Eastern Snake Plain Aquifer Model Calibration Report

Idaho Water Resources

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Eastern Snake Plain Model Aquifer Model Enhancement

Model Design and Calibration Document Number DDM-008

DESIGN DOCUMENTS

Design documents are a series of technical papers addressing specific design topics on the eastern Snake River Plain Aquifer Model upgrade. Each design document will contain the following information: topic of the design document, how that topic fits into the whole project, which design alternatives were considered and which design alternative is proposed. In draft form, design documents are used to present proposed designs to reviewers. Reviewers are encouraged to submit suggested alternatives and comments to the design document. Reviewers include all members of the Eastern Snake Hydrologic Modeling (ESHM) Committee as well as selected experts outside of the committee. The design document author will consider all suggestions from reviewers, update the draft design document, and submit the design document to the SRPAM Model Upgrade Program Manager. The Program Manager will make a final decision regarding the technical design of the described component. The author will modify the design document and publish the document in its final form in .pdf format on the SRPAM Model Upgrade web site.

The goal of a draft design document is to allow all of the technical groups which are interested in the design of the SRPAM Model Upgrade to voice opinions on the upgrade design. The final design document serves the purpose of documenting the final design decision. Once the final design document has been published for a specific topic, that topic will no longer be open for reviewer comment. Many of the topics addressed in design documents are subjective in nature. It is acknowledged that some design decisions will be controversial. The goal of the Program Manager and the modeling team is to deliver a well-documented, defensible model which is as technically representative of the physical system as possible, given the practical constraints of time, funding and manpower. Through the mechanism of design documents, complicated design decisions will be finalized and documented.

Final model documentation will include all of the design documents, edited to ensure that the “as-built” condition is appropriately represented.

INTRODUCTION

The Eastern Snake Plain aquifer consists of a series of basalt flows with interlayered pyroclastic and sedimentary material. It extends across southern Idaho in a swath about 170 mi long and 60 mi wide (Figure 1). The Eastern Snake Plain aquifer encompasses the broad depression extending from King Hill in the southwest to Ashton in the northeast. Its lateral boundaries are formed by contacts with less permeable rocks at the margins of the plain.

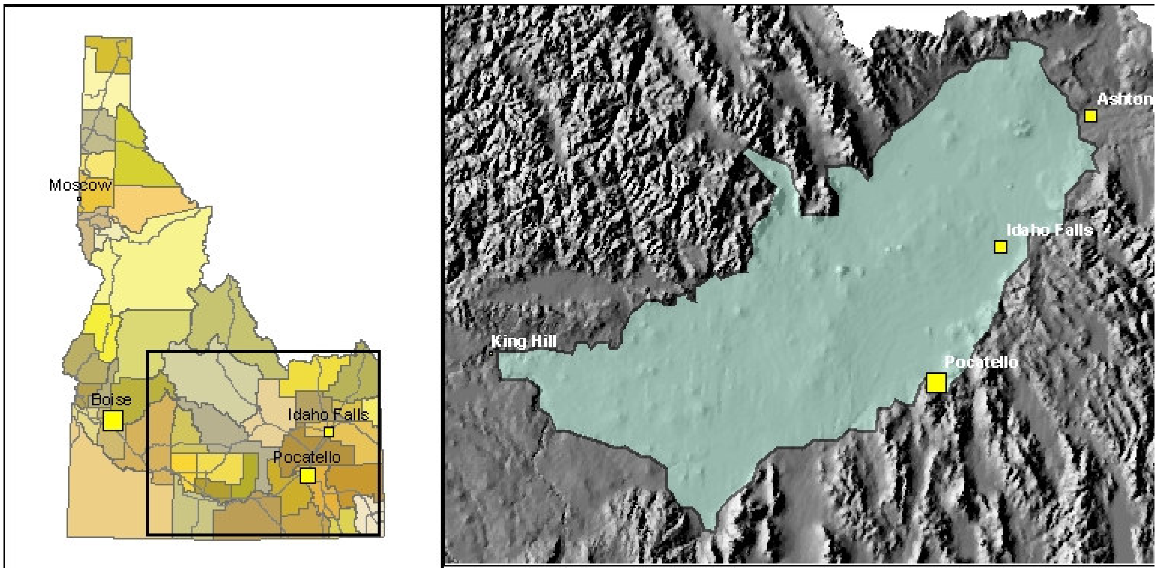

Figure 1. Location map.

Numerous investigators have modeled all or parts of the Eastern Snake Plain aquifer. Two models of particular interest include one constructed by The University of Idaho for the Idaho Department of Water Resources (IDWR) described in Cosgrove and others (1999) and one by the U.S. Geological Survey (Garabedian, 1992). The Garabedian model was constructed largely as an investigative tool to explore concepts of regional ground water flow and improve scientific understanding of the aquifer. The IDWR model was designed primarily as an aquifer planning and management tool.

The modeling effort this document supports, the Eastern Snake Plain Aquifer Model Enhancement Project, was undertaken to facilitate conjunctive management of the Eastern Snake Plain aquifer. Thus, the model must necessarily represent both the Snake River and the Eastern Snake Plain aquifer as accurately as possible.

The modeling process includes establishing calibration targets, identifying adjustable parameters, and quantifying known model inputs. For this effort, the calibration targets include aquifer water levels and Snake River reach gains and losses. The adjustable parameters include aquifer transmissivity, specific yield, and riverbed and drain conductance. The known inputs include precipitation, evapotranspiration, surface water irrigation, ground water pumping, seepage from rivers other than the Snake River, and underflow from tributary aquifers.

Geology

The Eastern Snake Plain is underlain by volcanic rock, primarily basalt with lesser amounts of rhyolite. The volcanic rocks are intercalated with occasional lenses of sedimentary material that thin towards the center of the basin. The character of the volcanism on the Eastern Snake Plain resembles both flood basalt volcanism of the Columbia Plateau and basaltic shield volcanism of the Hawaiian Islands (Greeley, 1982). The Snake Plain differs from the Greeley plains-style volcanism in two general ways. First, volcanic vents are not randomly distributed over the plain, but are primarily restricted to rift zones. Second, sediments occasionally fill low-lying areas between shields and rift zones. These sediments include loess, alluvial silts, sands, gravels, and lacustrine clays and silts.

Aquifer permeability is largely controlled by the distribution of basalt flow contacts (zone between the top of a basalt flow and the bottom of the overlying basalt flow) with some additional permeability contributed by fractures, vesicles, and intergranular pore spaces (Mundorff et al., 1964). While on a local scale, a basalt flow contact can act as an aquifer and the adjacent dense interiors can act as confining layers; on a regional scale, dense basalt flow interiors act as “grains” while the basalt flow contacts reflect “intergranular porosity”. These grains are formed as basalt flow sequences are deposited in an overlapping and coalescing manner, where younger flows build on the complex undulating topography of previous flows. Flow through the aquifer then follows a tortuous path, around, through, and between these large “grains” in the general direction of the regional hydraulic gradient.

Hydrology

The aquifer lies entirely within the Snake River drainage basin. Major tributaries to the Snake River in the model area include Henrys Fork, Blackfoot, Portneuf, and Big Wood Rivers. Flow in streams entering the plain along its northwest edge (with the exception of the Big Wood River) is completely lost to infiltration and evapotranspiration; these include the Big Lost River, the Little Lost River, Birch Creek, Medicine Lodge Creek, Beaver Creek, and Camas Creek.

Annual precipitation on much of the plain ranges from 8 to 10 in. (Figure 2), while precipitation on the surrounding mountains is much higher. Most precipitation in the mountains arrives in the form of snow during the winter months.

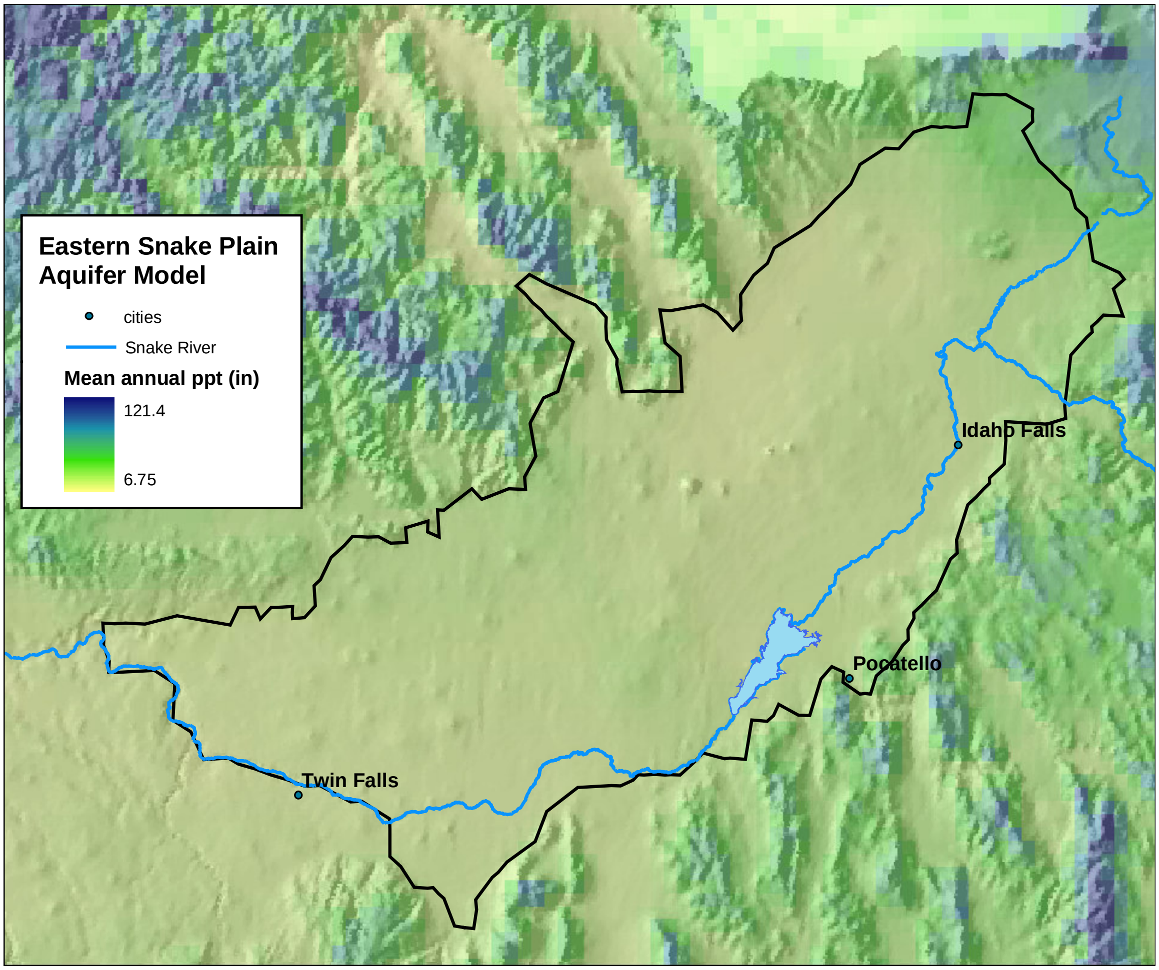

Figure 2. Mean annual precipitation on the eastern Snake Plain (1978-1997).

Water Budget

The water budget includes categories of recharge and discharge that are fixed and not used as calibration targets. These include precipitation, evapotranspiration, surface water diversions and canal losses, ground water pumping, seepage from rivers other than the Snake River and underflow from tributary valleys. Reach gains and losses from the Snake River and discharge of springs near the Snake River were used as model calibration targets and are not included in the recharge data set.

Recharge from precipitation on non-irrigated lands and precipitation on irrigated lands were based on GIS precipitation rasters (Daly and Taylor, 2001). Evapotranspiration (ET) on irrigated lands was based on crop coefficients from the countywide crop mix and reference ET calculated using the Kimberly-Penman equation and weather station data (Allen, 2002). Surface water diversions for irrigation were obtained from water master reports. Canal leakage was calculated as a fraction of total diversions. Offsite ground water pumping was represented for irrigation wells that are distant from the irrigated lands served, and pumping data were obtained from water master reports or water measurement district reports. Seepage from rivers other than the Snake River was calculated from USGS stream gaging records and water master reports. Subsurface underflow from tributary basins was based on the estimates used by Garabedian (1992), adjusted to represent changed model boundaries and given some temporal variation based on the discharge of Silver Creek, a spring-fed stream (Wylie, in prep.). Minor recharge and discharge components were included with recharge on non-irrigated lands or represented in a “fixed point” data set.

Prior to model calibration the recharge components listed above are adjusted to balance the inflows with the outflows using a least-squares procedure so that the sum of recharge equals the sum of calibration targets (net river gains and spring discharges) plus change in storage. A weighting procedure forces larger adjustments on less certain components.

Data

The model period extends from May 1, 1980 to April 30, 2002. Many observations over this time period were included as calibration targets. These observations include aquifer water level data collected by the United States Geological Survey (USGS) and by the IDWR (Shaub, 2001), river gaging data collected by the USGS and data collected jointly by the USGS and Idaho Power (USGS and Idaho Power, 2002), spring discharge data collected by Idaho Power (Bowling, 2004), and aquifer water levels collected by the University of Idaho (Janczak, 2001).

STEADY STATE DATA

Although steady state conditions rarely, exist in natural aquifers, most ground water modeling efforts include a steady state analysis because the transmissivity distribution tends to be more sensitive to steady state water levels than transient levels. The net change in aquifer storage, as indicated by beginning and ending ground water levels, (between May 1, 1982 and October 31, 2000) was small, so averaged observations during this period were chosen as steady state targets. Wells with only one observation during this time period were not used as targets. A total of 1008 steady state aquifer water level observations were used. Figure 3 shows the locations of the wells and the data are included in Appendix A on the accompanying CD.

The steady state calibration was accomplished by minimizing the difference between modeled steady state aquifer water levels and Snake River gains and losses; and averaged measured water levels and averaged measured Snake River gains and losses.

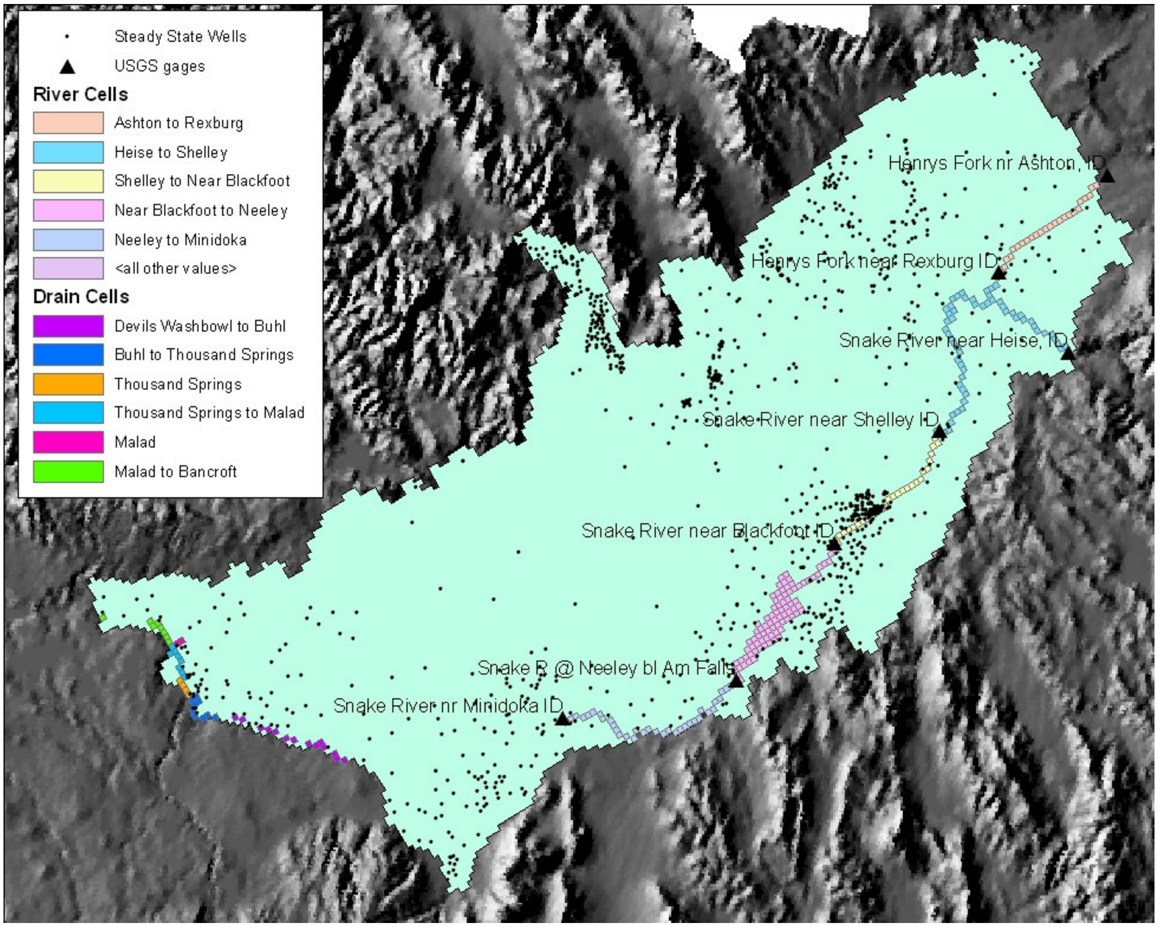

Figure 3. Location of steady state wells, river reaches, and spring reaches.

The Snake River was divided into 5 reaches above Minidoka dam based on the location of longstanding gaging locations (Figure 3). River gains and losses for these reaches were calculated using the IDWR Reach Gain And Loss program (Gilliland, 2004) and averaged over the steady state period. The data are tabulated in Appendix B on the accompanying CD. Between Minidoka Dam and Milner Dam, the IDWR Reach Gain And Loss program indicates little interaction with the aquifer, so that reach of the Snake River was not represented (Wylie, 2004).

Below Milner Dam the Snake River is incised, and springs emanate from the canyon wall. This segment of the river was divided into six “spring reaches” based on characteristics of spring discharge. The six reaches and relative discharge include:

1. Devil’s Washbowl to the Buhl Gage; contains intermittent springs with moderately large discharge.
2. Buhl Gage to Thousand Springs; contains springs with somewhat larger average discharge per river mile.

3. Thousand Springs; contains springs with extremely large discharge rates.
4. Thousand Springs to Malad Gorge; contains springs with moderate discharge.
5. Malad Gorge; contains extremely large discharge from springs near the confluence with the Snake River.
6. Below Malad Gorge; discharge is relatively small.

Steady state spring reach targets were calculated using a technique developed by Kjelstrom (1995) and modified by Johnson (2003) to partition the reach from Milner to King Hill into six sub-reaches and calculate annual gains from springs on the north side of the Snake River below Milner Dam.

TRANSIENT DATA

The transient calibration data include aquifer water level observations, monthly Snake River gains and losses, and spring discharge observations. Transient calibrations are undertaken primarily to determine specific yield. Specific yield is a function of change in aquifer water level, thus our transient model water level targets are change in water level, not the actual measured water level. Modeled aquifer water levels were also converted to change in water level for comparison with the targets. For this modeling effort we used three different types of transient aquifer water level data: 1) seasonal wells - wells with long time series consisting of frequent observations (9548 total observations in 39 wells over a maximum of 17 years, listed in Appendix C on the accompanying CD); 2) mass measurement wells - water level observations collected between spring 2001 and spring 2002 as part of this project (1766 total observations in 601 wells, listed in Appendix D on the accompanying CD); and 3) trend wells - wells with regular spring-time observations (1403 observations in 173 wells, listed in Appendix E on the accompanying CD). Figure 4 shows the locations of the various wells containing transient aquifer water level observations.

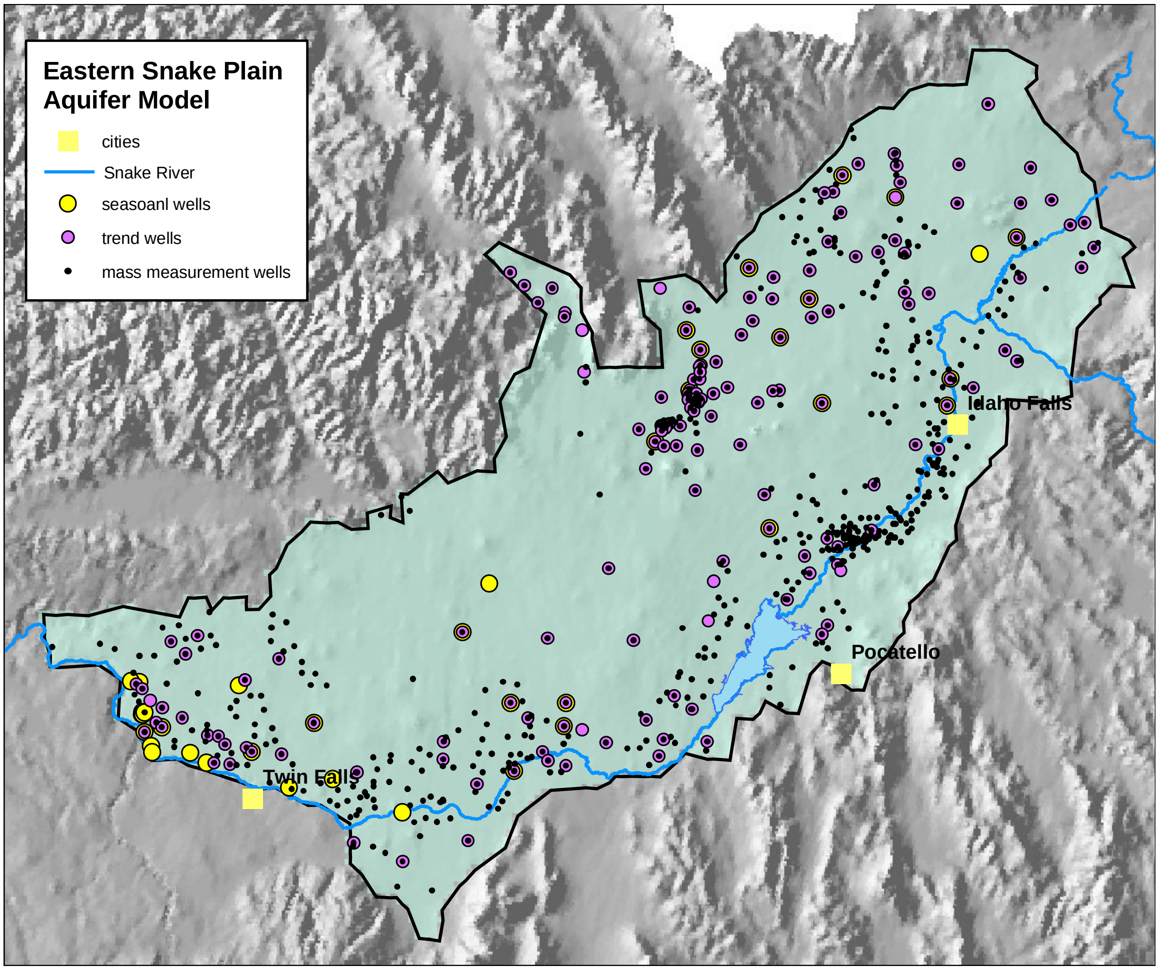

Figure 4. Location and type of transient wells.

Monthly gains and losses for the five river reaches above Milner Dam were computed using the IDWR Reach Gain And Loss program (Appendix F on the accompanying CD). These observations proved to contain significant measurement noise, so the data were filtered in a computer program called TSPROC and then set as targets. TSPROC uses a Butterworth filter to remove excessive noise in time series data sets. Doherty and Johnston (2003) explain TSPROC in greater detail.

Several springs contained significant time series and were thus used as transient targets. These are shown in Figure 5 and include Devils Washbowl, Devils Coral, Blue Lakes, Crystal Springs, Clear Lakes, Briggs Springs, Box Canyon Springs, Thousand Springs, and Malad Springs (Appendix G on the accompanying CD).

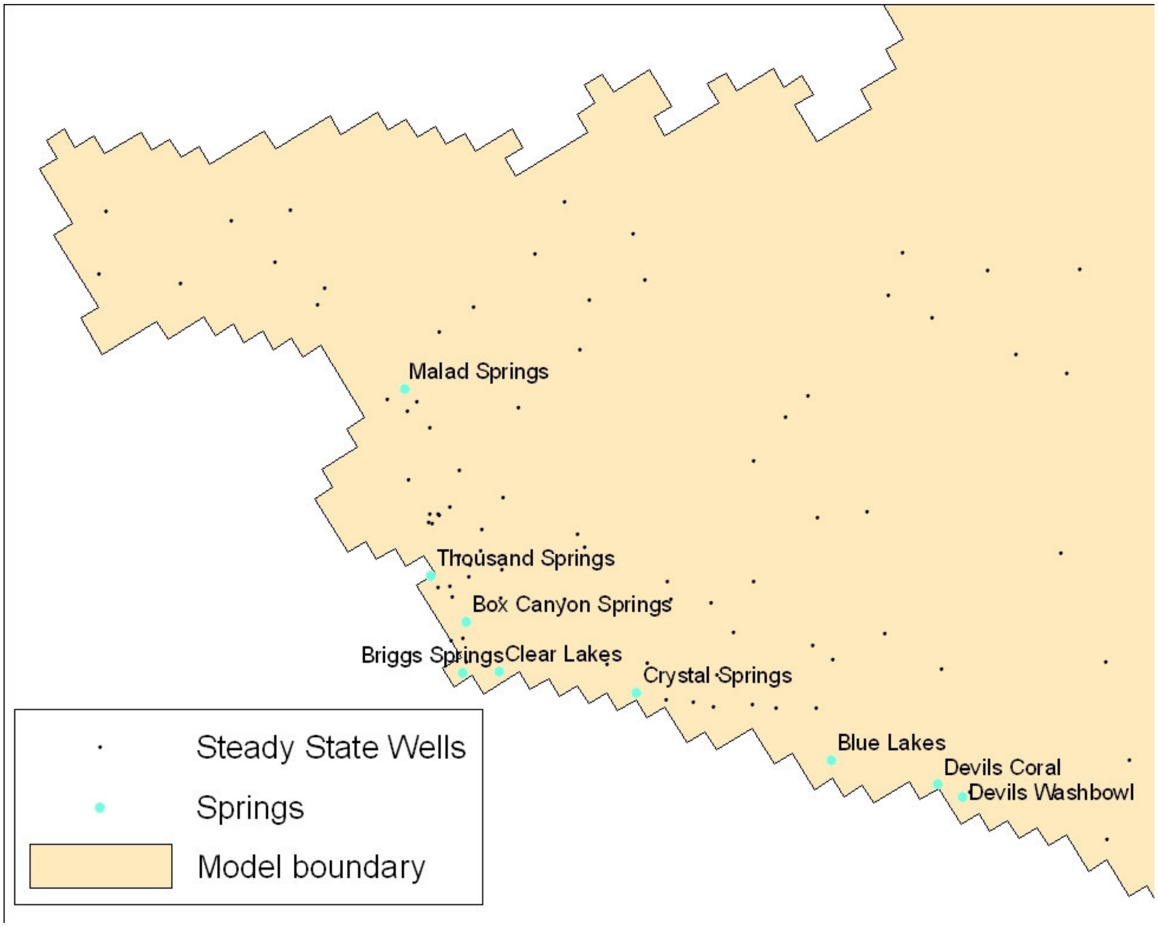

Figure 5. Springs with enough time series data to be used as transient targets.

Numerical model

We selected MODFLOW-2000 ver 1.10 (Harbaugh et al, 2000) as the model of choice for this project. The river package was used to simulate the Snake River above Milner Dam resulting in 230 river cells. The drain package was used to simulate springs below Milner resulting in 45 drain cells. All recharge except infiltration from the Snake River was computed using a GIS-based recharge model that produces a MODFLOW compatible recharge array (Cosgrove, in prep).

The model consists of one layer with a uniform 1 mi x 1 mi grid containing 104 rows and 209 columns rotated 31.4 degrees counter clock-wise relative to the IDTM central meridian to align the grid system with the primary flow direction in the aquifer. The rotation point and origin (Figure 6) is at the top left corner of the grid; the top left corner of the model cell whose row and column numbers are each 1. The coordinates of this point in IDTM is easting = 378,416.2 m and northing =233,007.2 m (corresponding to easting = 1,241,523 ft, northing 764,459.2 ft, latitude 43.118806^{o}, longitude –115.49619^{o}).

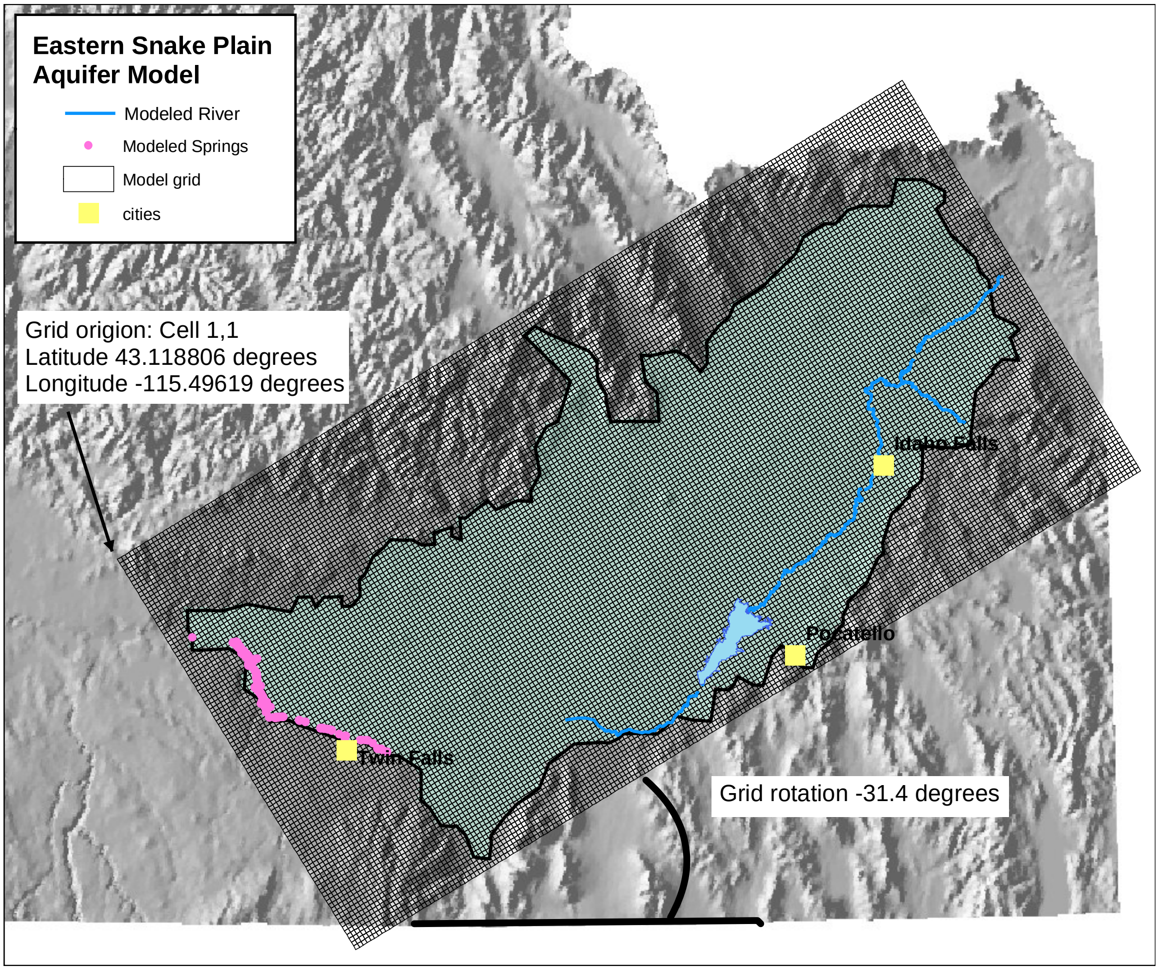

Figure 6. Model grid and grid orientation.

Steady state calibration

The goal was to simulate observed aquifer behavior by matching aquifer water levels, Snake River gains and losses, and spring discharges. River cells divided into reaches (as indicated in Figure 3) represented the Henrys Fork and Snake River. River-stage was estimated by digitizing the river and projecting it onto 10-meter (32.8 ft) digital elevation models. Spring elevations were originally estimated from topographic maps. Estimates of river or spring-conductance are model calibration parameters. The river-bottom elevation is the level below which leakage from the river cell reaches a maximum and is no longer hydraulically connected with the aquifer. This level was arbitrarily set to 30 ft below the water column in the river. The steady state calibration was used to adjust aquifer transmissivity and provide initial aquifer water levels for the transient calibration.

PEST, a nonlinear, least-squares inverse modeling program developed by Doherty (2003) was used to calibrate the model. (PEST is available for download on the web at ***www.sspa.com/pest***) The steady state model contains 1020 observations and 180 adjustable parameters. The observations include 1009 aquifer water level observations, five river reach gain/loss observations, and six spring gain observations. The adjustable parameters include 169 pilot points used to adjust the transmissivity distribution, five river parameters to adjust riverbed conductance for the five river reaches, and six drain parameters to adjust drain conductance for the six spring reaches.

PEST estimates transmissivity at the 169 pilot points then interpolates transmissivity from the pilot points to all active model cells. Doherty (2003) provides a more rigorous description of pilot points and how the process works. By adjusting transmissivity at the 169 pilot points, the five riverbed, and six drain conductance parameters, PEST minimizes the difference between observed and modeled water levels and river gains and losses. All of this is accomplished through a batch file that runs several utility programs as well as MODFLOW. Appendix H, on the accompanying CD, documents the batch file used during the steady state calibration.

Simulation results indicate a wide range in transmissivity from about 210 to 3.36×10^7 ft^2/day (Figure 7) and in riverbed and drain conductance from about 130 to 6.30×10^6 ft/day/ft. Model statistics indicate an overall correlation coefficient between measured and modeled observations of 0.9998. The standard error for the aquifer water level estimates is 18.19 ft indicating that about 95 percent of the modeled aquifer water levels are within about 36 ft of observed values, representing an accuracy of about 1.4%.

Figure 7 shows that estimated transmissivity values tend to be lower along the margins of the plain and higher towards the center. Two major exceptions to this generalization include the Mud Lake barrier and the Great Rift. The Mud Lake barrier extends east to west across the aquifer from the Bitterroot Mountains to just south of the confluence of the Henry’s Fork and the South Fork of the Snake River. The Great Rift extends north south across the plain from the Big Lost River Valley to just west of American Falls Reservoir. The transmissivity of both of these features is lower and impedes ground water flow as evidenced by the more tightly spaced equapotential lines in these areas. The calibrated transmissivity distribution matches our current understanding of the aquifer.

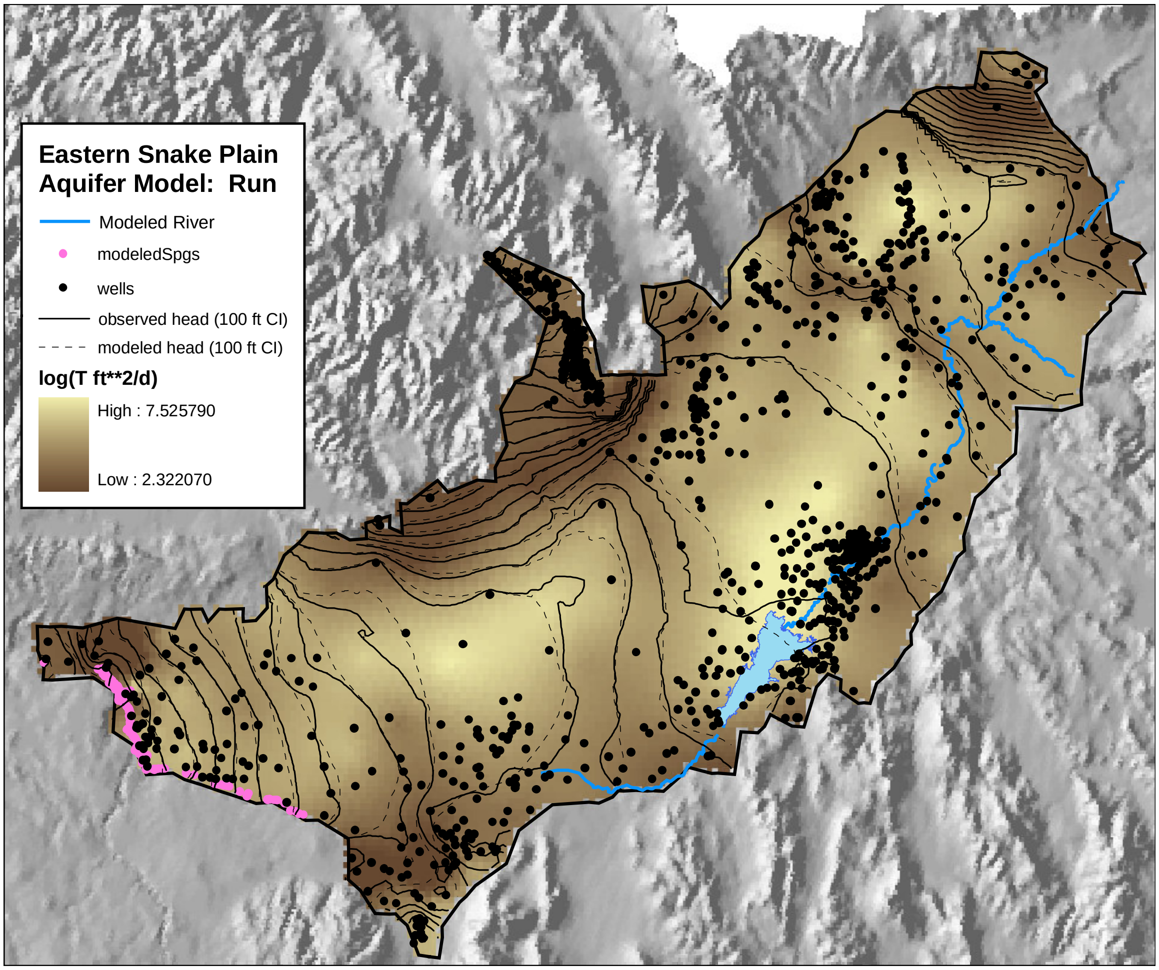

Figure 7. Estimated transmissivity map and observed and modeled aquifer water level match for the steady state simulation.

Transient calibration

Once the steady state calibration was achieved, transient calibration commenced. A transient calibration optimization run consisted of a coupled steady state model and a transient model. All parameters used in the steady state model were also used in the transient model. Thus any adjustment to achieve a better match in the transient model had to also honor the steady state model.

The objective of the transient model was to attempt to match observed river gains and losses, spring discharges and water level changes between May 1, 1985 and April 30, 2002. The transient model required a warm-up period of about five years because observations during 1980 are partly dependent on events that occurred years prior to 1980 as well as events during 1980. By allowing the model to run with estimated recharge and discharge data from 1980 to 1984, by 1985 the model was responding appropriately.

The transient model contains 16,007 observations and 292 adjustable parameters. The observations include 12,717 aquifer water level change observations, 725 Snake River gain/loss observations, 1526 spring discharge observations and the previously mentioned steady state observations. The adjustable parameters include 169 pilot points to adjust the transmissivity distribution, five river parameters to adjust riverbed conductance for the five river reaches, and 15 drain conductance parameters to adjust spring reaches, and nine drain elevation parameters

Transient simulation results indicate a wide range in transmissivity from about 70.8 to 5.89 x 10^7 ft^2/day (Figure 8). Riverbed and drain conductance ranges from 110 to 8.90x 10^6 ft/day/ft. Both distributions represent a wider range than that produced in just the steady state model. The specific yield distribution ranges from 3.5 x 10^{-3} to 0.286 (Figure 9). Model statistics indicate an overall correlation coefficient between measured and modeled observations of 1.000. The standard error for the steady state aquifer water level estimates is 17.69, for the seasonal aquifer water level observations it is 1.919, for the mass measurement observations the standard error is 5.196, for the trend observation it is 5.864. Table 1 and Figure 8 show that the estimated transmissivity values and riverbed and drain conductance tend to be similar to the steady state distribution, but with a slightly wider distribution.

Table 1. Comparison between steady state and combined steady state and transient calibration parameters.

	Steady state		Steady state + Transient	
	High	Low	High	Low
Transmissivity (ft^2/day)	3.4 x10^7	210	5.9 x 10^7	70.8
Specific yield			0.29	3.5 x 10^{-3}
River & drain conductance (ft/day/ft)	6.3 x 10^6	130	8.9 x 10^6	110

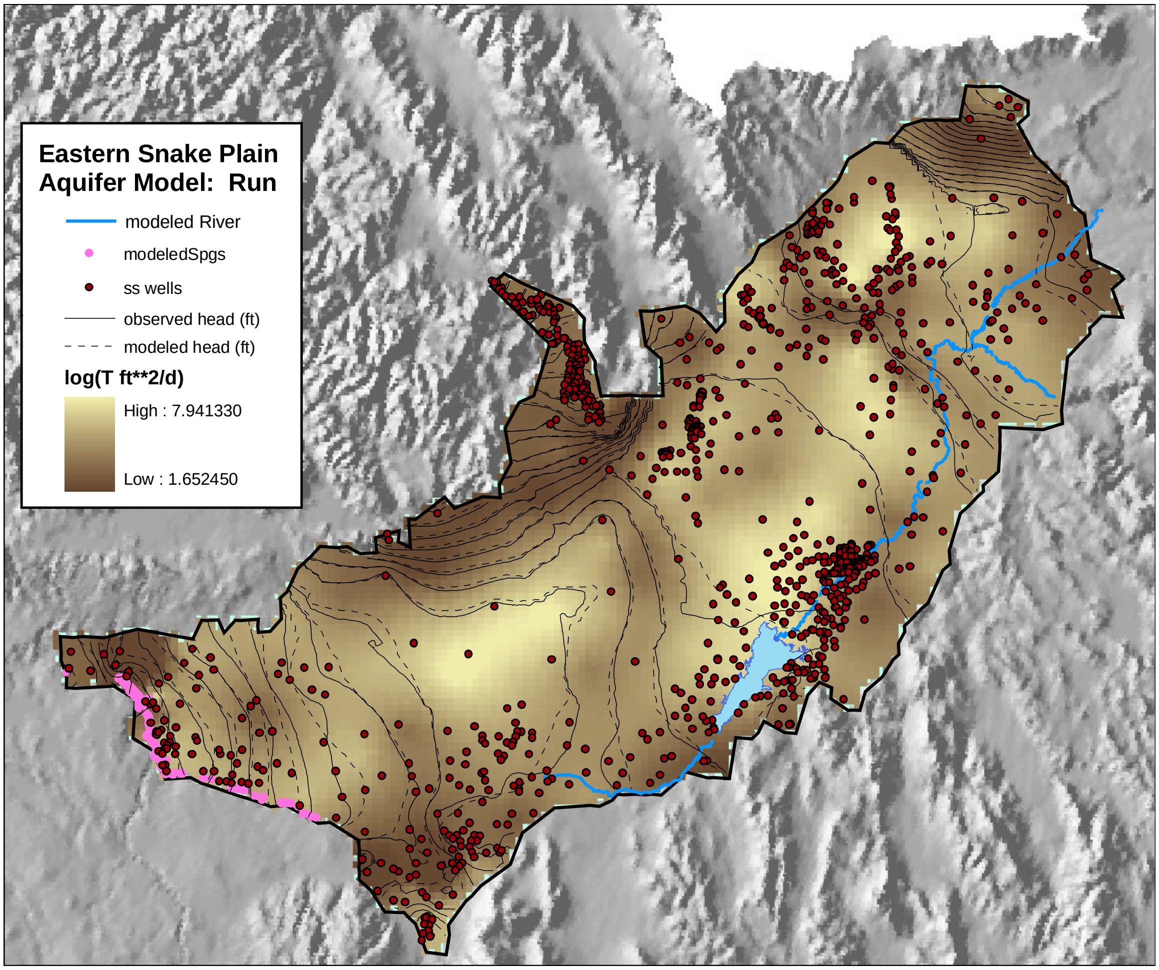

Figure 8. Transmissivity map produced from combined steady state and transient model.

Conclusions

The final calibration yielded a model with transmissivity values ranging from 70.8 to 5.89 x 10^7 ft^2/day, specific yield ranging from 3.5 x 10^{-3} to 0.286 and river and drain conductance ranging from 110 to 8.90x 10^6 ft/day/ft. Although this specific yield distribution is lower than the former Snake Plain Aquifer model, it is more consistent with the Garabedian model. Also, the spatial distribution for specific yield and transmissivity are consistent with the current widely accepted geologic understanding of the Snake Plain Aquifer.

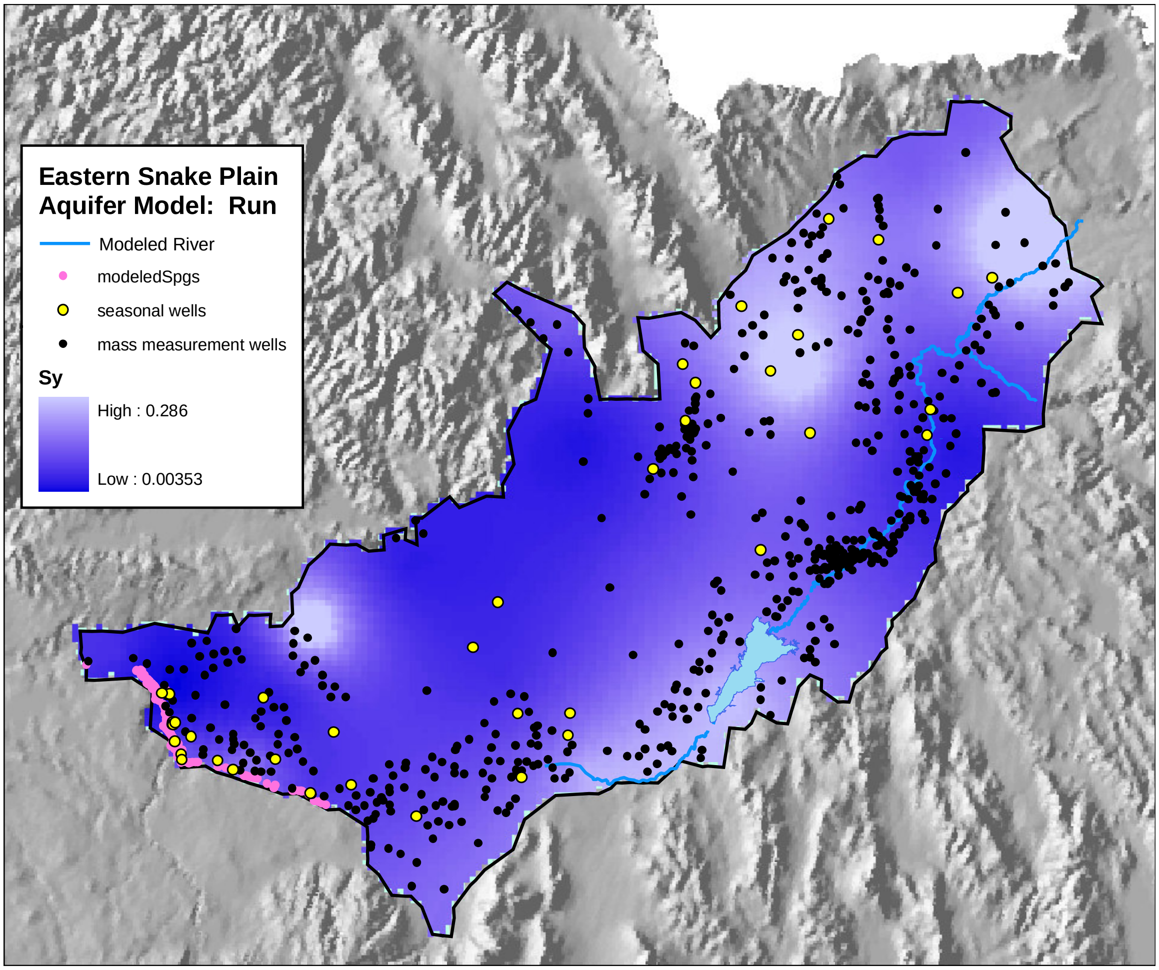

Figure 9. Specific yield map.

Model statistics indicate that the model does an acceptable job of matching the historical data between 1985 and 2002. The correlation coefficient between measured and modeled observation is 1.000. The standard error for the steady state aquifer water level estimates is 17.69, for the seasonal aquifer water level observations it is 1.919, for the mass measurement observations the standard error is 5.196, for the trend observation it is 5.864.

The combination of reasonable parameter distributions and an excellent fit between modeled values and field observations indicates that the model is useful for evaluating regional ground water to Snake River or Snake River to ground water issues.

References

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

Bowling, J., 2004. Memo to Gary Johnson.

Cosgrove, D.M., G.S. Johnson, S. Laney, and J. Lindgren, 1999. Description Of The IDWR/UI Snake River Plain Aquifer Model (SRPAM). Idaho Water Resources Research Institute

Cosgrove, D.M., G.S. Johnson, J. Hubbell, 1999. Response Functions As A Conjunctive Management Tool For The Snake River Plain, Idaho. (Abstract) Pacific Northwest Focus Ground Water Conference, February 17-19, 1999, Portland, Oregon.

Cosgrove, D.M., in prep. Eastern Snake Plain Recharge Tool.

Covington, H.R. and J.N. Weaver, 1990, Geologic Map And Profile Of The North Wall Of The Snake River Canyon. U.S. Geological Survey Miscellaneous Investigation Series, Maps I-1947A through I-1947E.

Daly, C. and G. Taylor 2001. PRISM Precipitation Maps, Oregon State University Spatial Climate Analysis Service And State Of Oregon Climate Service (http://www.ocs.orst.edu/prism/prism_new.html)

Doherty, J., 2003. Groundwater Model Calibration Using Pilot Points And Regularisation. Ground Water. vol 41, no 2, p 170-177.

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

Erickson, N. 2003. Water Elevation And Water Level Change Maps. Idaho Water Resources Research Institute, University of Idaho, DDF-009.

Garabedian, S.P., 1992. Hydrology And Digital Simulation Of The Regional Aquifer System, Eastern Snake River Plain, Idaho. U.S. Geological Survey Professional Paper 1408-F

Gilliland, B.K., DDM-017. Model Representation Of River Gains And Losses In The Heise/Ashton To Milner Reaches Of The Snake River. Idaho Water Resources Research Institute, University of Idaho, DDW-017

Gómez-Hernández JJ, Sahuquillo A, and Capilla JE. 1997. Stochastic Simulation Of Hydraulic Conductivity Fields Conditional To Both Hydraulic Conductivity And Piezometric Data. 1. Theory. J Hydrol; vol 20, p 162-174.

Gómez-Hernández JJ, Hendricks Fransen HJ, and Sahuquillo A., 2003. Stochastic Conditional Inverse Modeling Of Subsurface Mass Transport: A Brief Review Of The Self-Calibrating Method. Stoch Env Res Risk A vol 17, p 319-328.

Greeley, R., 1982. The Style Of Basaltic Volcanism In The Eastern Snake River Plain, Idaho, In Cenozoic Geology Of Idaho, (Bonnichsen and R.M. Breckenridge, eds.). Idaho Bureau of Mines and Geology Bulletin 26.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model-User Guide To Modularization Concepts And The Ground-Water Flow Process. USGS Open-File Report 00-92.

Hill, MC. 1989. Analysis Of Accuracy Of Approximate, Simultaneous, Nonlinear Confidence Intervals On Hydraulic Heads In Analytical And Numerical Cases. Water Resour Res, vol 25, no 2, p177-190.

Janczak, L.L., 2001. Relationships Between Spring Discharge And Aquifer Water Levels In The Thousand Springs Region, Idaho. Masters Thesis.

Johnson, G.S., 2003. Model Representation Of River Gains And Losses In The Milner To King Hill Reach Of The Snake River. Idaho Water Resources Reaearch Institute, University of Idaho, XXX-NNN

Kjelstrom, L.C., 1995, Methods To Estimate Annual Mean Spring Discharge To The Snake River Between Milner Dam And King Hill, Idaho. U.S. Geological Survey Water Resources Investigations Report 95-4055.

Mundorff, M.J., E.G. Crosthwaite, C. Kilburn, 1964. Groundwater For Irrigation In The Snake River Basin In Idaho. Water Supply Paper 1654, U.S. Geological Survey, Reston, Virginia.

Shaub, S., 2001. Depth To Water Measurements In The Eastern Snake River Plain Aquifer: 1980-2001. Idaho Water Resources Research Institute, University of Idaho, DDW-014.

USGS and Idaho Power, 2002. Report On The Progress Of A Seepage Study On The Main Stem And Henry’s Fork Of The Snake River, Idaho. Idaho Water Resources Research Institute, University of Idaho, DDF-001

Vecchia, A.V. and Cooley, R.L., 1987. Simultaneous Confidence And Prediction Intervals For Nonlinear Regression Models With Application To A Groundwater Flow Model. Water Resour. Res, vol 23, no 7, p 1237-1250.

Wylie, A., 2004, Model River Representation Above Milner Dam. Idaho Water Resources Research Institute, University of Idaho, DDM-010

Wylie, A., in prep., Tributary Underflow. Idaho Water Resources Research Institute, University of Idaho, DDW-004.