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# Wyoming State Geological Survey Statewide Groundwater Baseflow Study

By Karl G. Taboga and James E. Stafford

Open File Report 2016-8
November 2016

**Wyoming State Geological Survey**

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Open File Report 2016-8
Wyoming State Geological Survey
Laramie, Wyoming: 2016

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Citation: Taboga, K.G., and Stafford, J.E., 2016, Wyoming State Geological Survey statewide groundwater baseflow study: Wyoming State Geological Survey Open File Report 2016-8, 16 p.

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## INTRODUCTION

Groundwater recharge, "the process by which water enters the groundwater system or, more precisely, enters the phreatic zone," (Sharp, 2007) is typically "the most difficult component of the groundwater system to quantify," (Bredehoeft, 2007). Recharge is not a single physical mechanism but consists of a series of physical processes that begin at the land's surface and, driven by gravity, continue through the unsaturated (vadose) and capillary zones into the saturated (phreatic) zone. All of this occurs in subterranean environments that typically possess highly variable physical properties in three dimensions.

Recharge rates cannot be directly measured but are estimated using indirect approaches. Numerous recharge estimation methods, developed by researchers in the last 100 years, are available to the groundwater professional. The choice of an appropriate technique is determined largely by the environmental setting and scale of the area to be evaluated as well as cost and data limitations. Healy and Scanlon (2010) and Scanlon and others (2002) provide comprehensive descriptions of the methods in current use with critical appraisals of the theory and assumptions associated with each method.

Frequently, empirical models are used to estimate recharge over wide geospatial areas (Scanlon and others, 2002). Empirical models are data driven and do not require a detailed understanding of the internal physical processes of a system, in this case the conversion of precipitation to recharge. Instead, empirical models are used to find simple mathematical relationships between inputs (precipitation), environmental components (slope, aspect, land uses, soil characteristics, etc.), and outputs (such as baseflow and streamflow rates). Also called black box models, empirical models are suited to problems where internal processes are not well understood or difficult to observe.

One significant component of recharge is baseflow, that is, groundwater that discharges directly to stream channels, tributary springs, wetlands, lakes, and seeps. In semi-arid environments, baseflow contributions to streamflow are most visible during low precipitation months (usually October through February) and extended periods of drought. Baseflows constitute an important water resource in Wyoming. They are first accessed through the shallow (< 1,000 ft in depth) wells characteristic of Wyoming groundwater rights (Taboga and others, 2014a; 2014b; Taucher and others, 2013) and then by surface water users who typically hold senior water rights. Baseflow represents an interconnection between surface and groundwater resources that is recognized in Wyoming water law (WSEO, 2006a, b) and is the subject of increasing U.S. Geological Survey (USGS) research (Reynolds and Shafroth, 2016; Plume and Smith, 2013; Barlow and Leake, 2012; Eddy-Miller and others, 2009).

This report details the methodology and results of a Wyoming State Geological Survey (WSGS) project that provides estimates of the baseflow component of groundwater recharge using an empirical model and geospatial software. Baseflow represents an effective measure of total recharge given the hydrogeologic framework of Wyoming's structural basins.

Most recharge originates in mountainous and upland areas where seasonal precipitation rates are higher and evapotranspiration (ET) rates are lower than in the adjacent semi-arid basins. The greatest portion of this recharge discharges to headwater streams and tributary springs located within upland areas or along the margins of the semi-arid basins (Huntoon, 1993). Due to substantial decreases in basinward permeabilities, groundwater flows to basin interiors are likely less than 10 percent of total upland recharge received (Ball and others, 2014;Huntoon, 1993).

In contrast, low levels of precipitation, high ET rates, and relatively impermeable clayey soils limit direct precipitation recharge in basin interiors to infrequent episodes of high intensity precipitation in local areas (Guan and Wilson, 2004). Even then, most of the standing water held in puddles and playas may evaporate prior to infiltration. In wide areas of the semi-arid basins, potential ET exceeds the low rates of precipitation (Long and others, 2014; Sanford and Selnick, 2013; this study).

Finally, previous investigations indicate that groundwater in the uppermost basin aquifers of Wyoming discharges as baseflow to streams (Thamke and others, 2014; Bartos and others, 2011; Clarey and others, 2010; Avery and Pettijohn, 1984).

The primary objective of this project was to develop a simple model capable of making reasonable large-scale estimations of baseflow for the state of Wyoming using precipitation data, other readily available environmental data, and Geographic Information Systems (GIS) techniques. Accuracy was evaluated by comparing estimates generated by the WSGS model to streamflows in gaged watersheds and recharge estimates obtained from existing models in selected Wyoming basins.

## METHODS

The approach used in this study is based on a generalized water budget equation for watersheds (Scanlon and others, 2002):

$$\textit{Precipitation (P) + inflows } (Q_{in}) = \textit{evapotranspiration (ET) + outflows } (Q_{out}) + \textit{changes in storage } (\Delta S) \qquad (1)$$

Water inflows include groundwater and surface water inflows from adjacent areas and water imported from outside of the watershed. Outflows consist of stream and groundwater flows out of the watershed and water exported to other basins. WSGS chose USGS gaging stations located on free-flowing, unrestricted (without large dams or diversions) watersheds with streamflow records of 30 years or more so that changes in storage, water imports, and water exports can be considered to equal zero. Groundwater and surface water divides were assumed to be spatially coincident; watershed areas were generated from a USGS Digital Elevation Model (DEM) for all reaches upstream of each gaging station. In this way, groundwater inflows could be neglected. Finally, groundwater outflows need not be considered in evaluations of baseflow.

With this approach, equation 1, above, can be simplified to:

$$P\text{-}ET \approx \textit{streamflow (RO)} \qquad (2)$$

Streamflows (also called runoff) are composed primarily of overland flows that occur during precipitation events or rapid snowmelt, and baseflows as groundwater discharges directly into a streambed or from springs that flow into the stream. For this study, WSGS assumed that during long periods of time (several decades) all recharge not lost to ET or groundwater outflow is discharged to streams as baseflow (Schicht and Walton, 1961).

Because streamflow measurements are not available for many watersheds, WSGS constructed a Wyoming-specific model that estimates the fraction of precipitation lost to ET similar to the model developed by Sanford and Selnick (2013) for the contiguous states. The remaining fraction is discharged from the drainage as streamflow, some portion of which may be lost to consumptive uses. Irrigation typically constitutes the largest consumptive use in Wyoming's semi-arid river basins while industrial, domestic, and municipal water demands may account for significant consumptive uses in more developed areas (WWC and others, 2007).

WSGS investigated several environmental factors identified by previous researchers (Cherkauer and Ansari, 2005; Scanlon and others, 2002; Arnold and Allen, 1999; Hamerlinck and Arneson, 1998) as drivers of the spatial distribution of recharge. These include temperature, precipitation, the physical properties of soils and rocks, land cover, and topography.

### Geospatial data

WSGS used readily available geospatial environmental data from several websites accessible by the public:

- Yearly average climate data for precipitation, and minimum, maximum, and mean air temperatures were obtained from the PRISM (Parameter-elevation Relationships on Independent Slopes Model) Climate Group (http://prism.oregonstate.edu/) at Oregon State University for the 30-year period from 1981–2010. PRISM computes average values for precipitation and temperature for the preceding 30 years at the end of each decade, so the 1981–2010 period represents the most recent dataset.

- Land cover data were retrieved from the Multi-Resolution Land Characteristics (MRLC) Consortium (NLCD 2011) online at: http://www.mrlc.gov/.

- Yearly streamflow data at USGS stream gaging stations, 30 m DEM, and STATSGO1 (State Soil Geographic) database were accessed on the USGS website: http://www.usgs.gov/. Yearly data was used to construct average annual streamflows at selected USGS stream gaging stations for the 1981–2010 period of record (POR) covered by the climate data.

- WSGS reassigned the geologic units shown on the Geologic Map of Wyoming (Love and Christiansen, 1985) to broad rock types based on lithology. Characteristic hydraulic conductivities (Freeze and Cherry, 1979) were assigned to these rock types; units occurring in mountainous areas or on highland slopes of 4 percent or more were assumed to possess significant fracture permeability.

- Using ArcMap 10.3 GIS platform, all raster datasets were transformed to the same cell size (~0.8 km x 0.8 km; 0.5 x 0.5 mi) and boundaries. Minimum and maximum temperatures were converted to average annual temperature ranges. Land cover categories were reassigned to simplified classes (Sandford and Selnick, 2013). The digital elevation land surface model was converted to a slope model. Raster files of average soil permeabilities were created from the STATSGO1 database.

WSGS evaluated streamflow data from all USGS stream gage stations in Wyoming. Unrestricted watersheds were selected for inclusion in the project if the stream gauge had been in operation during the 1981–2010 POR of the PRISM meteorological data. Nineteen Wyoming watersheds met the selection criteria (fig. 1). WSGS then used a series of ArcGIS hydrography tools to delineate the spatial extent of the drainage basin for each qualifying gage from the USGS 30 m DEM. GIS was used to estimate precipitation, land cover, temperature, soil permeability, surface area, longest flowpath, and surface slope data for each selected basin.

**Evapotranspiration rates**

Mean observed annual ET rates (as fractions of precipitation) were calculated from PRISM precipitation and USGS streamflow data during the 1981–2010 POR for the selected Wyoming watersheds as:

$$\frac{ET}{P} \approx \frac{\text{Mean annual precipitation (P) - mean annual streamflow (R)}}{\text{Mean annual Precipitation (P)}} \qquad (3)$$

WSGS then developed a spreadsheet model to estimate the fraction of precipitation lost to ET (ET/P ratio) in each selected drainage from land cover, precipitation, mean air temperature, and temperature range data. The WSGS ET model uses the general form of the ET equation developed by Sanford and Selnick (2013) for the contiguous United States but incorporates unique parametric values (equation coefficients and exponents) for Wyoming. Model parameters were optimized with the Generalized Reduced Gradient (GRG) algorithm in the Solver platform of Microsoft Excel by minimizing the difference between model estimates and observed annual ET rates (eq. 3).

The ET spreadsheet equation was incorporated into ArcMap 10.3 GIS to estimate ET/P ratios in each 0.8 km x 0.8 km geospatial cell in Wyoming. The WSGS ET model was further evaluated by comparing ET/P estimates obtained from the GIS application to:

- River Basin Groundwater Plan water balance estimates (Taucher and others, 2013; Taboga and others, 2014a, b)

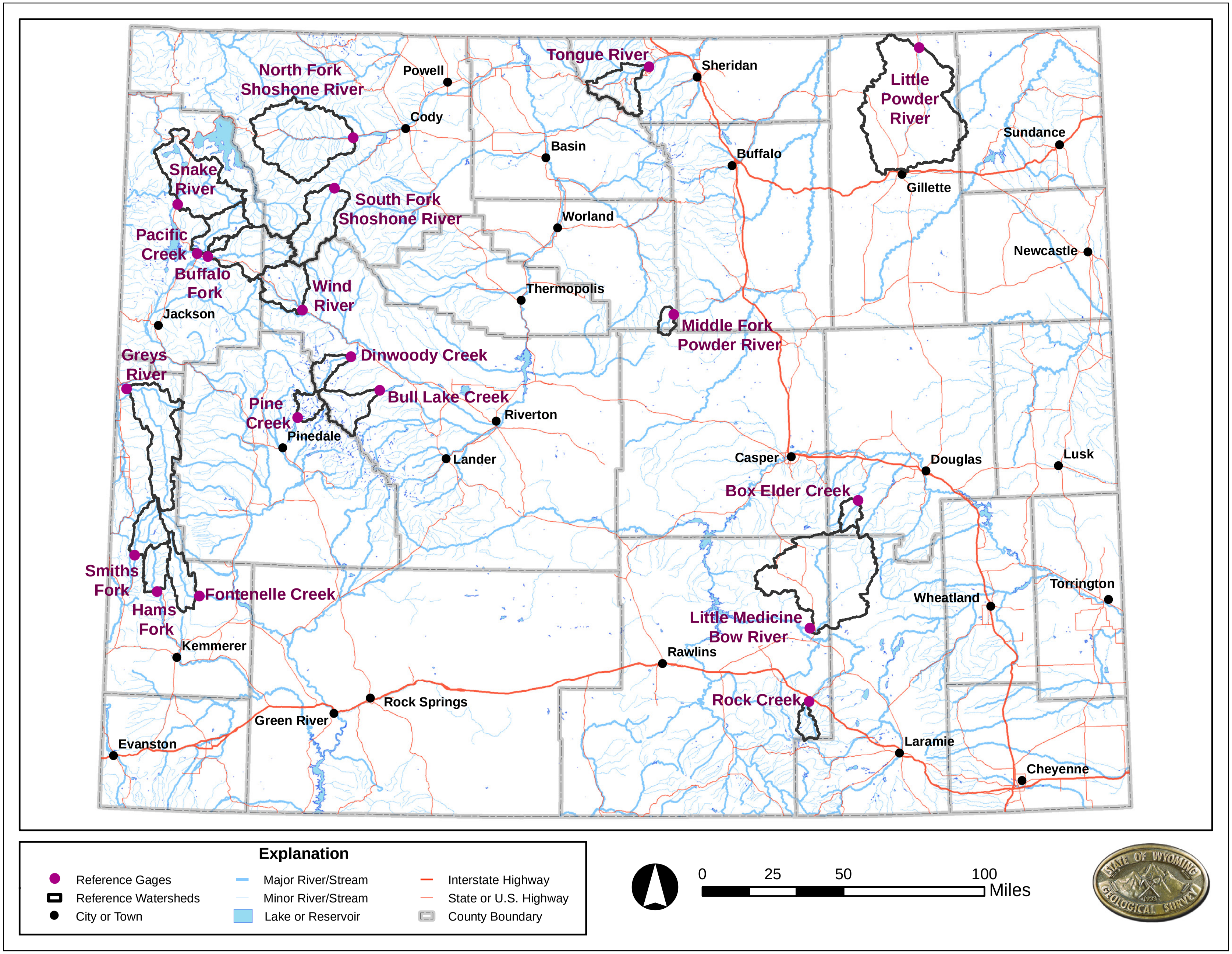



**Figure 1.** Free-flowing, unrestricted watersheds upstream of United States Geological Survey (USGS) gaging stations with streamflow records of 30 years or more selected for baseflow analysis.

- ET estimates for selected watersheds obtained from the application of the Sanford and Selnick (2013) ET model

Mean runoff fractions (RO/P) were calculated for each cell by subtracting ET/P from 1. Mean RO/P represents the average portion of precipitation discharged as streamflow during the 1981–2010 POR. Modeled values were compared to observed RO/P values obtained from the USGS stream gages at each site.

### Observation-based watershed baseflows

Baseflows for the selected watersheds were estimated using USGS data and software. WSGS used the USGS Groundwater Toolbox (http://water.usgs.gov/ogw/gwtoolbox/) to estimate the mean proportion of baseflow contribution to annual streamflows at each specified gaging station. The Groundwater Toolbox uses six hydrograph separation techniques: the Standard and Modified versions of the Base-Flow Index (BFI) method, Fixed Interval, Sliding Interval, and Local Minimum versions of the Hydrograph Separation (HYSEP) modeling package and the Streamflow Partitioning (PART) method to estimate baseflow from streamflow time series data. Results from all six hydrograph separation techniques were averaged to determine mean annual baseflows for the 19 selected Wyoming drainages. Descriptions of the methods and software used by the USGS to calculate these observation-based flows can be found on the Groundwater Toolbox website.

### Baseflow rates

Estimated runoff fractions (RO/P), slope, soil permeability, flowpath, watershed area, and rock conductivity values for each selected watershed were tabulated. Initial regression analyses were conducted to assess the degree of correlation between each of these environmental variables and observed baseflow fractions obtained from the USGS hydrograph separation analyses. WSGS then developed spreadsheet equations using various combinations of the above environmental variables to model baseflow fractions of runoff (BF/RO). The form of the equation was chosen such that the annual recharge rate would equal zero in cells where annual runoff is zero (annual rates of ET equal or exceed precipitation). As with the ET model, equation parameters were optimized using a GRG method in Microsoft Excel's Solver program. Modeled baseflow fractions from parameterized equations were evaluated by constructing linear regressions against observed baseflow fractions. Equations that produced recharge estimates in substantial agreement with observed values ($R^2 \geq 0.70$) were incorporated into an ArcMap 10.3 GIS model based on a statewide grid with cells ~ 800 meters square (0.5 mi x 0.5 mi).

To evaluate the GIS model, WSGS plotted modeled baseflow levels against the observational levels obtained from the USGS Groundwater Toolbox in each of the selected watersheds. Further evaluations were conducted by comparing WSGS model outputs to recharge estimates derived from Hamerlinck and Arneson (1998) for watersheds at varied scales and to recent areal recharge estimates obtained from USGS soil water balance models for the Powder River Structural Basin (Long and others, 2014) and the High Plains aquifer in Wyoming (Stanton and others, 2011).

## RESULTS

### Geospatial data and evapotranspiration rates

Environmental data for the 19 selected watersheds (fig. 1) obtained from the GIS extractive processes and the WSGS ET model are shown in table 1. The selected drainages are located across Wyoming (fig.1) and in every major river basin; many, however, are found in the mountainous western part of the state, specifically the Snake-Salt River Basin. The selected watersheds occur in a wide range of western environmental settings. Climate types (Peel and others, 2007) range from cold semi-arid steppe (Little Powder River and Little Medicine Bow River Basins) to the humid, snow-dominated, cool-summer type in the Pacific Creek drainage (Peel and others, 2007). Annual average precipitation ranges from 37 cm (14.5 in) in the Little Medicine Bow River watershed to 100 cm (40 in) in the Snake River watershed. Average annual temperatures vary from -0.51°C (31°F) on the Dinwoody Creek site to 7.54°C (45.6°F) at the Little Powder River site.

**Table 1.** Calculated and modeled evapotranspiration fractions in selected Wyoming watersheds (adapted from Sanford and Selnick, 2012). Tm=mean annual daily temperature (°C); Tx=mean annual maximum temperature (°C); Tn=mean annual minimum daily temperature (°C); P=mean annual precipitation (cm) $\Lambda$=(1+cLd+eLf+hLs+jLg+kLa+rLm), where Li is the fraction of landcover type i within the watershed and subscripts d, developed; f, forested; s, shrubland; g, grassland; a, agricultural; m, marsh.

$$ET/P = \Lambda(\tau\Delta/(\tau\Delta+\Pi))$$

$$\tau=(T_m+T_o)m/(T_m+T_o)m+a;\ \Delta=(T_x-T_n)/(T_x-T_n)+a,\ \Pi=P/P_o$$

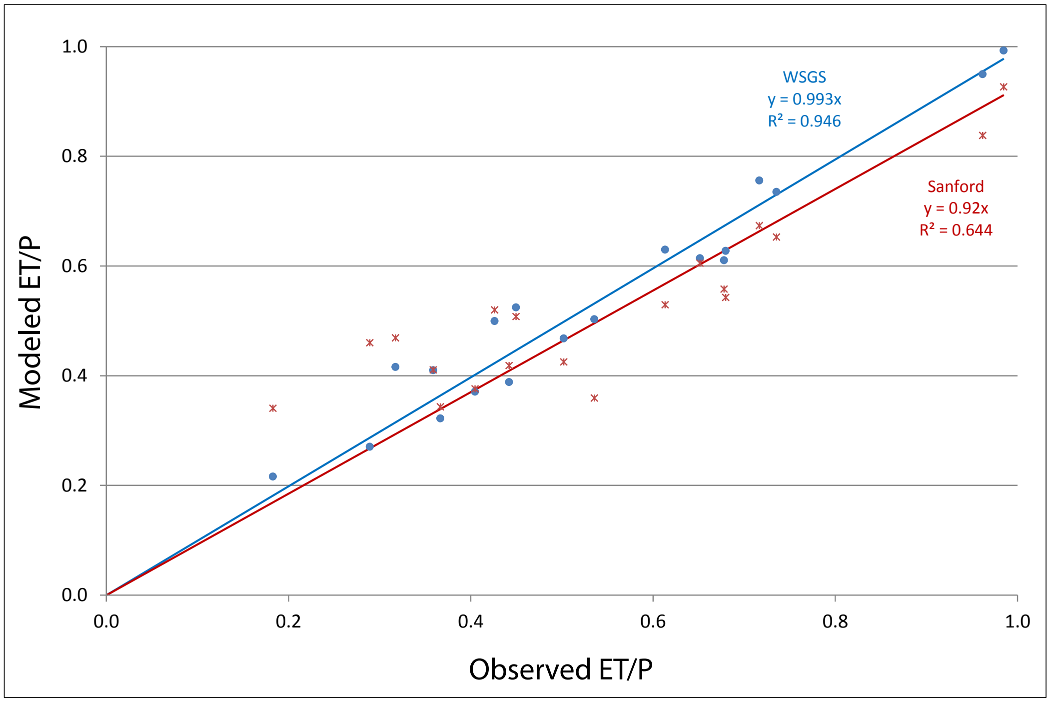
| $T_o$ | $P_o$ | m | n | a | b | c | e | h | j | k | r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.396 | 89.056 | 3.000 | 2.431 | 7.450 | 19.996 | 0.000 | 1.000 | 0.157 | 0.282 | 0.816 | 1.000 |

| WATERSHED | ET/P | $\tau$ | $\Delta$ | $\Pi$ | $\Lambda$ | | | | | | ET/P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Observed | $T_m$ (dC) | $T_x - T_n$ (dC) | P (cm) | Ld | Lf | Ls | Lg | La | Lm | Modeled |
| Box Elder Creek | 0.72 | 3.784 | 12.606 | 64.789 | 0.000 | 0.612 | 0.365 | 0.007 | 0.000 | 0.015 | 0.76 |
| Buffalo Fork | 0.40 | 0.612 | 12.982 | 91.329 | 0.002 | 0.534 | 0.320 | 0.099 | 0.003 | 0.031 | 0.37 |
| Bull Lake Creek | 0.32 | 0.224 | 12.029 | 75.229 | 0.000 | 0.309 | 0.229 | 0.372 | 0.001 | 0.004 | 0.42 |
| Dinwoody Creek | 0.29 | -0.513 | 12.389 | 77.502 | 0.000 | 0.172 | 0.250 | 0.434 | 0.000 | 0.003 | 0.27 |
| Fontenelle Creek | 0.74 | 2.614 | 14.109 | 59.199 | 0.000 | 0.276 | 0.484 | 0.219 | 0.003 | 0.017 | 0.73 |
| Greys River | 0.43 | 2.613 | 13.355 | 83.999 | 0.000 | 0.555 | 0.326 | 0.106 | 0.000 | 0.009 | 0.50 |
| Hams Fork | 0.68 | 2.515 | 12.585 | 73.845 | 0.000 | 0.564 | 0.267 | 0.137 | 0.000 | 0.030 | 0.61 |
| Little Medicine Bow River | 0.96 | 4.368 | 14.874 | 36.684 | 0.002 | 0.035 | 0.797 | 0.152 | 0.002 | 0.009 | 0.95 |
| Little Powder River | 0.98 | 7.536 | 14.990 | 37.321 | 0.006 | 0.031 | 0.304 | 0.627 | 0.010 | 0.010 | 0.99 |
| Middle Fork Powder River | 0.65 | 3.010 | 10.391 | 61.135 | 0.000 | 0.155 | 0.255 | 0.580 | 0.000 | 0.009 | 0.61 |
| North Fork Shoshone River | 0.45 | 1.382 | 12.243 | 74.678 | 0.002 | 0.442 | 0.305 | 0.193 | 0.002 | 0.003 | 0.52 |
| Pacific Creek | 0.36 | 1.606 | 13.774 | 89.054 | 0.000 | 0.412 | 0.497 | 0.044 | 0.000 | 0.029 | 0.41 |
| Pine Creek | 0.18 | -0.091 | 11.810 | 95.745 | 0.000 | 0.165 | 0.340 | 0.402 | 0.000 | 0.001 | 0.22 |
| Rock Creek, Platte | 0.50 | 1.267 | 12.873 | 89.022 | 0.000 | 0.767 | 0.058 | 0.142 | 0.001 | 0.025 | 0.47 |
| Smiths Fork | 0.54 | 2.707 | 12.904 | 81.923 | 0.000 | 0.508 | 0.341 | 0.140 | 0.001 | 0.006 | 0.50 |
| Snake River | 0.37 | 1.214 | 13.521 | 99.389 | 0.002 | 0.414 | 0.447 | 0.070 | 0.000 | 0.026 | 0.32 |
| South Fork Shoshone River | 0.44 | 0.237 | 11.770 | 79.556 | 0.000 | 0.392 | 0.245 | 0.243 | 0.003 | 0.007 | 0.39 |
| Tongue River | 0.61 | 1.599 | 11.668 | 70.037 | 0.010 | 0.604 | 0.205 | 0.170 | 0.000 | 0.010 | 0.63 |
| Wind River | 0.68 | 0.918 | 13.603 | 70.129 | 0.004 | 0.566 | 0.289 | 0.079 | 0.002 | 0.037 | 0.63 |

Dominant landcover types differ widely in the selected drainages. Forested landcover occurs typically in mountainous areas; however, some mountainous drainages are dominated by shrublands and grasslands. Typical of Wyoming, less than 1 percent of the surface area of the selected drainages has been developed. Agriculture, too, accounts for 1 percent or less of land use in the watersheds, although this is probably the result of selecting unrestricted watersheds where the presence of irrigation diversions is less likely.

WSGS modeled ET/P estimates (in blue) correlate closely with observed ET/P (fig. 2) in the selected watersheds. The accuracy of estimates from Sanford and Selnick (2013), in red, point to the robust nature of their model generated from baseflow analyses of 838 watersheds across the conterminous United States. The development of the ET model allows for the calculation of runoff in watersheds where streamflow gages are not present.

**Figure 2.** Linear regressions of WSGS (blue) and Sanford and Selnick (red) modeled (y) and observed ET/P (x) rates for 19 selected Wyoming watersheds. Regression equation and coefficient of determination ($R^2$) values are shown in inset.




## Watershed hydrologic characteristics and baseflow

Selected watershed hydrologic characteristics are shown in table 2. Mean annual runoff spans a large range of values (0.08–73 cm). Observed average annual baseflow fractions, calculated from the USGS Groundwater Toolbox, range from 0.3 (Little Powder River) to nearly 0.9 (Smiths Fork). Regression analyses of observed baseflow fractions (not shown) showed positive non-linear correlations with runoff ($R^2$=0.88) and watershed slope ($R^2$=0.44), and negative correlations with longest flow path ($R^2$=0.47) and watershed area ($R^2$=0.48). Observed baseflow fractions did not correlate well with soil permeability ($R^2$=0.06) and rock conductivity ($R^2$=0.06).

A wide variety of equations and variables were tested first by evaluating correlations between observed and modeled baseflow fractions. Equations that produced outputs in substantial agreement with observed values ($R^2 \geq 0.70$) were incorporated into a geospatial model based on a statewide grid with cells about 800 meters square (approximately 0.5 mi x 0.5 mi). Results from the GIS models were compared to observed baseflow fractions for the selected watersheds. The resultant equation is:

$$BF/RO = 0.485\ (RO^{4.069}\ (M^{2.751} + 0.013)\ P^{0.010})^{0.0253} \qquad (4)$$

where, BF = baseflow; RO = runoff (cm); M = slope (degrees); and P = soil permeability (cm/hr).

**Table 2.** Spatially averaged environmental data for 19 selected Wyoming watersheds evaluated for use in the construction of the empirical baseflow model. LFP – Longest streamflow path.

| Drainage | Obs. Baseflow (fraction of runoff) | Runoff (cm) | Precip. (in) | Slope (degrees) | Soil Perm. (cm/hr) | Bedrock K (cm/hr) | LFP (miles) | Surface Area (miles$^2$) |
|---|---|---|---|---|---|---|---|---|
| Box Elder Creek | 0.679 | 13.25 | 25.50 | 12.42 | 14.17 | 0.29 | 18.16 | 167 |
| Buffalo Fork | 0.788 | 57.34 | 36.00 | 14.37 | 9.92 | 1.22 | 44.73 | 851 |
| Bull Lake Creek | 0.781 | 44.06 | 29.60 | 18.36 | 6.40 | 0.62 | 28.63 | 485 |
| Dinwoody Creek | 0.806 | 49.41 | 30.50 | 22.26 | 6.56 | 1.90 | 22.17 | 227 |
| Fontenelle Creek | 0.846 | 19.58 | 23.30 | 12.06 | 7.73 | 0.35 | 35.85 | 397 |
| Greys River | 0.866 | 40.63 | 33.10 | 18.84 | 8.22 | 0.34 | 64.09 | 1,160 |
| Hams Fork | 0.783 | 29.82 | 29.10 | 11.40 | 7.57 | 0.44 | 30.12 | 333 |
| Little Medicine Bow River | 0.587 | 3.54 | 14.40 | 3.96 | 7.35 | 0.08 | 70.91 | 2,514 |
| Little Powder River | 0.315 | 0.08 | 14.70 | 4.92 | 5.46 | 0.22 | 110.70 | 3,190 |
| Middle Fork Powder River | 0.712 | 25.14 | 24.10 | 7.27 | 4.59 | 18.00 | 9.30 | 117 |
| North Fork Shoshone River | 0.873 | 39.69 | 29.40 | 23.51 | 8.15 | 0.24 | 50.22 | 1,811 |
| Pacific Creek | 0.759 | 53.24 | 35.10 | 11.42 | 9.67 | 1.97 | 31.07 | 421 |
| Pine Creek | 0.835 | 73.55 | 37.70 | 18.61 | 6.94 | 0.21 | 16.31 | 198 |
| Rock Creek, Platte | 0.719 | 47.29 | 35.00 | 10.22 | 10.05 | 0.09 | 17.79 | 163 |
| Smiths Fork | 0.896 | 40.50 | 32.25 | 17.64 | 9.03 | 0.61 | 31.19 | 426 |
| Snake River | 0.782 | 67.41 | 39.10 | 9.06 | 10.96 | 0.79 | 50.87 | 1,266 |
| South Fork Shoshone River | 0.743 | 47.97 | 31.30 | 26.07 | 10.01 | 0.30 | 36.45 | 794 |
| Tongue River | 0.800 | 27.65 | 27.60 | 11.06 | 5.63 | 2.32 | 30.61 | 534 |
| Wind River | 0.817 | 30.57 | 27.60 | 12.51 | 6.22 | 5.15 | 28.19 | 595 |

Observed and modeled baseflow levels for the 19 study watersheds are listed in table 3. The average error of estimates generated by equation 4 is 9.9 percent from the spreadsheet model and 11.9 percent for the GIS model. Minimum, maximum, mean, and ranges of values generated for model cells are shown. The final form of the baseflow equation was determined by evaluating the results obtained from its application in GIS. Model outputs were reviewed to minimize average error, the frequency of maximum BF/RO values exceeding 1.0 (100 percent), and the maximum difference between observed and modeled values in any single watershed (almost always in the Little Powder River site).

BF/RO values of zero occur in cells where estimated ET equals or exceeds mean annual precipitation, meaning that there is no precipitation available for recharge. Zero values constitute the minimum BF/RO in almost all of the selected watersheds (table 3, fig. 3). Statewide, estimated baseflow is zero for about 43 percent of all model cells, most of which are located within basin interiors.

Results for the spreadsheet and GIS models are plotted against observed baseflow fractions in figures 4a and 4b. Dashed lines indicate an error envelope of ±20 percent of observed values; the solid line, with a slope of 1, depicts full agreement between observed and modeled values.

Migration of the baseflow equation from the spreadsheet model to the ArcMap 10.3 model increased the average error from around 10 percent to 12 percent (table 3). The observed increase in error is likely due to the use of watershed-averaged values (inputs) for precipitation, slope, and soil porosity in the spreadsheet model, while the GIS model estimates recharge from input values determined for each cell. Other than the Little Powder River watershed where

**Table 3.** Observed and calculated baseflow for 19 Wyoming study watersheds. Calculations were made with equation 4, in spreadsheet and GIS formats.

| WATERSHED | Baseflow, fraction of runoff | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Observed | Spreadsheet Model | % difference | GIS Modeled BF/RO | | | | |
| | | | | min | max | range | average | % difference |
| Box Elder Creek | 0.68 | 0.75 | 11.2% | 0.00 | 0.87 | 0.87 | 0.57 | 16.5% |
| Buffalo Fork | 0.79 | 0.89 | 12.4% | 0.00 | 1.04 | 1.04 | 0.79 | 0.1% |
| Bull Lake Creek | 0.78 | 0.88 | 12.3% | 0.00 | 1.03 | 1.03 | 0.79 | 1.4% |
| Dinwoody Creek | 0.81 | 0.90 | 11.6% | 0.00 | 1.03 | 1.03 | 0.83 | 3.2% |
| Fontenelle Creek | 0.85 | 0.78 | 7.3% | 0.00 | 0.94 | 0.94 | 0.70 | 17.7% |
| Greys River | 0.87 | 0.87 | 0.6% | 0.00 | 1.02 | 1.02 | 0.78 | 9.8% |
| Hams Fork | 0.78 | 0.82 | 4.1% | 0.00 | 0.96 | 0.96 | 0.73 | 6.2% |
| Little Medicine Bow River | 0.59 | 0.61 | 3.7% | 0.00 | 0.86 | 0.86 | 0.51 | 13.0% |
| Little Powder River | 0.32 | 0.42 | 33.2% | 0.00 | 0.71 | 0.71 | 0.50 | 58.7% |
| Middle Fork Powder River | 0.71 | 0.78 | 9.1% | 0.00 | 0.87 | 0.87 | 0.71 | 0.2% |
| North Fork Shoshone River | 0.87 | 0.88 | 1.1% | 0.00 | 1.07 | 1.07 | 0.71 | 18.2% |
| Pacific Creek | 0.76 | 0.87 | 14.0% | 0.27 | 0.99 | 0.71 | 0.84 | 10.2% |
| Pine Creek | 0.83 | 0.93 | 10.9% | 0.00 | 1.03 | 1.03 | 0.90 | 7.3% |
| Rock Creek, Platte | 0.72 | 0.85 | 18.1% | 0.00 | 0.92 | 0.92 | 0.81 | 13.1% |
| Smiths Fork | 0.90 | 0.87 | 3.2% | 0.00 | 1.02 | 1.02 | 0.84 | 6.3% |
| Snake River | 0.78 | 0.87 | 11.7% | 0.50 | 1.01 | 0.51 | 0.84 | 8.0% |
| South Fork Shoshone River | 0.74 | 0.91 | 22.2% | 0.00 | 1.03 | 1.03 | 0.84 | 12.5% |
| Tongue River | 0.80 | 0.81 | 0.9% | 0.00 | 0.95 | 0.95 | 0.75 | 6.5% |
| Wind River | 0.82 | 0.82 | 0.7% | 0.00 | 1.05 | 1.05 | 0.67 | 17.5% |
| Average Error | | | 9.9% | | | | | 11.9% |

the model overestimated recharge by nearly 60 percent, modeled results fall within 20 percent of observed values. It is likely the anomalous result obtained for the Little Powder River watershed is due to its large surface area (3,190 $mi^2$) or low runoff (0.08 cm). The model underestimated BF/RO in the Little Medicine Bow drainage, which has the next largest surface area (2,514 $mi^2$) and next lowest runoff (3.54 cm).

To evaluate the model's applicability to larger areas, WSGS modeled baseflow in Wyoming's large river basins: Bear, Platte, Green, Snake-Salt, Wind-Bighorn, and Powder-Tongue-Northeast combined basins. Modeled recharge volumes (table 4) were compared to river outflows adjusted for inflows originating outside of Wyoming, streamflow depletions from consumptive uses (primarily irrigation), and evaporative losses from reservoirs and streams. Adjusted outflows represent the volumes of water that originate from baseflows and overland flows within Wyoming and should be larger than modeled baseflow volumes if all significant streamflow depletions have been considered.

Table 4 shows that WSGS modeled baseflow volumes differ from earlier GIS-based recharge estimates developed by Hamerlinck and Arneson (1998). WSGS estimates fall below adjusted river streamflows for all major river basins and are lower in the Platte, Greater Green, and combined Powder/Tongue/Northeast river basins where Hamerlinck and Arneson (1998) estimates range from 99 to 110 percent of adjusted streamflows. In contrast, WSGS baseflow volumes are somewhat higher in the Bear River Basin and much higher in Snake/Salt River Basin.

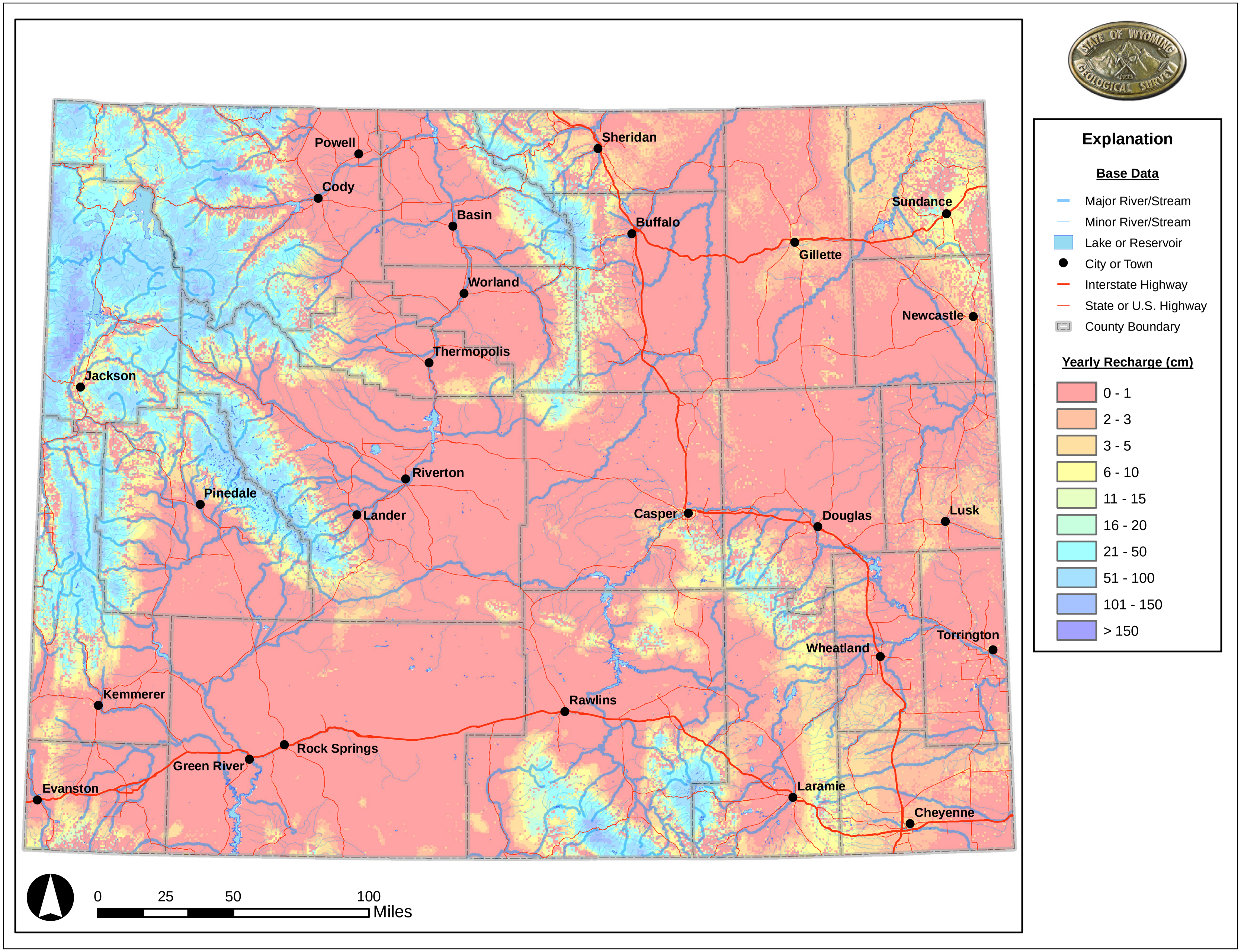



**Figure 3.** WSGS modeled baseflow depths (cm/year) for the state of Wyoming.

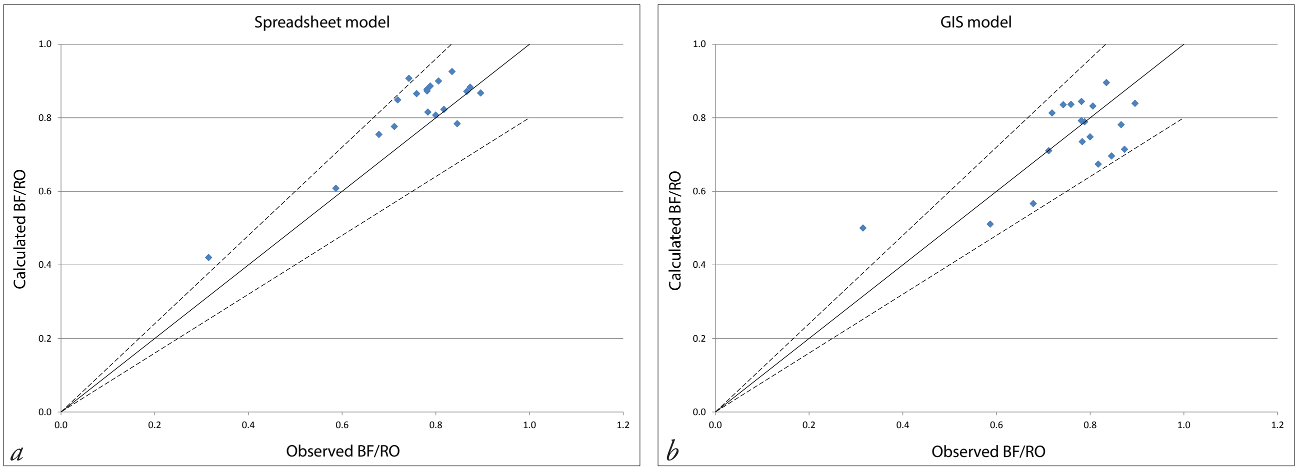



**Figure 4.** Calculated baseflow plotted against observed values for 19 Wyoming study watersheds. Calculations were made with equation 4, in a) spreadsheet and b) GIS formats. Error bars (±20%) are shown as dashed lines; the solid line, with a slope of 1, depicts full agreement between observed and modeled values.

**Table 4.** Comparison of WSGS modeled baseflows to net river outflows and recharge estimates by Hamerlinck and Arneson (1998) for Wyoming combined river basin systems. All values shown are in units of acre-ft/year.

| Basin Name | Outflows[1] | Inflows[1] | Streamflow Depletions[2] | Net Annual Outflows[3] | WSGS Base-flow | H&A Recharge[4] |
|---|---|---|---|---|---|---|
| Bear | 348,604 | 185,241 | 101,370 | 264,733 | 254,257 | 201,880 |
| Green/Great Divide/Little Snake | 1,841,836 | 442,131 | 636,348 | 2,036,054 | 1,907,840 | 2,129,986 |
| North Platte/South Platte | 1,428,394 | 509,649 | 829,564 | 1,748,309 | 1,554,486 | 1,735,521 |
| Powder/Tongue/NE Basins | 851,299 | 3,332 | 312,233 | 1,160,200 | 851,360 | 1,271,844 |
| Snake/ Salt/ Falls Rivers/ Teton Creek | 5,216,626 | 43,901 | 202,965 | 5,375,690 | 4,505,935 | 2,942,359 |
| Wind/Bighorn/Yellowstone/ Missouri Headwaters | 6,369,781 | 408,154 | 1,365,402 | 7,327,029 | 5,867,476 | 5,661,326 |

[1] Stafford, and others (2009)

[2] WWC (2007), Meyers (1962)

[3] Outflows minus inflows and streamflow depletions

[4] Hamerlinck and Arneson (1998)

A second evaluation compared the WSGS model to USGS recharge estimates for the Wyoming portion of the Powder River Structural Basin (PRSB). Long and others (2014) used a soil water balance model (SWB) (Westenbroek and others, 2010; Dripps and Bradbury, 2007) to quantify recharge in the Williston and Powder River Structural Basins of the United States and Canada. The SWB model estimated that average annual precipitation recharge for the Powder River Basin of Wyoming and Montana was 0.12 in for the 1981–2011 POR. The USGS provided the GIS raster dataset from the SWB model to WSGS (written commun. Andrew Long, Kyle Davis, USGS, 2016). GIS analysis of that raster indicated that average annual diffuse recharge for the Wyoming portion of the Powder River Basin was about 0.18 in for the 1981–2010 POR. The rate estimated by the WSGS empirical model for this area is 0.20 in/year during the 1981–2010 POR.

WSGS estimated an average annual baseflow of 0.31 in for the High Plains aquifer (HPA) in Wyoming. In comparison, Stanton and others (2011) estimated an average potential recharge rate of 0.53 in/year for the HPA in Wyoming during 2000–2009 using the USGS SWB model (Westenbroek and others, 2010; Dripps and Bradbury, 2007).

### Model limitations

Maximum BF/RO values in some of the target drainages exceed 1.00 (table 2), that is, the amount of baseflow exceeds the amount of water available for streamflows once ET losses are subtracted from precipitation. This occurs sporadically in drainages with average slopes starting at 14 degrees and in Snake and Wind Rivers drainages, which have moderate average slopes (9.1 and 12.5 degrees, respectively) but contain high slope cells in the adjacent Wind River and Teton Ranges. During the regression analyses conducted at the outset of this project, it was noted that the best fit line was parabolic; that is, watershed slope had a positive correlation with observed BF/RO for slopes under 18 degrees but a negative correlation (inversely proportional) for watersheds with average slopes above 18 degrees.

This relationship runs counter to other studies where watershed slope (Cherkauer and Ansari, 2005) or relief (Santhi and others, 2008) have negative correlations to recharge, which is intuitively reasonable. The proportion of overland flows would be expected to increase and baseflow proportions to decrease in drainages with high surface relief. The relationship observed in this project between slope and baseflow fraction is likely influenced by a combination of variations in the lithology and climate characteristic of Wyoming's mountains and basins. Little runoff is available for baseflows in semi-arid basin interiors where precipitation is low and ET rates are high. In contrast, due to orographic effects, the increased precipitation and lower ET characteristic of mountainous areas result in higher levels of runoff. Compare the runoff available in the low relief Little Powder River (0.08 cm) to that of the more rugged Tongue River watershed (11.06 cm). The increase in BF/RO that occurs in conjunction with increased slope below 18 degrees is probably due to the fact that moist mountain terrain is steeper than the semi-arid, low-relief basins. On the other hand, bedrock units in the steepest mountain terrain consist of uplifted and fractured Precambrian crystalline rocks that are largely non-porous. Instead of infiltrating ground surface as recharge, large runoff fractions discharge to tributary streams as overland flows.

WSGS applied several baseflow equations containing a parabolic component for the slope variable to the GIS model but was unable to obtain modeled estimates that improved on the initial method. Consequently, a power regression that provided the next best fit to the observed data was used to incorporate watershed slope data into the final baseflow equation. Unfortunately, this appears to result in overestimation of baseflow in steep terrain as evidenced by the high output for the Snake/Salt River Basin where more than 200 model cells, primarily located in the Teton Range, predicted BF/RO ratios above 1.0. Baseflow estimates should be viewed with caution in drainages with average watershed slopes exceeding 20 degrees.

## CONCLUSIONS

WSGS developed an empirical baseflow model for 19 unrestricted perennial streams located throughout Wyoming using regression and GIS analyses of watershed meteorological and physical hydrological characteristics. The empirical equation was applied to the Bear, Platte, Greater Green, Snake-Salt, Wind-Bighorn, and Powder-Tongue-Northeast river basins. Modeled baseflow volumes were less than total streamflow volumes obtained from Wyoming water sources in all of these river systems.

WSGS modeled baseflow rates compared favorably to USGS areal recharge estimates obtained from a SWB model for the Wyoming portions of the Powder River Structural Basin (Long and others, 2014) and the High Plains aquifer (Stanton and others, 2011).

This report does not constitute a comprehensive examination of groundwater recharge in Wyoming but is intended to provide low-resolution preliminary baseflow estimations over large watersheds. The empirical model presented in this report is based on yearly averages of certain meteorological and hydrological factors. Much previous research indicates significant groundwater recharge in semi-arid environments occurs in limited areas during intense episodic precipitation and snowmelt events (Scanlon and others, 2002; Fetter, 2001). The results of any baseflow or recharge model should be used with care.

This document was prepared as a WSGS Open File Report that will be supplemented periodically as new information becomes available. It is expected that new data and recharge models will be developed for areas within Wyoming as the state's water resources are evaluated. This report is intended to provide a preliminary approximation of baseflow levels. WSGS makes no guarantees regarding the accuracy of the data contained herein and encourages readers of this report to consult other reports, publications, and data sources, and to seek information from other qualified groundwater professionals before seeking to develop groundwater resources in this or any other area of the state. Additional information involving water resources and hydrogeology in particular areas of Wyoming can be found on the Wyoming Water Development Commission website: http://www.wsgs.wyo.gov/Research/Water-Resources/River-Basin-Plans.aspx.

## ACKNOWLEDGEMENTS

The authors thank Andrew Long, USGS, for his insightful review of this report. The work in this report was supported by the Wyoming State Geological Survey (WSGS) Hydrogeology Program. The authors gratefully acknowledge the guidance and support provided by WSGS leadership during this project. Special thanks are extended to WSGS colleagues Christina George and Andrea Loveland for their edits and James Rodgers for report layout.

## REFERENCES


Arnold, J.G., and Allen, P.M., 1999, Automated methods for estimating baseflow and ground water recharge from streamflow records: Journal of the American Water Resources Association, 35, no. 2, p. 411-424.

Avery, C.F., and Pettijohn, R.A., 1984, Generalized potentiometric-surface map of the High Plains aquifer in Wyoming: U.S. Geological Survey Water-Resources Investigations Report 84–4033, 1 sheet, scale 1:250,000.

Ball, L.B., Caine, J.S., and Ge, S., 2014, Controls on groundwater flow in a semiarid folded and faulted intermountain basin: Water Resources Research v. 50, no. 8, p. 6788-6809.

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p.

Bartos, T.T., and Hallberg, L.L., 2011, Generalized potentiometric surface, estimated depth to water, and estimated saturated thickness of the High Plains aquifer system, March–June 2009, Laramie County, Wyoming: U.S. Geological Survey Scientific Investigations Map 3180, 1 sheet.

Bredehoeft, J., 2007, It is the discharge: Ground Water [Groundwater] v. 45, no. 5, p. 523.

Cherkauer, D.S., and Ansari, S.A., 2005, Estimating groundwater recharge from topography, hydrogeology and land cover: Ground Water [Groundwater] v. 43, no. 1, p. 102–112.

Clarey, K.E., Bartos, T.T., Copeland, D., Hallberg, L.L., Clark, M.A., and Thompson, M., 2010, Available groundwater determination technical memorandum no. 6, WWDC Green River Basin water plan update, level I (2007–2009): Wyoming State Geological Survey, Laramie, Wyoming, variously paged.

Dripps, W.R., and Bradbury, K.R., 2007, A simple daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas: Hydrogeology Journal v. 15, no. 3, p. 433–444.

Eddy-Miller, C.A., Wheeler, J.D., and Essaid, H.I., 2009, Characterization of interactions between surface water and near-stream groundwater along Fish Creek, Teton County, Wyoming, by using heat as a tracer: U.S. Geological Survey Scientific Investigations Report 2009–5160, 53 p., http://pubs.usgs.gov/sir/2009/5160/.

Fetter, C.W., 2001 Applied Hydrogeology (4th Ed.): Upper Saddle River, N.J., Prentice Hall, 598 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, 604 p.

Guan, H., and Wilson, J. L., 2004, Mountain-block hydrology and mountain-front recharge, in J.F. Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., Groundwater Recharge in a Desert Environment: The Southwestern United States, Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C., p. 113-137.

Hamerlinck, J.D., and Arneson, C.S., eds., 1998, Wyoming groundwater vulnerability assessment handbook: Volume 1. Background, model development, and aquifer sensitivity analysis: Laramie, Wyoming, University of Wyoming Spatial Data and Visualization Center Publication 98-01-1, variously paged.

Healy, R.W., and Scanlon, B.R., 2010, Estimating groundwater recharge: Cambridge, United Kingdom: Cambridge University Press, 245 p.

Huntoon, P.W., 1993, The influence of Laramide foreland structures on modern ground-water circulation in Wyoming artesian basins, in Snoke, A.W., Steidtmann, J.R., and Roberts, S., eds., Geology of Wyoming: Wyoming State Geological Survey Memoir 5, p. 756-789, http://sales.wsgs.wyo.gov/geology-of-wyoming/.

Long, A.J., Aurand, K.R., Bednar, J.M., Davis, K.W., Mckaskey, J.D.R.G., and Thamke, J.N., 2014, Conceptual model of the uppermost principal aquifer systems in the Williston and Powder River structural basins, United States and Canada: U.S. Geological Survey Scientific Investigations Report 2014–5055, 41 p.

Love, J.D., and Christiansen, A.C., compilers, 1985, Geologic map of Wyoming: U.S. Geological Survey map and explanation, scale 1:500,000, 3 sheets.

Meyers, J.S., 1962, Evaporation from the 17 western states: U.S. Geological Survey Professional Paper 272-D, 97 p.

NLCD (National Land Cover Database), 2011, http://www.mrlc.gov/nlcd2011.php.

Peel, M.C., Finlayson, B.L., and McMahon, T.A., 2007, Updated world map of the Köppen-Geiger climate classification, Hydrology and Earth System Sciences v. 11, p. 1633–1644, doi:10.5194/hess-11-1633-2007.

Plume, R.W., and Smith, J.L., 2013, Properties of basin-fill deposits, a 1971–2000 water budget, and surface-water-groundwater interactions in the upper Humboldt River basin, northeastern Nevada: U.S. Geological Survey Scientific Investigations Report 2013-5077, 38 p.

Reynolds, L.V. and Shafroth, P.B., 2016, Riparian groundwater and baseflow studies in the Upper Colorado River Basin: Ruth Powell Hutchins Water Center at Colorado Mesa University Scientific and Technical Report No. 2, 8 p.

Sanford, W.E., and Selnick, D.L., 2013, Estimation of evapotranspiration across the conterminous United States using a regression with climate and land-cover data: Journal of the American Water Resources Association v. 49, no. 1, p. 217–230.

Santhi, C., Allen, P.M., Muttiah, R.S., Arnold, J.G., Tippad, P., 2008, Regional estimation of baseflow for the conterminous United States by hydrologic landscape regions: Journal of Hydrology no. 351, p. 139–153.

Scanlon, B.R., Healy, R.W., and Cook, P.G., 2002, Choosing appropriate techniques for quantifying groundwater recharge: Hydrogeology Journal v. 10, no. 1, p. 18–39.

Schicht, R.J., and Walton, W.C., 1961, Hydrologic budgets for three small watersheds in Illinois: Illinois State Water Survey Report of Investigations 40, 40 p.

Sharp, J.M., Jr., 2007, A glossary of hydrogeological terms: The University of Texas, Austin, Texas, 63 p.

Stafford, J.E., and Gracias, T., 2009, Surface water resource map of Wyoming: streamflows and storage: Wyoming State Geological Survey Map Series 91, 1 sheet, scale 1:500,000.

Stanton, J.S., Qi, S.L., Ryter, D.W., Falk, S.E., Houston, N.A., Peterson, S.M., Westenbroek, S.M., and Christenson, S.C., 2011, Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009: U.S. Geological Survey Scientific Investigations Report 2011–5183, 79 p.

Taboga, K.G., Bartos, T.T., Taucher, P., Hallberg, L.L., Clark, M.L., Stafford, J.E., Gracias, T., and Wittke, S.J., 2014a, Available groundwater determination technical memorandum no. 6, WWDC Bear River Basin water plan update, level II (2010–2014): Wyoming State Geological Survey, Laramie, Wyoming, 390 p.

Taboga, K.G., Bartos, T.T., Taucher, P., Hallberg, L.L, Clark, M.L., Stafford, J., Larsen, M.C., and Gracias, T., 2014b, Available groundwater determination technical memorandum no. 7, WWDC Snake/Salt River Basin water plan update, level I (2011-2014): Wyoming State Geological Survey, Laramie, Wyoming, 424 p.

Taucher, P., Bartos, T.T., Taboga, K.G., Hallberg, L.L., Clark, M.L., Stafford, J.E., Gracias, T., Hinckley, B., Worman, B., Clarey, K., Lindemann, L., Quillinan, S.A., Copeland, D., Hays, R., and Thomson, M., 2013, Available groundwater determination technical memorandum no. 5, WWDC Platte River Basin water plan update, level I (2009–2013): Wyoming State Geological Survey, Laramie, Wyoming, 491 p.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather soil-water-balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6-A31, 60 p.

WSEO, 2006a, Documents on the use and control of Wyoming's interstate streams, Wyoming's compacts, treaties and court decrees, North Platte Decree: p. 152 - 190, https://sites.google.com/a/wyo.gov/seo/interstate-streams.

WSEO, 2006b, Documents on the use and control of Wyoming's interstate streams, Wyoming's compacts, treaties and court decrees, Amended Bear River Compact: p. 16 -31, https://sites.google.com/a/wyo.gov/seo/interstate-streams.

WWC Engineering, Inc., (in association with Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., and States West Water Resources Corporation), 2007, Wyoming framework water plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, v. 1 and 2, [variously paged].