Design Document: Tributary underflow estimates and seasonal distribution of flux; *DRAFT 3*

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Design document description and purpose

The U.S. Geological Survey (USGS), in collaboration with the Idaho Department of Water Resources (IDWR) is constructing a MODFLOW numerical groundwater-flow model of the Wood River Valley aquifer system in order to simulate potential anthropogenic and climatic effects on groundwater and surface-water resources. This model will serve as a tool for water-rights administration and water-resource management and planning. The study will be conducted over a 3-year period from late 2012 until model and report completion in 2015.

One of the goals of the modeling study is to develop the model in an open and transparent manner. To this end, a Technical Advisory Committee was formed to provide for transparency in model development and to serve as a vehicle for stakeholder input. Technical representation was solicited by the IDWR and includes such interested parties as water-user groups and current USGS cooperating organizations in the Wood River Valley.

The design, construction, and calibration of a groundwater-flow model requires a number of decisions such as the number of layers, model cell size, or methodologies used to represent processes such as evapotranspiration or pumpage. While these decisions will be documented in a final USGS report, intermediate decision documents will be prepared in order to facilitate technical discussion and ease preparation of the report. These decision documents should be considered preliminary status reports and not final products.

Background

One of the most difficult water-budget components to estimate is subsurface inflow or outflow from an aquifer because direct measurement is not possible and the data required for indirect estimates are often lacking. The groundwater-flow model of the Wood River Valley aquifer system requires estimates of the volumetric flux of subsurface outflow from the tributary canyons into the main aquifer system.

Smith (1960) inferred geologic sections at 27 streamgages in the Malad River basin in order to qualitatively estimate what amount of the basin yield (estimated as “the sum of surface runoff and ground-water underflow from a basin.”) is represented by streamflow measurements. Ten of the streamgages evaluated were in the Wood River Valley, four of which are applicable to the estimate of tributary underflow: Big Wood River near Ketchum, Warm Springs Creek at Guyer Hot Springs near Ketchum, Warm Springs Creek near Ketchum, and Trail Creek at Ketchum. Smith’s estimates are:

- Big Wood River near Ketchum: “The ground-water component probably is more than 10 percent of the water yield.”
- Warm Springs Creek at Guyer Hot Springs near Ketchum: “Underflow probably is less than 1 percent of the water yield.”
- Warm Springs Creek near Ketchum: “The …alluvium probably transmits a moderate amount of ground water past the gage site. The amount cannot be estimated.”
- Trail Creek at Ketchum: “Underflow…is believed to be an appreciable percentage of the water yield of the…drainage area.”

The groundwater budget described in Bartolino (2009) identifies recharge from 28 tributary canyons as the largest component of recharge to the Wood River Valley aquifer system. This estimate was based on the USGS StreamStats tool (Ries and others, 2004) which uses regression equations from gaged streams to estimate flow in ungagged streams. For 23 of the tributaries Bartolino (2009) assumed that all of this estimated flow was recharged; the remaining five major tributaries were assumed to recharge 50 percent of the measured or estimated flow. Previous estimates of tributary recharge, such as Smith (1959) and Wetzstein and others (1989), were made with basin-yield calculations or model results: they are roughly comparable to those in Bartolino (2009).

Because Bartolino (2009) constructed a water budget for the entire aquifer system no effort was made to differentiate subsurface flux from recharged tributary streamflow. Thus, these estimates are not directly comparable to estimates of tributary underflow.

Design decision

Mean tributary underflow determination

Several approaches for determining the volumetric flux of tributary underflow were investigated. First, specification of a constant head boundary in the groundwater-flow model using groundwater levels measured in 2006 or 2012 was judged unrealistic and not defensible. Second, water-table gradients taken from water-level contours representing 2006 conditions (Skinner and others, 2007) incorporated interpolation errors inherent in the contouring process and scarce data in many tributary canyons. While water levels from drillers' logs are more plentiful, the wide variability of measurement dates do not allow a water-table gradient to be defined. The cross-sectional area of model cells in the tributaries are not representative because of errors inherent in discretization. It was therefore decided to estimate a cross-sectional area of the saturated thickness in tributary canyons from well and geophysical data and apply a Darcian analysis for flux.

ArcMap GIS was used to manually draw a straight line across a given tributary canyon roughly perpendicular to the canyon axis ending at the aquifer boundary on each end (the cross-sectional line). These lines were drawn in areas with existing data on depth to bedrock either from drillers' logs or geophysical data. This cross-sectional line was then copied and rotated 90° about the center of both lines so that a second line of equal length was perpendicular to the first line and parallel to the canyon axis (the axial line). The ArcMap "Add surface information" tool and the "Field Calculator" and "Calculate Geometry" attribute table options were applied to 1/3 arc-second National Elevation Dataset (USGS, 2009) to determine the:

- Length of the cross-sectional line,
- Lowest elevation along the cross-sectional line, and
- Average gradient of the axial line.

By making several explicit assumptions a flux can be estimated:

- That the tributary contains a perennial stream the surface of which is represented by the lowest altitude of the cross-sectional line and that this altitude represents a flat, level water table across the cross-sectional line;
- That the water table parallels the land surface along the canyon axis, that the water-table gradient is represented by the average gradient of the axial line, and that this represents the hydraulic gradient;
- That the altitude of the aquifer base at the center of the cross-sectional line is taken as the altitude of bedrock in the nearest well or geophysical measurement; and

- That the cross-sectional area of the saturated thickness is taken as half of an ellipse with:
  - a width of the cross-sectional line length and
  - a height of the distance between the estimated water table and bedrock altitudes.

Volumetric flux is then estimated by calculating the cross-sectional area of the saturated thickness in a given tributary canyon and using this area in the Darcy equation. The cross-sectional area for a segment of an ellipse is represented by equation 1:

$$Area = \left(\frac{aB}{4}\right)\left[\cos^{-1}\left(1-\frac{2H}{a}\right)-\left(1-\frac{2H}{a}\right)\sqrt{\frac{4H}{a}-\frac{4H^2}{a^2}}\right] \quad (1)$$

where

a is height of the ellipse in length units,

B is the width of the ellipse in length units,

H is the height of the segment in length units, and

Cos^{-1} is in radians.

Volumetric flux can then estimated using the Darcy equation (equation 2):

$$Q = KAh \quad (2)$$

where

Q is discharge (volumetric flux) in length^3/time units,

K is hydraulic conductivity in length/time units,

A is the cross sectional area in length^2 units, and

h is the hydraulic gradient, dimensionless.

Values of hydraulic conductivity were taken as 85 ft/d (26 m/d) which is the average of the two geometric means of hydraulic conductivity in the unconfined aquifer taken from table 2 in Bartolino and Adkins (2012).

An implicit assumption in the volumetric flux estimated by the Darcy equation is that the saturated thickness and hydraulic gradient remain constant, implying an unlimited supply of water. While this assumption may be valid for larger tributary canyons with perennial streamflow, estimates of volumetric flow in smaller tributary canyons with ephemeral streamflow may quickly exceed the total amount of precipitation that falls within the drainage (henceforth referred to as basin yield, it is the maximum possible value because it does not represent evapotranspiration or sublimation). This assumption, in combination with uncertainty due the lack of well or geophysical data typical of the smaller tributaries, causes overestimation of volumetric fluxes in smaller tributary canyons (Chocolate, Cold Springs, Ohio, Lees, and Townsend Gulches and Clear Creek Canyon) (table 1).

Table 1. Initial estimates of tributary underflow and selected tributary basin information.

Tributary	Saturated thickness (ft)	Tributary width (ft)	Area (ft²)	Land surface gradient	Estimated underflow, initial (acre-ft/yr)	Basin Area (mi²)	Average precipitation (in)	Basin yield (acre-ft/yr)	Estimated underflow/ Basin yield
Adams Gulch (Adm)	48	650	24,694	0.0482	851	11	30	17,600	0.048
Chocolate Gulch (ChG)	59	709	32,778	0.0727	1,703	0.75	21.6	864	1.97
Clear Creek (Clr)	35	623	17,074	0.0795	971	2.2	19.5	2,288	0.424
Cold Springs Gulch (Cld)	63	344	17,112	0.0576	705	2.9	21.6	3,341	0.211
Cove Canyon (Cov)	7	3,058	15,909	0.0127	145	14	15	11,200	0.013
Croy Creek (Cry)	40	1,391	43,660	0.0226	704	28	15.8	23,595	0.030
Deer Creek (DrC)	74	2,277	131,783	0.0155	1,462	55	25.3	74,213	0.020
Eagle Creek (Eag)	75	1,066	62,946	0.0226	1,015	11	29.4	17,248	0.059
East Fork (EstF)	43	1,414	48,259	0.0137	471	86	26.3	120,629	0.004
Elkhorn Gulch (Elk)	8	387	2,483	0.0289	51	13	18.4	12,757	0.004
Greenhorn Gulch (Grn)	78	860	52,395	0.0182	682	21	27.2	30,464	0.022
Indian Creek (InS)	83	1,070	69,452	0.0485	2,407	11	17.3	10,149	0.237
Lake Creek (Lak)	68	1,335	71,257	0.0472	2,406	12	27	17,280	0.139
Lees Gulch (Lee)	57	827	37,328	0.0556	1,484	2.8	15	2,240	0.662
Ohio Gulch (OhG)	85	1,243	83,032	0.0664	3,940	5.1	15.7	4,270	0.923
Quigley Creek (QgC)	60	1,325	62,378	0.0126	560	17	17.1	15,504	0.036
Seamans Creek (Sea)	156	1,391	170,357	0.0160	1,949	23	15.3	18,768	0.104
Slaughterhouse Gulch (Slh)	60	745	35,380	0.0200	506	13	16.6	11,509	0.044
Townsend Gulch (Twn)	63	728	35,835	0.0476	1,218	1.2	15	960	1.27
Trail Creek (Trl)	125	2,152	212,020	0.0191	2,898	64	32.6	111,274	0.026
Upper Big Wood River (UBW)	118	940	87,037	0.0097	607	178	33	313,278	0.002
Warm Springs Creek (WmS)	46	1,617	58,006	0.0117	487	96	35.3	180,735	0.003
TOTAL:					**29,100**				

The USGS StreamStats tool (Ries and others, 2004) was used to delineate a basin area above the cross-sectional line described above. This basin area was then multiplied by the average precipitation in the basin as provided by StreamStats to estimate precipitation volume (table 1). The areas of the tributary basins were then plotted on an exponential scale and a natural break was found between 5.1 and 11 mi^2. For all tributary basins of 11 mi^2 or greater, the ratio of basin yield to estimated underflow was calculated, the mean value of which was 0.06. This mean ratio is then applied to the StreamStats derived precipitation volume to determine the volumetric flux of tributary basins less than 11 mi^2 (table 2).

Table 2. Revised estimates tributary underflow volumetric flux and selected tributary basin information.

[*, denotes a basin for which tributary underflow was calculated by multiplying basin yield by 0.06]

Tributary	Basin Area (mi^2)	Revised estimated underflow (acre-ft/yr)	Tributary	Basin Area (mi^2)	Revised estimated underflow (acre-ft/yr)
Adams Gulch (Adm)*	11	851	Indian Creek (InS)	11	2,407
Chocolate Gulch (ChG)*	0.75	52	Lake Creek (Lak)	12	2,406
Clear Creek (Clr)*	2.2	137	Lees Gulch (Lee)	2.8	134
Cold Springs Gulch (Cld)*	2.9	200	Ohio Gulch (OhG)*	5.1	256
Cove Canyon (Cov)	14	145	Quigley Creek (QgC)	17	560
Croy Creek (Cry)	28	704	Seamans Creek (Sea)	23	1,949
Deer Creek (DrC)	55	1,462	Slaughterhouse Gulch (Slh)	13	506
Eagle Creek (Eag)	11	1,015	Townsend Gulch (Twn)*	1.2	58
East Fork (EstF)	86	471	Trail Creek (Trl)	64	2,898
Elkhorn Gulch (Elk)	13	51	Upper Big Wood River (UBW)	178	607
Greenhorn Gulch (Grn)	21	682	Warm Springs Creek (WmS)	96	487
(*continued to right*)			**TOTAL:**		**18,040**

Temporal variation of tributary underflow

Because mean tributary underflow as estimated above is a long-term average that does not account for variability in precipitation and snowmelt timing, actual underflow for a given month or quarter may be higher or lower than the mean. Thus a technique to represent temporal variation in tributary underflow is needed. One way to do this is to apply a scaling index to convert the long-term average underflow into a monthly or quarterly value. The scaling index is typically the ratio between short and long-term means of a proxy such as precipitation or stream discharge. Hsieh and others (2007) used a scaling index to apportion tributary underflow for the Spokane Valley-Rathdrum Prairie groundwater-flow model.

In order to choose an appropriate technique for the application of temporal variability to tributary underflow a statement of the conceptual model is useful. The process of tributary underflow begins with infiltration of precipitation or snowmelt; this water eventually reaches the water table and then moves down gradient to become tributary underflow. Depending on soil moisture, topographic gradients, and hydraulic conductivity, there is likely a lag time of some months between infiltration and movement of the tributary underflow into the unconfined aquifer. Because of multiple recharge events and the time lag, recharge tends to be “smeared” or integrated over time rather than having distinct peaks. Thus some form of scaling index is needed to represent temporal variation in tributary underflow.

The most obvious basis for a scaling index are groundwater-levels in wells in each of the tributary canyons. However, pumping effects and the dearth of wells with continuous water level measurements for the model period make this approach impracticable.

Precipitation data were considered as a basis for calculating a scaling index but were rejected for three reasons: (1) Only two weather stations in the Wood River Valley have sufficient data to make such an estimate, (2) these stations likely do not represent conditions in the higher elevations of the tributary valleys; and (3) snowmelt and infiltration may occurs several months after the precipitation falls as snow thus requiring another adjustment. Weather data were used to adjust the timing of precipitation and snowmelt for areal recharge in the WRV groundwater-flow model (McVay, 2014) but surface elevations range over 1,400 ft within the model domain. Because elevations in tributary canyons may range over 6,400 ft with large variability between tributaries, existing weather data is not likely to adequately represent conditions in the tributaries.

Stream discharge integrates the various components of streamflow for all of the tributary basins above the streamgage and thus captures the timing of both precipitation and snowmelt (although detailed spatial and temporal resolution is sacrificed). Because discharge data provide a reasonable representation of the timing and amount of precipitation and snowmelt above the streamgage it can serve as a basis for the calculation of a scaling index. Additionally, streamgages often provide a long-term continuous record often lacking in meteorological data from small weather stations.

The Big Wood River at Hailey (13139510) streamgage was chosen as a basis for temporal variation for a variety of reasons. It has continuously recorded discharge data since 1915 making it the oldest continuously operated streamgage in the Wood River Valley. Of the 22 tributary basin for which tributary underflow were calculated, 15 are up-valley from the streamgage including the five largest. Finally, there is only one major irrigation diversion upstream (the Hiawatha Canal).

Monthly mean discharge at the Hailey streamgage from January 1994 to December 2010 was retrieved from the USGS NWIS (USGS, 2014) (fig. 1). (Data for 1994 were retrieved for use in calculation of a moving average, described below.) This record shows extreme variability, sometimes with large month-to-month fluctuations. Because the conceptual model of tributary underflow described above suggests that the processes of infiltration and groundwater movement both integrate and lag specific recharge events, a process is needed to incorporate this before the scaling index can be calculated.

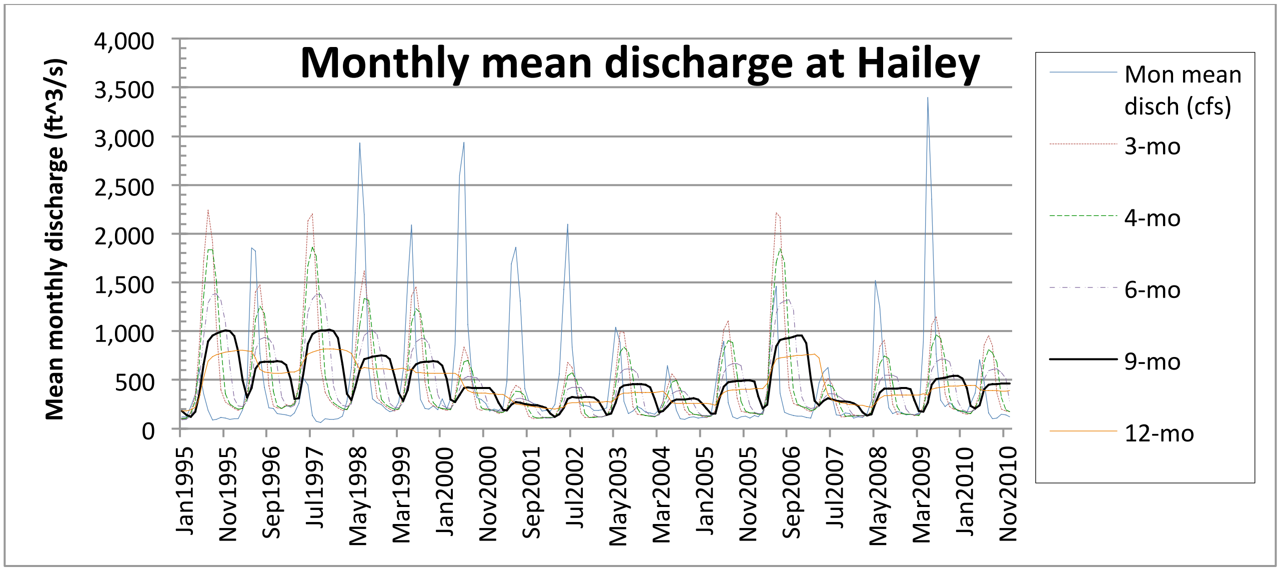

Figure 1. Monthly mean discharge at the Big Wood River at Hailey (13139510) streamgage and moving averages of discharge with windows of selected lengths, 1995-2010.

Initially, a quarterly (or seasonal) mean discharge was calculated to integrate the monthly mean discharge. Although this provided a quarterly discharge, large quarterly variability remained: more than the conceptual model suggested. Therefore, a simple moving (or running) average of the monthly mean discharge was investigated. The moving average was calculated using monthly mean discharge for different periods (of a specified number of months preceding and including a given month). A window (or period) of 3, 4, 6, 9, and 12 months were calculated; results are shown in figure 1. A 9-month window was chosen as the best compromise between timing and magnitude of monthly mean discharge. Because the window was chosen to incorporate discharge for a given month and preceding months, it has the effect of integrating recharge events in accordance with the conceptual model of tributary underflow described above. After the monthly mean discharge was calculated using a 9-month window, monthly mean discharge was aggregated into quarterly (or seasonal) mean discharge for each of the 64 quarters encompassing the 1995-2010 model period. Because the moving average is considered a type of data smoothing or filtering, monthly mean discharge calculated with the 9-month moving average will henceforth be referred to as smoothed mean discharge.

Scaling index

Once the moving average was applied to discharge at the Hailey streamgage and aggregated into quarters the scaling index was calculated. The scaling index was calculated by dividing the smoothed quarterly mean discharge by the smoothed mean discharge of all 64 quarters in the model simulation period. The calculation of the scaling index is presented in Equation 3:

$$SI = \frac{D_{sqm}}{D_{spm}} \qquad (3)$$

where

SI is the scaling index, dimensionless,

D_{sqm} is smoothed quarterly mean discharge at the Hailey streamgage in length^3/time units, and

D_{spm} is smoothed mean discharge at the Hailey streamgage for the model simulation period, in length^3/time units.

Figure 2 and table 3 show the scaling index for each quarter of the model simulation period. Scaling index values range from 0.32 to 2.2 and represent 32 to 220 percent of the smoothed mean discharge for the model simulation period..

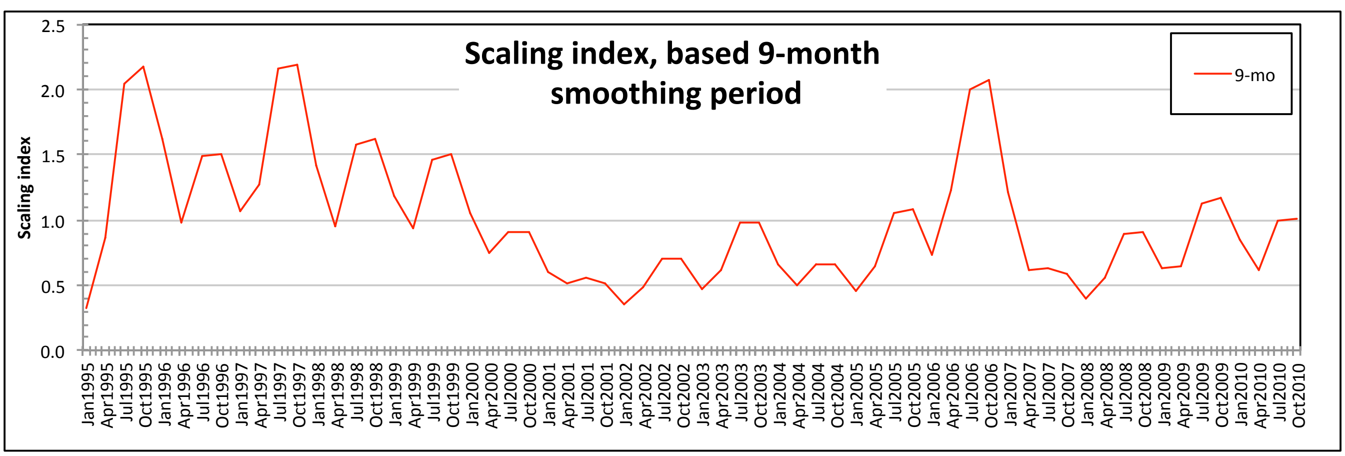

Figure 2. Scaling index by quarter, 1995-2010.

Table 3. Scaling index by quarter, 1995-2010.

Quarter	Scaling index	Quarter	Scaling index	Quarter	Scaling index	Quarter	Scaling index
Jan1995	0.32	Jan1999	1.2	Jan2003	0.47	Jan2007	1.2
Apr1995	0.86	Apr1999	0.93	Apr2003	0.61	Apr2007	0.61
Jul1995	2.0	Jul1999	1.5	Jul2003	0.98	Jul2007	0.63
Oct1995	2.2	Oct1999	1.5	Oct2003	0.99	Oct2007	0.59
Jan1996	1.6	Jan2000	1.1	Jan2004	0.65	Jan2008	0.39
Apr1996	0.98	Apr2000	0.75	Apr2004	0.50	Apr2008	0.56
Jul1996	1.5	Jul2000	0.91	Jul2004	0.65	Jul2008	0.89
Oct1996	1.5	Oct2000	0.91	Oct2004	0.66	Oct2008	0.90
Jan1997	1.1	Jan2001	0.60	Jan2005	0.45	Jan2009	0.63
Apr1997	1.3	Apr2001	0.51	Apr2005	0.64	Apr2009	0.65
Jul1997	2.2	Jul2001	0.56	Jul2005	1.0	Jul2009	1.1
Oct1997	2.2	Oct2001	0.51	Oct2005	1.1	Oct2009	1.2
Jan1998	1.4	Jan2002	0.35	Jan2006	0.74	Jan2010	0.84
Apr1998	0.96	Apr2002	0.49	Apr2006	1.2	Apr2010	0.62
Jul1998	1.6	Jul2002	0.70	Jul2006	2.0	Jul2010	0.99
Oct1998	1.6	Oct2002	0.70	Oct2006	2.1	Oct2010	1.0

Parameterization for PEST calibration

Given the uncertainty in tributary underflow estimates, they will be evaluated during model calibration using the parameter estimation program PEST (Doherty, 2004). For calibration, 23 estimation parameters will be defined in PEST: estimated mean tributary underflow for 22 tributaries and a single reduction factor to vary the amplitude of the scaling index through the model simulation period.

A stream hydrograph is a type of digital signal in the time domain because it consists of discrete measurements of discharge (the dependent variable) over time (the independent variable). A low-pass filter reduces the amplitude of the hydrograph (bringing high and low values closer to the mean) but leaves the mean the same. Thus the application of a low-pass filter for signal amplitude reduction allows tributary recharge to be varied with a single parameter.

The signal amplitude reduction algorithm chosen (McCoy, 2011) dampens the quarterly mean discharge before it is used to calculate the scaling index. The amount of amplitude reduction/damping is controlled by a reduction factor which must be greater than or equal to 1. A reduction factor of 1 does not change the quarterly mean discharge; thus damping is applied when the reduction factor is greater than 1 and the amount of damping increases with the reduction factor.

The signal amplitude reduction algorithm is implemented in two steps. The first, shown in equation 4, calculates a temporary signal:

$$TS = \frac{D_{sqm}}{RF} \tag{4}$$

where

TS is the temporary signal, in length^3/time units,

D_{sqm} is smoothed quarterly mean discharge at the Hailey streamgage in length^3/time units, and

RF is the reduction factor, dimensionless.

Then

$$SAR = D_{spm} - TS_m + TS \tag{5}$$

where

SAR is the single amplitude reduction, in length^3/time units,

D_{spm} is smoothed mean discharge at the Hailey streamgage for the model simulation period, in length^3/time units,

TS is the temporary signal, in length^3/time units, and

TS_m is the mean temporary signal for the model simulation period, in length^3/time units.

Once the damped quarterly discharge has been calculated, the scaling index is calculated as described in the previous section. Figure 3 shows the scaling index with selected values of the reduction factor.

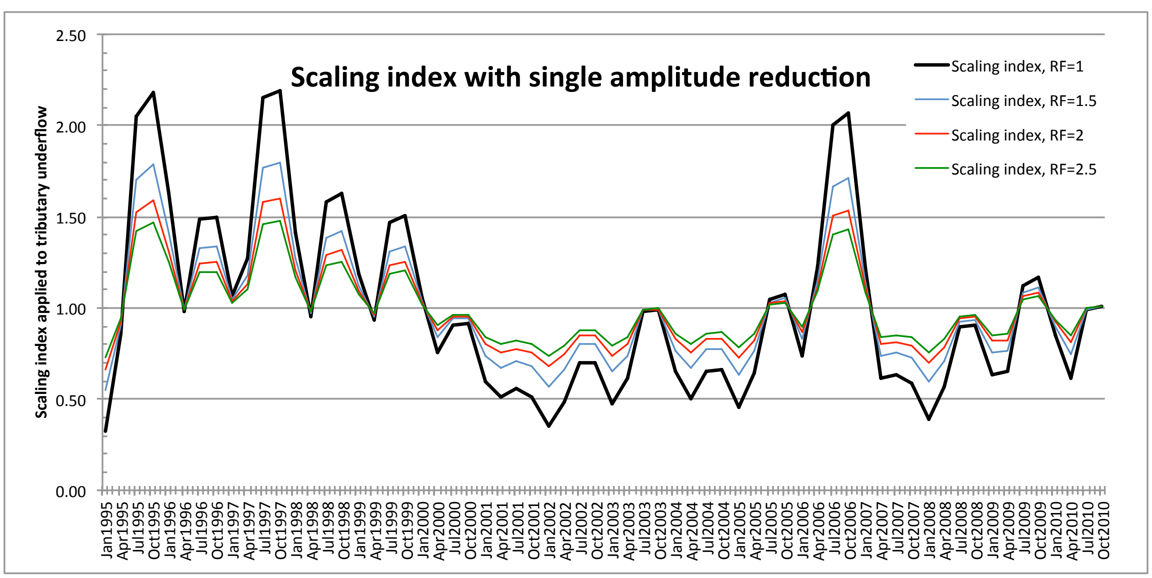

Figure 3. The scaling index with single amplitude reduction at selected values of the reduction factor.

During steady-state calibration PEST will be allowed to vary the estimated mean tributary underflow for 22 tributaries. During the transient calibration the 22 mean tributary underflow values and the reduction factor will be allowed to vary.

Summary

Mean underflow into the Wood River Valley aquifer system from 22 tributary valleys is estimated using the estimates saturated cross-sectional area in tributary canyons and water-table gradients in the Darcy equation. Underflow from the smallest tributary valleys is estimated as a fraction of basin yield determined from an analysis of the ratio of estimated flux to basin yield in larger tributaries. These estimates of tributary underflow are then adjusted to represent seasonal variation on the basis of the monthly mean discharge at the Big Wood River at Hailey streamgage. A 9-month moving average is applied to the mean monthly discharge values from which a scaling index is calculated. During steady-state calibration PEST will be allowed to vary the estimated mean tributary underflow for 22 tributaries. During the transient calibration the 22 mean tributary underflow values and the reduction factor will be allowed to vary.

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