Spatial and Seasonal Variability of Base Flow in the Verde Valley, Central Arizona, 2007 and 2011

By Bradley D. Garner and Donald J. Bills

Prepared in cooperation with the Verde River Basin Partnership, the Town of Clarkdale, and Yavapai County

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Abstract

Synoptic base-flow surveys were conducted on streams in the Verde Valley, central Arizona, in June 2007 and February 2011 by the U.S. Geological Survey (USGS), in cooperation with the Verde River Basin Partnership, the Town of Clarkdale, and Yavapai County. These surveys, also known as seepage runs, measured streamflow under base-flow conditions at many locations over a short period of time. Surveys were conducted on a segment of the Verde River that flows through the Verde Valley, between USGS streamflow-gaging stations 09504000 and 09506000, a distance of 51 river miles. Data from the surveys were used to investigate the dominant controls on Verde River base flow, spatial variability in gaining and losing reaches, and the effects that human alterations have on base flow in the surface-water system. The most prominent human alterations in the Verde Valley are dozens of surface-water diversions from streams, including gravity-fed ditch diversions along the Verde River.

Base flow that entered the Verde River from the tributary streams of Oak Creek, Beaver Creek, and West Clear Creek was found to be a major source of base flow in the Verde River. Groundwater discharge directly into the Verde River near these three confluences also was an important contributor of base flow to the Verde River, particularly near the confluence with Beaver Creek. An examination of individual reaches of the Verde River in the Verde Valley found three reaches (largely unaffected by ditch diversions) exhibiting a similar pattern: a small net groundwater discharge in February 2011 (12 cubic feet per second or less) and a small net streamflow loss in June 2007 (11 cubic feet per second or less). Two reaches heavily affected by ditch diversions were difficult to interpret because of the large number of confounding human factors. Possible lower and upper bounds of net groundwater flux were calculated for all reaches, including those heavily affected by ditches.

Introduction

The Verde River of central Arizona has perennial (or year-round) flow. In the absence of storm- or snowmelt-related runoff, this perennial flow is sustained by groundwater discharge—a flow component known as base flow. Base flow varies over space and time. Streams may gain base flow from groundwater discharge in some reaches (gaining reaches) and lose base flow in others (losing reaches) where groundwater gradients and streambed characteristics allow surface water to infiltrate into the subsurface. The quantity of water entering or leaving a stream can vary over time in response to short-term and long-term factors. Over time, a stream reach can change from a gaining reach to a losing reach, or from a losing reach to a gaining reach.

Human development of water resources during the 20th century caused many perennial streams in Arizona to become intermittent or ephemeral (Thomas and Pool, 2006; Webb and others, 2007). Presently (2007), Arizona perennial streams such as the San Pedro River are showing decreased base flow, at least in part as a result of human activity (Upper San Pedro Partnership, 2007). This has raised concerns about possible similar base-flow decreases in the Verde River and its associated perennial tributary streams. For centuries, humans and ecosystems have been sustained by base flow in the Verde River and its perennial tributaries (Blasch and others, 2006; Konrad and others, 2008; Ross, 2010; National Park Service, 2012). This report focuses on a portion of the Verde River that flows through the Verde Valley, which is in the middle of the Verde River watershed in central Arizona.

Synoptic base-flow surveys (also known as seepage runs) aid in investigating the groundwater component of streamflow (Harvey and Wagner, 2000; Rosenberry and LaBaugh, 2008, p. 15). Base-flow conditions are ideal times for conducting these surveys, as they minimize some confounding variables. Storm- and snowmelt-related runoff components of streamflow can be minimized if a survey is timed correctly. Conducting a survey in the winter months minimizes the effects of vegetation transpiration and diversion of surface water through human infrastructure such as ditches and pumps. Data collected in winter, therefore, are expected to be more indicative of groundwater hydrologic processes; conversely, data collected in summer are expected to reflect additional vegetation and human hydrologic components.

The U.S. Geological Survey (USGS), in cooperation with Yavapai County, Arizona (in 2007) and the Verde River Basin Partnership and the Town of Clarkdale, Arizona (in formations, including Paleozoic sedimentary rocks that contain a regional aquifer, Tertiary volcanic rocks that could be relatively impermeable, Tertiary sedimentary rocks of variable lithology that also contain an aquifer, and thin stringers of Quaternary alluvium associated with the modern stream channel of the Verde River (fig. 2; Blasch and others, 2006; Pool and others, 2011). The Verde River has incised into alluvial fans and Tertiary sedimentary rocks, and these units have been continually reworked into a broad alluvial channel that varies in altitude from 2,900 to 3,500 feet (ft). Geographic distribution and water-bearing characteristics of geologic formations likely affect the distribution of base-flow increases and decreases.

More than 67 river diversions in the Verde Valley deliver surface water to agricultural fields and residential customers (for example, fig. 3). The largest diversions are gravity-fed ditches along the Verde River, some of which divert nearly all available base flow away from the river for one-half of the year or longer (Alam, 1997). Dozens of smaller ditches and pumps (portable and permanent) flank the banks of the Verde River and its perennial tributaries throughout the Verde Valley.

Ditch diversions complicate the ability to investigate and understand natural base-flow processes, because the ditches have altered the hydrology of the Verde Valley considerably. Many ditches have been diverting water for more than 120 years (Alam, 1997), and at least one ditch has been in use for more than a millennium (National Park Service, 2012). Any changes that ditches have imparted to the hydrologic system are challenging to understand, because most ditches were constructed before the first hydrologic investigations in the area.

The ditches diverting water from the Verde River have not been studied comprehensively. Ross (2010) monitored flow rates into and out of four ditches at their headgates and final return flows back to the stream channels; no conclusions were reached about total water volumes delivered to customers, consumptive-use rates, or the spatial distribution or temporal variably of return flows other than the terminal return flow . Alam (1997) published anecdotal estimates of diverted amounts of water based on surveys of ditch operators. A comprehensive investigation of ditch-diversion hydrology would be possible, but would be a large undertaking well beyond the scope of the present study. Discussion about ditches in this report, therefore, is limited to information that was readily available and measurable.

Figure 3. Surface-water diversion dam for Tavasci Ditch, Verde Valley, central Arizona. This dam allows water to divert by gravity flow into Pecks Lake and the Tavasci Ditch.

Usage of the Term Base Flow

A precise definition and explanation of this report's usage of the term "base flow" is warranted because "an exact definition of base flow varies depending on the author and focus of the study" (Kennedy and Gungle, 2010, p. 5). Base flow "is the portion of streamflow that is derived from persistent, slowly varying sources" (Dingman, 2002, p. 373). In the Verde River watershed, groundwater discharge is the slowly varying source of base flow. However, base flow in the Verde Valley is not necessarily equal to the net discharge of groundwater to streams; such equivalence is possible only in basins with no human alteration of the surface-water system. In the Verde Valley, increases and decreases in base flow can be caused by multiple processes—particularly surface-water ditch diversion.

This report describes streamflow measurements made in the absence of storm- or snowmelt-related runoff ("base-flow conditions") as "base-flow measurements." Such measurements in the Verde Valley may have been altered by human activities, but this usage is consistent with previous reports covering the Verde Valley (Owen-Joyce and Bell, 1983; Owen-Joyce, 1984; Blasch and others, 2006; Pool and others, 2011). Base flow is a term that merits qualification and consideration; therefore the following observations might aid in understanding how the term is used in this report:

- Increases and decreases in base flow are not necessarily equal to net groundwater discharge in a river reach. Other processes, human and natural, may remove or add water to a river reach under base-flow conditions.

- In arid regions, base flow should not be confused with the total amount of groundwater moving toward a stream. A substantial part of groundwater moving toward a stream may be removed by evapotranspiration before it discharges to the stream (Thomas and Pool, 2006).

- So-called summer base-flow, winter base-flow, and annual-average base-flow values all are expected to differ from one another in the Verde Valley, given that some human activities and natural hydrologic processes affect base flow and vary seasonally.

- Even under wholly natural conditions, base flow is not constant, because groundwater gradients change

A field-based survey of crop consumptive water use estimated 10,000 acre-feet of evapotranspiration from irrigated fields (ET_f) for the 2010 growing season throughout the Verde Valley (B. Forbes, U.S. Geological Survey, written commun., 2011). Assuming a 3- to 6-month growing season, this value is equal to 28 to 55 ft^3/s of constant water use. This range is less than the amount of unaccounted-for water in June 2007. Because so little is known about the ditch systems, the number of possible explanations for this discrepancy is large.

Perhaps the most important fact to consider when interpreting these data is that a synoptic base-flow survey is a snapshot of a short period of time, and although helpful, it should not be over generalized. In the summer months, flow at the Camp Verde gage can vary on hourly, daily, weekly, and monthly timescales (fig. 11), reflecting many superimposed, time-lagged human and natural processes that occur upstream from this gage. This complex flow at the Camp Verde gage suggests that a synoptic base-flow survey 1 week earlier or later could have produced different flow measurements and different estimates of groundwater flux.

Despite all that is not yet known about Verde Valley ditches and their hydrology, recent studies and reconnaissance have led to an improved understanding of the ditches as a collection of networked and interrelated canals (fig. 12). A steady-state computer model was constructed to simulate surface-water flow in the Verde River and the four major ditches in reach IV–V (fig. 6; Ross, 2010). Recently, continuous stage-measuring equipment has been installed at key locations in some ditches (J. Haney, The Nature Conservancy, oral commun., 2011). Future studies could improve understanding of ditches through hydrologic monitoring networks and analyses designed specifically to monitor the many hydrologic components outlined in the conceptual model presented in this report (fig. 5). Because ditch operations vary hour-to-hour and ditches likely are never under steady-state conditions in the summer, any such study would need to collect data

Table 4. Water-flow data for major active ditch diversions on the Verde River, June 20–21, 2007, Verde Valley, central Arizona.

[All units cubic feet per second; D_{div}, $D_{retMeas}$, and $\Sigma D_{retMeas}$ are variables defined for equations in the main body of the text associated with this table]

June 20–21, 2007				
Name of ditch	**Initial diversion from Verde River, measured or calculated[a] (D_{div})**	**Return flows, measured or estimated[a,b] ($D_{retMeas}$)**	**Sum of measured return flows ($\Sigma D_{retMeas}$)**	**Unaccounted for diverted water[c]**
Tavasci	8[d]	5[d,e,f]	5[g]	3[g]
Hickey	23	0.3; 1.1	1.4	22
Cottonwood	34[d,h]	0.7; 0.8; 2.0; 2.5; 1.6	7.6	26
OK	14	none observed	0	14
Eureka	14[d]	3.8 or 0[e,i]	0 to 3.8	10 to 14
Verde	41[d]	8; 0; 14[d,e]	22	19
Diamond S	28	0.9; 16[e]	17	11
TOTAL	162[a,c]		57[j]	105[a,b,j]

[a]Values represent only times they were measured, not average operational conditions. Summertime ditch operations vary on hourly, daily, weekly, and monthly time scales. Multiple entries in this column indicate multiple return-flow measurements.

[b]Return-flow measurements not comprehensive and ditches were not under steady-state conditions . Estimation of flows was by using the float method (Weight and Sonderegger, 2001, p. 225)

[c]Calculated by subtraction of total measured return flows from diverted amount of water.

[d]Imprecise; calculated by subtracting two discharge measurements in Verde River.

[e]Return flow at end of ditch where it returns to stream channel.

[f]Includes some (unmeasured) amount of spring discharge.

[g]Use of one significant figure produces this value.

[h]Does not include spillback from Hickey ditch at its first siphon, which was not measured.

[i]Repeat visits on two days showed that this terminal return flow, which empties to Beaver Creek, was variable.

[j]The larger measured value for Eureka Ditch return flows was used to calculate this value.

Table 5. Water-flow data for major active ditch diversions on the Verde River, February 1–3, 2011, Verde Valley, central Arizona.

[All units cubic feet per second; D_{div}, $D_{retMeas}$, and $\Sigma D_{retMeas}$ are variables defined for equations in the main body of the text associated with this table]

February 1–3, 2011				
Name of ditch	**Initial diversion from Verde River, measured or calculated[a] (D_{div})**	**Return flows, measured or estimated[a,b] ($D_{retMeas}$)**	**Sum of measured return flows ($\Sigma D_{retMeas}$)**	**Unaccounted for diverted water[c]**
Tavasci	0	0.9[d,e]	0.9	−1[e,f]
Hickey	15	2; 0.2; 0.7[g]	2.9	12
Cottonwood	22[g,h]	0.4; 1.5; 0	1.9	20
OK	8[g]	2.7[i]	2.7	5
Eureka	0	none observed	0	0
Verde	0	none observed	0	0
Diamond S	0	none observed	0	0
TOTAL	45[a,c]		8.4	37[a,b]

[a]Values represent only times they were measured, not necessarily average operational conditions.

[b]Return-flow measurements not comprehensive and ditches were not under steady-state conditions . Estimation of flows was by using the float method (Weight and Sonderegger, 2001, p. 225)

[c]Calculated by subtraction of total measured return flows from diverted amount of water . Rounding causes columns to appear to sum incorrectly.

[d]Return flow at end of ditch where it returns to stream channel.

[e]Includes some (unmeasured) amount of spring discharge, causing an apparently negative unaccounted value.

[f]Use of one significant figure produces this value.

[g]Imprecise; calculated by subtracting two discharge measurements in Verde River.

[h]Does not include spillback from Hickey ditch at its first siphon, which was not measured.

[i]Imprecise; inferred by subtracting an in-ditch measurement from calculated diverted amount. The location of this return flow is not known.

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