springs.

The Group C springs are not measured routinely or the data have not been compiled, and thus do not have transient targets for calibration. Unlike the Group A and B springs, flow data for each of the Group C springs are limited to a single value reported by Covington and Weaver (1990). This value is converted to a ratio, which compares the spring discharge to the largest Group C spring in the same reach (i.e., Kimberly to Buhl, Buhl to Lower Salmon Falls, and Lower Salmon Falls to King Hill). These ratios are used during model calibration, along with reach gain, Group A and B spring discharge data, and base flow data, to apportion discharge between the Group C springs. Table 20 presents the Group C targets.

The ESPAM2.1 is calibrated to monthly flow data measured at Group A and B springs, Hydrographs showing the measured (and modeled) spring discharge data are discussed in Section VI. D4. Measured discharge data from Devils Washbowl, Devils Corral, Blue Lakes, Crystal Springs, Niagara Springs, Clear Lakes, Briggs Springs, Box Canyon Springs, Sand Springs, Thousand Springs, National Fish Hatchery, Rangen Springs, Three Springs, and Malad Springs were used to develop Group A and B calibration targets. At the request of the modeling team, Idaho Power used power generation records to estimate a portion of the discharge at Malad Springs and Thousand Springs. Because hydropower production is a function of head, water flow, and system efficiency, diversion rates can be calculated from power production records.

The model cells containing the Thousand Springs (44,12) and National Fish Hatchery (43,12) complexes each contain a portion of the Magic Springs complex (Figure 69), which presents a unique situation. The average discharge data reported for the Magic Springs complex by Sea Pac was apportioned between cells (44,12) and (43,12) based on measurements made by IDWR in 2010 and 2011. An additional complication is that two springs in the cell containing Thousand Springs (44,12) are either unused or not fully utilized, hence their total discharge is not measured. As a result, the ESHMC chose to scale up the transient data for the National Fish Hatchery and the Thousand Springs Power Plant to account for Magic Springs and the unmeasured springs. The National Fish Hatchery data are scaled up by a factor of 2.049, and the Thousand Springs Power Plant data are scaled up by a factor of 1.259. Sukow (2011) explains the apportionment of discharge and derivation of the factors.

Box Canyon Springs is another spring complex requiring compensation for ungaged discharge. Figure 70 shows a map of Box Canyon Springs with an overlay of the model drain cells. Note that the USGS gage for Box Canyon Springs is near the cell boundary separating the northeast cell from the Box Canyon cell to the southwest. The ESHMC agreed to scale up the data from the USGS gage using the ratio of the measured spring flow above the USGS gage to the total estimated spring flow in the two cells. A scaling factor of 2.0 was calculated based on discharge estimates presented in Covington and Weaver (1990). The ESHMC also reviewed miscellaneous USGS measurements, which are presented in Table 21. Scaling factors calculated based on the USGS miscellaneous measurements ranged from 1.8 to 2.2. The scaling factor of 2.0 was retained for calibration of ESPAM2.1.

VI. C2. c. Magic Valley Base Flow CalibrationTargets

The base flow targets account for water that enters the Snake River without a surface expression. These flows cannot be measured directly. Instead, the base flow targets are calculated by subtracting the average of the Group A and B springs and the sum of all the Group C springs from the gains arising from the north side of the canyon using the following equation:

$$Average\ Base\ flow = Average\ Reach\ Gain - Average\ Spring\ Discharge \qquad \text{(Equation 15)}$$

The above calculation was applied to three Magic Valley reaches: Kimberly-to-Buhl, Buhl-to-Lower Salmon Falls, and Lower Salmon Falls-to-King Hill (Figure 71). More local, site specific information has also been incorporated in the vicinity of Crystal Springs, Blue Heart Springs, and Thousand and Magic Springs (Wylie, 2012). Crystal Springs is in the Kimberly-to-Buhl reach, and Blue Heart, Thousand Springs, and Magic Springs are in the Buhl-to-Lower Salmon Falls reach. The USGS has measured the Snake River gains above and below these springs, which allowed the development of smaller, more localized base flow targets consisting of average gains for the model period. Figure 71 shows the location of Crystal Springs, Blue Heart Spring, Magic Springs, and Thousand Springs within the larger Magic Valley base flow reaches.

VI. C3. Aquifer Water Level Calibration Targets

Water-level measurements used as calibration targets include: synoptic water-level measurements collected during 1980, 2001, 2002, and 2008; and annual, semi-annual, quarterly, monthly and bimonthly water levels collected by the USGS, IDWR, and consultants. A total of 43,165 water-level measurements collected in 1,121 different wells were used in the model calibration. Data from 32 wells also were used to develop 3,027 water-level difference targets. Wells with multiple measurements each year for a long time period were selected as water-level difference targets. Water-level differences were calculated by subtracting the first measurement collected after May 1, 1985 from each of the later measurements. The water-level difference targets were used because changes in aquifer water level are a function of aquifer storage. Using water-level difference targets provides additional targets for calibration of aquifer storage that are independent of the absolute water-level elevation.

Water table elevations were calculated using surveyed or estimated wellhead elevations and the measured depth to water. For wells that have not been surveyed, the wellhead elevation was estimated by intersecting a USGS 10-meter digital elevation maps (DEM) with the approximate well location using GIS software. An analysis of the accuracy of this technique was performed by comparing the elevations determined using 10-meter DEMs with surveyed elevations where they existed. The analysis found that, on average, the elevation determined from the DEMs is within 1.21 ft of the surveyed elevation. This was considered an acceptable level of accuracy by the ESHMC. More detail on the use of DEMs for estimating wellhead elevation can be found in ESPAM1.1 Design Document DDM-011. Additional details on the collection of aquifer water level data can be found in ESPAM1.1 Design Document DDW-014.

VI. C4. Irrigation Return-Flow Calibration Targets

Irrigation return flows were used as calibration targets to constrain calibration of On-Farm algorithm parameters that impact the calculation of incidental recharge from surface-water irrigation. Measured irrigation return flows are available for 10 ESPAM2.1 irrigation entities. Figure 72 shows the entities that have measured returns. PEST attempted to match the runoff calculated by MKMOD with the measured return flows for these 10 entities.

Flow measurements are not available for 11 other irrigation entities with surface returns to the Snake River, and PEST was not provided with calibration targets for those 11 entities. Return-flow calibration targets are discussed in more detail in ESPAM2.1 Design Document DDW-V2-15.

VI. D. ASSESSMENT OF MODEL CALIBRATION

VI. D1. Comparison of Simulated and Observed Transient Heads

One of the measures of the fit of a transient calibration is how closely the simulated and observed water levels match. For the 1,121 wells with absolute water level elevation targets, the standard deviation for the difference between observed and modeled water levels is 22.6 feet. Across the model domain, aquifer head ranges from over 6,000 feet above mean sea level in the northeast to approximately 2,800 feet above mean sea level in the southwest. Figures 73 through 75 compare model-predicted water levels to observed water levels in seven wells located across the eastern Snake Plain. No attempt was made to match water level data during the transient model warm-up period (prior to May 1985).

For the 32 wells with water level change targets, the standard deviation for the difference between observed and modeled water level changes is 7.1 ft. Figures 76 and 77 compare model-predicted and observed water level change in four wells, and illustrate that the ESPAM2.1 does a good job of matching the head change data.

VI. D2. Comparison of Simulated and Observed River Reach Gains

Figures 78 through 82 show simulated and observed reach gains for the Ashton-to-Rexburg, Heise-to-Shelley, Shelley-to-Near Blackfoot, Near Blackfoot-to-Neeley, and Neeley-to-Minidoka reaches. Charts at the bottom of each figure present the same data differently: the left chart shows cumulative departure; the middle chart shows average monthly observed and modeled gains; and the scatter plot on the right shows modeled values plotted against observed values. No attempt was made to match the data that were collected during the model warm-up period (prior to May 1985). As can be seen in Figures 78 through 82, the model does a reasonable job of simulating average gains for each of the five Snake River reaches.

The charts at the bottom of Figures 78 through 82, show the cumulative departures are small and do not consistently trend upward or downward. Figure 78 shows that the model generally does not match the persistent spike in the Ashton-to-Rexburg gains during June. Otherwise the model matches the calculated gain estimates well for this reach. The model also does a good job of matching the average gains in the Heise-to-Shelley reach (Figure 79).

In the Shelley—Near Blackfoot reach (Figure 80), the model is unable to simulate spikes in the calculated reach gains in 1986 and 1997, and is unable to simulate the apparent seasonal phase shift that occurs in the calculated reach gains beginning in 2000. The model also does a poor job replicating spikes that are evident in the Near Blackfoot-Neeley reach gain data in 1984, 1987, 1995, 1997, and 1999 (Figure 81). These spikes in calculated reach gains likely result from gage error or unmeasured surface water inflows or outflows and are not representative of interaction between the ESPA and the river.

For the Neeley-Minidoka reach (Figure 82), the model generally under-predicts the month-to-month variation in the gains data; however, inspection of the plotted reach gains data shows a significant amount of noise, reflecting uncertainty in monthly river gage measurements. Figure 82 shows that the model simulates an almost constant but modest gain for the Neeley-to-Minidoka reach. The calculated data also have a slight gain on average, hence the model representation of this reach is considered reasonable.

VI. D3. Comparison of Simulated and Observed Gains between Kimberly and King Hill

Figures 83 through 86 show the modeled versus calculated gains for the Snake River between Kimberly and King Hill, Kimberly-to-Buhl, Buhl-to-Lower Salmon Falls, and Lower Salmon Falls-to-King Hill, respectively. Although the model generally matches the average gains well, the scatter plots indicate that the model persistently under-predicts seasonal fluctuations.

VI. D4. Comparison of Simulated and Observed Spring Discharges

Figures 87 through 100 show the model-predicted and measured discharges for the following Group A or B springs: Devils Washbowl, Devils Corral, Blue Lakes, Crystal, Niagara, Clear Lakes, Briggs, Box Canyon, Sand Springs, Thousand Springs, National Fish Hatchery, Rangen, Three Springs, and Malad. No attempt has been made to match data during the model warm-up period (prior to May 1985).

The model generally does an excellent job of predicting the average magnitude of the spring discharge for each spring. As shown by the scatter plots and the average monthly spring flow plots, the model does a much better job of matching the seasonal variation for the springs than for the gains between Kimberly and King Hill. The model matches the seasonal variation well for eleven springs, including Devils Washbowl, Crystal, Niagara, Clear Lakes, Box Canyon, Sand Springs, Thousand Springs, National Fish Hatchery, Rangen, Three Springs, and Malad Gorge. The model significantly under-predicts the seasonal variation at Briggs Spring (Figure 93). For both Devils Corral (Figure 88) and Blue Lakes (Figure 89), the observed data are not sufficient to define the seasonal variation, so the seasonality of the model predictions could not be evaluated.

VI. D5. Comparison of Simulated and Observed Base Flow

Figure 101 is a plot of model-predicted versus calculated average base flow for the Kimberly-to-Buhl, Buhl-to-Lower Salmon Falls, and Lower Salmon Falls reaches and three local sites where available data indicate that there is base flow to the Snake River. The plot indicates excellent agreement between the simulated and calculated rates of base flow.

VI. E. Calibrated Model Parameters

VI. E1. Aquifer Transmissivity

The calibrated transmissivity ranges from 100 to 4.9 x 10^9 ft^2/day. Riverbed and drain conductance ranges from 1.0 to 3.0 x 10^8 ft^2/day. Final values for riverbed, drain, and general head boundary conductance can be found in Tables 3, 4, and 5, respectively.

The map of the calibrated model transmissivity (Figure 102) 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 are in the model cells used to represent the aquifer along the Mud Lake barrier and the Great Rift. The Mud Lake barrier extends west to east 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 low relative to adjacent areas, and this impedes groundwater flow as evidenced by the more tightly spaced equipotential lines in these areas (Figure 6). The calibrated transmissivity distribution is consistent with our current understanding of the aquifer.

VI. E2. Aquifer Storage

In ESPAM2.1, the unconfined aquifer is represented using a fixed transmissivity array with storage coefficients typical of unconfined aquifer systems (0.01 to 0.3). During calibration, aquifer storage was adjusted at 28 pilot points (Figure 103) and interpolated to every model cell. Aquifer storage has a much narrower range of variation than transmissivity, so fewer pilot points are required for calibration. Unlike the transmissivity array, the aquifer storage array tends to be higher along the edge of the model domain and lower towards the center, especially for cells used to represent the aquifer at the intersection with tributary valleys. This is consistent with our understanding of the aquifer because porous sediments often are interlayered with basalt at the margins of the aquifer. The storage is expected to be lower near the center of the aquifer because there generally is less sediment and the basalt generally is less porous.

VI. E3. Components of Recharge

The ESHMC decided to allow PEST to adjust several components of recharge within the estimated bounds of uncertainty during model calibration. These adjustments are discussed in this section.

VI. E3. a. Recharge on Non-Irrigated Lands

Eleven scalars were used to adjust recharge on non-irrigated lands polygons within a range of 0.0001% to 200%. The 11 polygons are based on soil thickness as discussed in section V. B4. Figure 46 shows the starting estimated recharge on non-irrigated lands. Figure 104 and Table 22 show the model calibrated scalars used to adjust non-irrigated recharge.

VI. E3. b. ET on Surface-Water Irrigated Lands.

The ESHMC decided to allow adjustment of ET on sprinkler and gravity irrigated lands by ±5% during calibration. Figure 105 shows maps of the ET adjustments on surface-water irrigated lands. Table 23 shows the starting, adjusted, and percent change for ET on sprinkler and gravity irrigated lands. Although PEST was allowed to adjust ET by ±5%, ET was adjusted by less than 1% in all irrigation entities except the Northside Canal Company service area, where ET on sprinkler irrigated lands was increased by 2.4%. ET on gravity irrigated lands within the Northside service area was increased by only 0.4%. Because there were more gravity irrigated lands within the Northside service area in 1980 than in 2008, the ET adjustment increased incidental recharge in the 1980s relative to incidental recharge in the 2000s in this entity.

VI. E3. c. Seepage from Non-Snake River Sources

The adjustments to seepage from non-Snake River sources are shown in Table 24 and Figure 106. PEST was allowed to adjust seepage by ±20%. The largest adjustments to perched seepage were made at Mud Lake (+20%), the Malad River (+18%), and the Big and Little Wood Rivers (-5%). Adjustments to perched seepage from other sources were less than 4%.

VI. E3. d. Underflow from Tributary Basins

PEST adjustments to underflow from tributary basins are presented in Table 25 and shown on Figure 106. During calibration it became apparent that ESPAM2.1 would not calibrate well with the tributary valley aggregations used in calibration of ESPAM1.1. With the Camas Creek and Beaver Creek constant flux boundaries tied together, the Camas flux appeared to be too high when the Beaver Creek valley flux was adjusted properly because the simulated water levels near the Camas Creek valley were consistently higher than observed. Similarly, there appeared to be too much underflow from Rattle Snake/Pine Creek constant flux boundary when the Henrys Fork constant flux boundary was adjusted properly. Once these aggregated boundaries were separated and the maximum and minimum allowable adjustments were relaxed, PEST could adjust the tributary underflows independently and the model calibration improved.

PEST was allowed to adjust the scalar multiplier for most tributary basins between 25% and 200%. PEST was allowed to adjust Camas Creek and Henrys Fork tributary underflow within ranges of 0.0001% to 200% and 25% to 1,300%, respectively. The final adjustment at Henrys Fork was 466%. Final adjustments at other tributary basins ranged from 59% to 147% (Table 25).

VI. E3. e. Canal Seepage

PEST adjustments to canal seepage are presented in Table 26 and shown on Figure 108. With the exception of the Mud Lake canals, PEST was allowed to adjust canal seepage by ± 5% and the final adjustments were less than 2%. PEST was allowed to adjust canal seepage in the Mud Lake canals within a range of -90% to +5%, and the final adjustment lowered the seepage by approximately 74%. For the Mud Lake canals, a large negative seepage adjustment seems reasonable because:

1) the canals are paralleled by drainage ditches that collect seepage and pump it back into the canal,
2) the canals sits on top of ancient lake bed sediments and are not incised into loess, gravel or basalt, and
3) the canals are relatively short.

VI. E3. f. DPin and DPex

The On-Farm algorithm (Equation 11) determines the portion of irrigation water delivered to farm headgates that is not consumed by ET, and partitions this water between deep percolation to the ESPA and return flow to the Snake River (runoff) utilizing the parameters DPin and DPex. DPin apportions an initial fraction of the applied water, and DPex apportions any water remaining after meeting the crop irrigation requirement. DPin and DPex were set to 1.0 for all entities that do not return water to the Snake River; indicating 100% of both the initial fraction and any excess water recharges the aquifer. PEST was allowed to adjust DPin and DPex between 0.60 and 0.98 for those entities returning water to the Snake River.

Through the process of regularization (Doherty, 2003), PEST was encouraged to make DPin and DPex equivalent within each entity, while attempting to match irrigation return-flow targets. Table 27 lists the calibrated DPin and DPex values. The maps in Figure 109 show the distribution of DPin and DPex. Figures 110 through 117 show the match between modeled and observed irrigation return flows for different irrigation entities.

VI. E3. g. Soil Moisture Parameters

The On-Farm algorithm (Equation 11) and MKMOD program (Appendix B) incorporate an accounting of soil moisture into calculation of incidental recharge on surface water irrigated lands. The adjustable parameters impacting the soil moisture reservoir are wilting point (soil moisture content below which plants can not withdraw water), field capacity (volume of water in soil/volume of soil), and crop rooting depth. For all irrigation entities, the starting values were a wilting point of 0.02, field capacity of 0.20, and crop rooting depth of 3.0 feet. Table 28 lists the final parameter values by entity. Note that very little adjustment took place during calibration. Mud Lake is the only entity with significantly different values for field capacity and crop rooting depth. As noted before, Mud Lake soils are finer grained and tend to hold more moisture than most other soils on the eastern Snake Plain because they were deposited in the low energy environment of a lake.

VI. F. MODEL LIMITATIONS

As with any model of a natural system, the ESPAM2.1 has limitations and uncertainty. Simplifying assumptions must be made to model complex, natural systems. Components of the aquifer water budget which have the least certainty are recharge on non-irrigated lands, tributary underflow, and irrigation return flows for entities with no measured returns. As discussed in the Water Budget section, these elements were estimated based on the collective professional judgment of the ESHMC using existing published material for reference. As previously discussed, there is a shortage of data on spring discharges and irrigation return flows, but ESPAM2.1 calibration has been enhanced by the addition of measured spring discharge data and irrigation return-flow measurements that were not available during calibration of ESPAM1.1. Future calibrations of the ESPAM would benefit further from additional spring discharge and irrigation return-flow data.

The ESPAM2.1 is a regional groundwater model. For this reason, the model is best used for broad-scale predictions. The user should avoid the temptation to model localized phenomena, such as the impact of a single well on a specific spring. This limitation exists because the input data used to compute the agricultural impacts are still coarse. Data are available to support fairly accurate estimates of surface-water diversions on an entity scale, precipitation on a 4 km x 4 km scale, and crop distribution on a county scale. Unlike ESPAM1.1, ESPAM2.1 can be used to compute regional impacts on selected individual springs because it was calibrated to spring-specific discharge measurements.

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 hydrologic impacts to the river and to Group A and B springs. The model can be used to provide a general sense of groundwater to groundwater impacts; however, the model is best used for prediction of impacts to surface-water resources resulting from regional groundwater use or from changes in the magnitude, timing, and spatial distribution of aquifer recharge.

Despite these limitations, the ESPAM2.1 is the most thoroughly calibrated model of the ESPA in existence. In general, the extensive use of a state-of-the-art model calibration tool and the prevalence of available data yielded an excellent model calibration.

VII. RELATED REPORTS

For the ESPAM1.1, design documents were written to document important decisions concerning the model and water budget. Design documents were also written for the same purpose for the ESPAM2.1. Some ESPAM2.1 design documents refer to ESPAM1.1 documents because certain aspects of the model have not changed appreciably. Each design document chronicles the design alternatives, the final design, and the rationale for selecting the final design. The design documents were distributed in draft form to the IDWR and ESHMC for review and feedback. Many of the design documents went through multiple iterations as a result of feedback from ESHMC members either during or after design reviews. Throughout the ESPAM project, draft and final design documents were made available to the ESHMC via the IDWR website. If, in the course of final model development or calibration, the documented final design had to be changed, an ‘as-built’ version of the pertinent design document was released to document the change. Table 29 lists the ESPAM design documents currently available for the ESPAM2.1.

VIII. SUMMARY AND CONCLUSIONS

This report documents the successful reformulation and calibration of ESPAM, the numerical groundwater model used for water management on the eastern Snake Plain. ESPAM2.1 was calibrated to 23.5 years of recharge and discharge data (28.5 years were simulated), as compared to ESPAM1.1, which was calibrated to 17 years of data (22 years were simulated). Calibration to data from a period that included some of the driest and wettest years on record ensures that the model is capable of accurately simulating the response of the river/aquifer system to a broader spectrum of stresses.

ESPAM2.1 was calibrated using the PEST parameter estimation tool. Using PEST enabled the modeling team to optimize the fit of the model to thousands of observed aquifer water levels, and spring discharge and streamflow measurements. The final calibrated ESPAM2.1 shows a significantly better fit to observed data than ESPAM1.1.

A significant aspect of the ESPAM reformulation and calibration was the involvement of the ESHMC. The ESHMC, comprised of interested parties representing agencies, private industry and water user groups, oversaw and participated in the production of ESPAM2.1 and the calibration process. Although the collaborative process used to develop ESPAM2.1 took more time than a more streamlined, conventional model development process, it allowed ESHMC members an active voice in model design and implementation decisions and helped to eliminate bias. By including a broad spectrum of interested parties in the model production and calibration, the committee members were able to gain a better understanding of model design details.

The outcome of any groundwater modeling effort is enhanced insight into the hydrologic processes being modeled. This was also true for the production and calibration of ESPAM2.1.

Several significant gaps in either data or in the understanding of the underlying hydrologic processes have become apparent during the development of ESPAM2.1. As with any model, there is always room for improvements and enhancements. Recommendations for further work include:

a) incorporate METRIC data to enhance evapotranspiration estimates,
b) develop new reach gain targets using flow data from the Snake River near Menan gage (USGS #13057000),
c) calibrate to both filtered and unfiltered river gains and losses,
d) improve estimates of tributary underflow,
e) enhance the representation of groundwater/surface water interaction along the Portneuf River,
f) introduce more pilot points for model calibration,
g) calibrate to both absolute values of measured spring discharge and to the slope on a cross plot of modeled vs. observed spring discharge, and
h) refine estimates of aquifer recharge in areas with complex irrigation delivery systems, such as the Mud Lake area and the Big and Little Wood Rivers area.

Although every model represents a simplification of complex processes, with the ESPAM being no exception, ESPAM2.1 is the best available tool for understanding the interaction between groundwater and surface water on the eastern Snake Plain. The science underlying the production and calibration of ESPAM2.1 reflects the best knowledge of the aquifer system available at this time. ESPAM2.1 was calibrated to 43,165 observed aquifer water levels, 2,248 river gain and loss estimates, and2,485 transient spring discharge measurements collected from 14 different springs. Calibration parameters indicate an excellent fit to the observed data, providing confidence that the ESPAM provides an excellent representation of the complex hydrologic system of the eastern Snake Plain.

Complex water management decisions on the eastern Snake Plain will be greatly enhanced by use of the ESPAM2.1. The participation of the ESHMC members in the model design and calibration process has provided members with the opportunity to gain substantial insight into the details of this complex numerical groundwater model, allowing committee members to make informed judgments regarding how the model is applied to aquifer management.

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