# Design Document: Tributary volumetric flux estimates

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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 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 streamflow. However, the ground-water flow model currently under development requires separate estimates of these components.

## Design decision

Several approaches for determining the volumetric flux of tributary underflow were investigated. First, specification of a constant head boundary 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 are not directly comparable. 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 used 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

$\mathrm{Cos}^{-1}$ is in radians.

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

$$Q = KAh \tag{2}$$

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 basin information.

| Tributary | Saturated thickness (ft) | Tributary width (ft) | Area ($ft^2$) | Land surface gradient | Estimated underflow (Acre-ft/yr) | Basin Area ($mi^2$) | Average precipitation (in) | Basin yield (Acre-ft/yr) | Estimated underflow/ Basin yield |
|---|---|---|---|---|---|---|---|---|---|
| Adams Gulch | 48 | 650 | 24,694 | 0.0482 | 851 | 11 | 30 | 17,600 | 0.048 |
| Chocolate Gulch | 59 | 709 | 32,778 | 0.0727 | 1703 | 0.75 | 21.6 | 864 | 1.972 |
| Clear Crk | 35 | 623 | 17,074 | 0.0795 | 971 | 2.2 | 19.5 | 2,288 | 0.424 |
| Cold Springs Gulch | 63 | 344 | 17,112 | 0.0576 | 705 | 2.9 | 21.6 | 3,341 | 0.211 |
| Cove Canyon | 7 | 3058 | 15,909 | 0.0127 | 145 | 14 | 15 | 11,200 | 0.013 |
| Croy Creek | 40 | 1391 | 43,660 | 0.0226 | 704 | 28 | 15.8 | 23,595 | 0.030 |
| Deer Crk | 74 | 2277 | 131,783 | 0.0155 | 1462 | 55 | 25.3 | 74,213 | 0.020 |
| Eagle Crk | 75 | 1066 | 62,946 | 0.0226 | 1015 | 11 | 29.4 | 17,248 | 0.059 |
| East Frk | 43 | 1414 | 48,259 | 0.0137 | 471 | 86 | 26.3 | 120,629 | 0.004 |
| Elkhorn Gulch | 8 | 387 | 2,483 | 0.0289 | 51 | 13 | 18.4 | 12,757 | 0.004 |
| Greenhorn Gulch | 78 | 860 | 52,395 | 0.0182 | 682 | 21 | 27.2 | 30,464 | 0.022 |
| Indian Sprgs Crk | 83 | 1070 | 69,452 | 0.0485 | 2407 | 11 | 17.3 | 10,149 | 0.237 |
| Lake Crk | 68 | 1335 | 71,257 | 0.0472 | 2406 | 12 | 27 | 17,280 | 0.139 |
| Lees Gulch | 57 | 827 | 37,328 | 0.0556 | 1484 | 2.8 | 15 | 2,240 | 0.662 |
| Ohio Gulch | 85 | 1243 | 83,032 | 0.0664 | 3940 | 5.1 | 15.7 | 4,270 | 0.923 |
| Quigley Crk | 60 | 1325 | 62,378 | 0.0126 | 560 | 17 | 17.1 | 15,504 | 0.036 |
| Seamans Creek | 156 | 1391 | 170,357 | 0.0160 | 1949 | 23 | 15.3 | 18,768 | 0.104 |
| Slaughterhouse Gulch | 60 | 745 | 35,380 | 0.0200 | 506 | 13 | 16.6 | 11,509 | 0.044 |
| Townsend Gulch | 63 | 728 | 35,835 | 0.0476 | 1218 | 1.2 | 15 | 960 | 1.269 |
| Trail Crk | 125 | 2152 | 212,020 | 0.0191 | 2898 | 64 | 32.6 | 111,274 | 0.026 |
| Warm Sprgs Crk | 46 | 1617 | 58,006 | 0.0117 | 487 | 96 | 35.3 | 180,735 | 0.003 |
| TOTAL: | | | | | 26,600 | | | | |

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. It is proposed that this mean ratio be 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 of tributary underflow and selected 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) |
|---|---|---|
| Adams Gulch | 11 | 851 |
| Chocolate Gulch * | 0.75 | 52 |
| Clear Crk * | 2.2 | 137 |
| Cold Springs Gulch * | 2.9 | 200 |
| Cove Canyon | 14 | 145 |
| Croy Creek | 28 | 704 |
| Deer Crk | 55 | 1,462 |
| Eagle Crk | 11 | 1,015 |
| East Frk | 86 | 471 |
| Elkhorn Gulch | 13 | 51 |
| Greenhorn Gulch | 21 | 682 |
| Indian Sprgs Crk | 11 | 2,407 |
| Lake Crk | 12 | 2,406 |
| Lees Gulch * | 2.8 | 134 |
| Ohio Gulch * | 5.1 | 256 |
| Quigley Crk | 17 | 560 |
| Seamans Creek | 23 | 1,949 |
| Slaughterhouse Gulch | 13 | 506 |
| Townsend Gulch * | 1.2 | 58 |
| Trail Crk | 64 | 2,898 |
| Warm Sprgs Crk | 96 | 487 |
| TOTAL: | | 17,400 |

## Summary

The volumetric fluxes of tributary underflow into the Wood River Valley aquifer system were made using the estimated saturated cross-sectional area in tributary canyons and estimated water-table gradients in a form of the Darcy equation. Volumetric flux from the smallest tributary canyons were estimated as a fraction of basin yield determined from an analysis of the ratio of estimated flux to basin yield in larger tributaries.

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