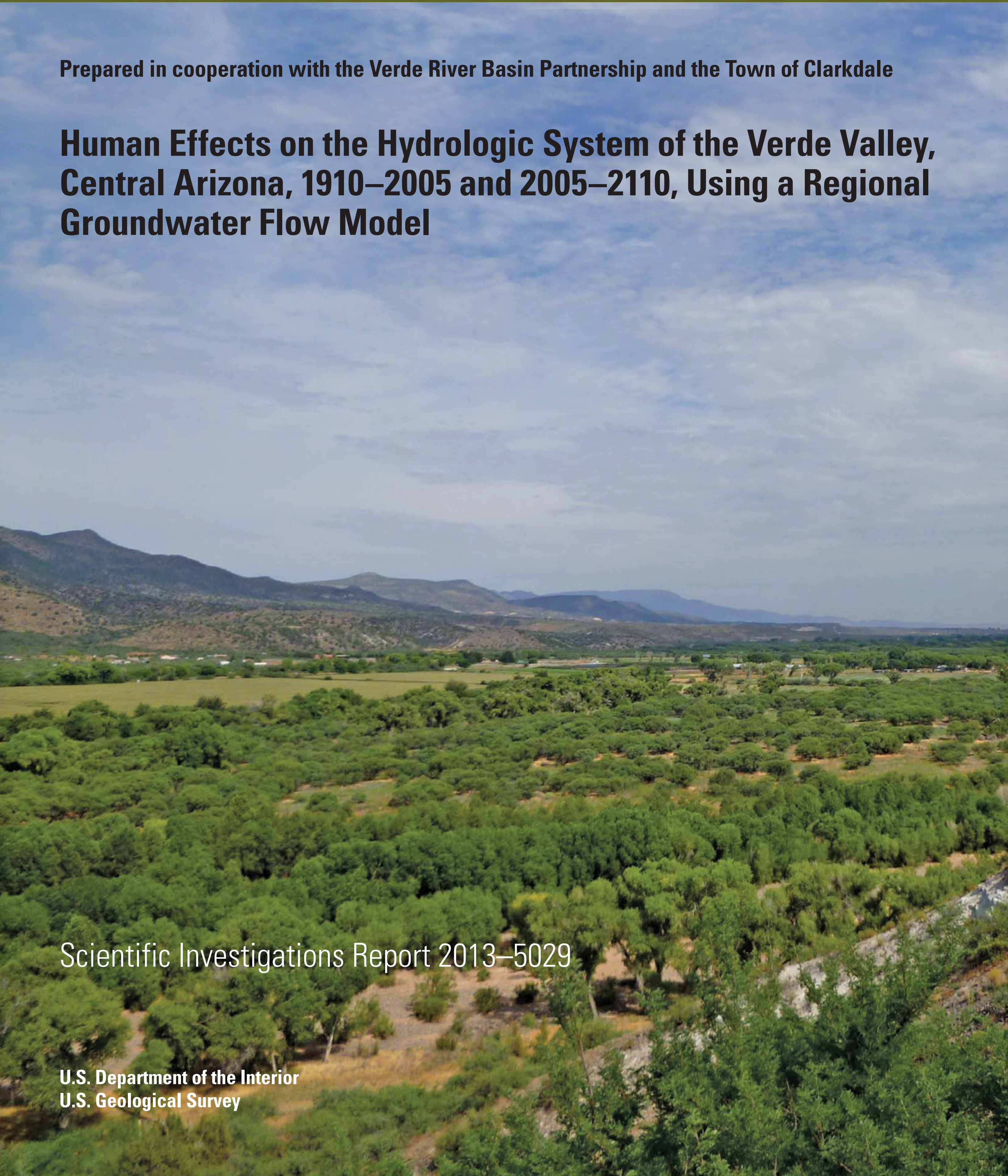
Prepared in cooperation with the Verde River Basin Partnership and the Town of Clarkdale

Human Effects on the Hydrologic System of the Verde Valley, Central Arizona, 1910–2005 and 2005–2110, Using a Regional Groundwater Flow Model



Scientific Investigations Report 2013–5029

U.S. Department of the Interior
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COVER
Verde Valley of central Arizona, June 2010. Photograph by Brandon T. Forbes.

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By Bradley D. Garner, D.R. Pool, Fred D. Tillman, and Brandon T. Forbes

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Conversion Factors

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
acre-foot per year (acre-ft/yr)	0.001380	cubic foot per second (ft^3/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	0 .0254	meter per hour (m/h)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Human Effects on the Hydrologic System of the Verde Valley, Central Arizona, 1910–2005 and 2005–2110, Using a Regional Groundwater Flow Model

By Bradley D. Garner, D.R. Pool, Fred D. Tillman, and Brandon T. Forbes

Abstract

Water budgets were developed for the Verde Valley of central Arizona in order to evaluate the degree to which human stresses have affected the hydrologic system and might affect it in the future. The Verde Valley is a portion of central Arizona wherein concerns have been raised about water availability, particularly perennial base flow of the Verde River. The Northern Arizona Regional Groundwater Flow Model (NARGFM) was used to generate the water budgets and was run in several configurations for the 1910–2005 and 2005–2110 time periods. The resultant water budgets were subtracted from one another in order to quantify the relative changes that were attributable solely to human stresses; human stresses included groundwater withdrawals and incidental and artificial recharge but did not include, for example, human effects on the global climate. Three hypothetical and varied conditions of human stresses were developed and applied to the model for the 2005–2110 period. On the basis of this analysis, human stresses during 1910–2005 were found to have already affected the hydrologic system of the Verde Valley, and human stresses will continue to affect the hydrologic system during 2005–2110. Riparian evapotranspiration decreased and underflow into the Verde Valley increased because of human stresses, and net groundwater discharge to the Verde River in the Verde Valley decreased for the 1910–2005 model runs. The model also showed that base flow at the upstream end of the study area, as of 2005, was about 4,900 acre-feet per year less than it would have been in the absence of human stresses. At the downstream end of the Verde Valley, base flow had been reduced by about 10,000 acre-feet per year by the year 2005 because of human stresses. For the 2005–2110 period, the model showed that base flow at the downstream end of the Verde Valley may decrease by an additional 5,400 to 8,600 acre-feet per year because of past, ongoing, and hypothetical future human stresses. The process known as capture (or streamflow depletion caused by the pumping of groundwater) was the reason for these human-stress-induced changes in water-budget components.

Introduction

The Verde Valley of central Arizona has experienced population growth that has led to increased water demands. These water demands are met through surface-water diversions and groundwater withdrawals from local and regional aquifers. Because the human population is expected to continue to grow in the region (Arizona Department of Administration, 2012), concerns have been raised about past, present, and future human-induced stresses on the hydrologic system. The term “Verde Valley” is informal—more geomorphic than hydrologic in its connotation—therefore, for this report the Verde Valley is defined as the 1,500-mi^2 area of the Verde Valley subbasin located between two streamflow-gaging stations operated by the U.S. Geological Survey (USGS; fig. 1). The upstream gage is the Verde River near Clarkdale, Arizona (station identifier 09504000; hereafter, the Clarkdale gage) and the downstream gage is the Verde River near Camp Verde, Arizona (station identifier 09506000; hereafter, the Camp Verde gage).

The USGS, in cooperation with the Verde River Basin Partnership and the Town of Clarkdale, Arizona, undertook a study of the Verde Valley that calculated a water budget for the year 2005 and explored the effects of past and possible future human stresses on the hydrologic system of the Verde Valley and northern Arizona. This report, which is a presentation of those findings, may aid resource managers and policymakers concerned about water availability in the Verde River watershed.

Human alterations to a hydrologic system can be described, in the most general sense, as stresses. Stresses to hydrologic systems produce responses, either directly or indirectly. Withdrawing water from a surface-water stream produces a direct response: a decrease in the downstream rate of streamflow and a decrease in surface-water stage. Pumping of groundwater, by contrast, produces both direct and indirect responses. A direct response is the lowering of the groundwater altitude in and around the pumped well. An indirect response is the decrease in discharge or increase in recharge to the groundwater system that eventually must occur in order to offset the amount of groundwater withdrawn (also

Figure 1. Map showing the location of the Verde River watershed and Verde Valley, central Arizona.

known as capture or streamflow depletion; see Theis, 1940; Leake and Pool, 2010; Leake, 2011; Barlow and Leake, 2012).

A water budget can aid understanding of stresses, direct responses, and indirect responses to a hydrologic system by expressing the general availability of water in a given area through accounting. Because water budgets use the same accounting principles as those used in financial accounting, they can be understood by people with a variety of scientific and nonscientific backgrounds. For the purposes of this study, stresses were divided into natural stresses and human stresses to the hydrologic system. Natural stresses consisted of natural recharge to the groundwater system. Human stresses included groundwater withdrawals by pumping, incidental and artificial recharge, and consumptive use of surface water through irrigation; each of these processes can produce responses (changes) in water-budget components.

Among the many water-budget components in the Verde Valley, there is particular interest in base flow of the Verde River and how it responds to human stresses. Base flow is that portion of a stream's flow not attributable to surface runoff. Verde River base flow is sustained by groundwater discharging from local and regional aquifers (Owen-Joyce and Bell, 1983; Owen-Joyce, 1984; Dingman, 2002; Blasch and others, 2006; Leake and Pool, 2010; Garner and Bills, 2012). Given that stresses imposed on aquifers supplying base flow to the Verde River eventually can manifest as changes in Verde River base flow, the central questions addressed in this report are:

1. How have human stresses on the hydrologic system affected Verde River base flow?

2. How have human stresses outside the Verde Valley affected base flow within the Verde Valley?

3. How might future human stresses to the hydrologic system affect Verde River base flow?

Purpose and Scope

The purpose of this report is to describe the results of an investigation of how human stresses have affected and might yet affect the hydrologic system of the Verde Valley, Arizona. Specifically, this report quantifies the relative effects of human stresses on various components of the Verde Valley water budget, both over the 95-year period from 1910 to 2005, and into the future (2005–2110). Particular emphasis is placed on water-budget components related to base flow in the Verde River. Water budgets in this report are derived entirely from the Northern Arizona Regional Groundwater Flow Model (NARGFM); limitations of and assumptions implicit to the NARGFM (see Pool and others, 2011) apply also to this report. Not all components of the hydrologic cycle were simulated by the NARGFM; unsimulated components are discussed briefly.

Summaries of field and remote-sensing investigations of certain water-budget components are presented in appendixes 2–4. The results of these investigations serve as independent means for assessing the reasonableness of water-budget values derived from the NARGFM.

The U.S. Geological Survey and Verde River Basin Partnership (2009) developed a hydrology science plan for carrying out scientific studies in the Verde River Basin as called for in Federal Public Law 109-110, Title II (U.S. Congress, 2005). This report fulfills Section 204(b) of Title II and parts of work elements 1, 2, and 3 of that hydrology science plan.

Description of the Study Area

The study area is the Verde Valley of central Arizona (fig. 1). As described in the "Introduction" section, for the purposes of this report the Verde Valley is defined precisely with respect to two USGS streamflow-gaging stations on the Verde River (the upstream Clarkdale gage and downstream Camp Verde gage). The Verde River is a perennial stream that flows generally from northwest to southeast through the Verde Valley. Three perennial tributaries in the Verde Valley—Oak Creek, Beaver Creek, and West Clear Creek (fig. 1)—also contribute perennial flow to the Verde River (Garner and Bills, 2012). The study area is entirely within the Arizona Department of Water Resources (ADWR) "Verde Valley subbasin of the Verde River groundwater basin" (Blasch and others, 2006), with the lightly populated portion of that subbasin upstream of the Clarkdale gage excluded from the study area[1].

Physiography

The Verde Valley is in the Transition Zone of Arizona, a province containing features of both the Colorado Plateau and Basin and Range physiographic provinces (Fenneman, 1931). Most of the study area lies within a north-northwest trending basin associated with Tertiary Basin and Range tectonism (fig. 2). Normal faulting associated with this tectonism lowered the basin floor relative to surrounding terrain, downfaulting pre-Basin-and-Range rocks, which subsequently were buried by hundreds of feet of alluvial and lacustrine sediments derived from erosion of the surrounding higher elevation terrain.

Part of the study area along the Oak Creek drainage system extends into the Colorado Plateau physiographic province. The Colorado Plateau is a relatively flat and tectonically stable region (Barrs, 1983) consisting of thick sequences of relatively flat-lying Paleozoic and Mesozoic rocks that in places are capped by Cenozoic sedimentary or volcanic deposits. Depths to water are considerably greater on the plateau than in the Transition Zone, and there is no major perennial streamflow on the surface of the plateau within the study area.

[1] The ArcHydro watershed-delineation software was used to determine the boundary of this area excluded from the study area.

Climate

The study area climate is semiarid to arid, except for small areas of high elevation that are humid (Blasch and others, 2006). Precipitation typically is greater at higher elevations than lower elevations; winter snow is common above 5,000 ft. The central, lower elevation part of the study area—including municipalities such as Cottonwood and Camp Verde—receives less precipitation than higher elevation areas; it experiences mild winters and hot summers with daytime summer temperatures commonly exceeding 100 °F.

Precipitation occurs primarily during the summer North American monsoon and in winter frontal storms (Adams and Comrie, 1997; Blasch and others, 2006). The summer monsoon is characterized by generally short (less than a few hours), intense (greater than 1 inch per hour), and localized thunderstorms. Winter storms characteristically are longer (12–48 hours), less intense (less than 0.25 inch per hour), more regional in extent, and contribute more recharge to the study area than summer monsoon storms (Blasch and others, 2006).

Hydrogeology

Groundwater in the study area generally originates as precipitation in higher elevation areas that percolates downward through the earth to the water table, flows through aquifers, and discharges in three possible ways: as discharge to streams that supports base flow, through near-stream riparian evapotranspiration (ET), or by pumping from wells. The largest amounts of recharge to the groundwater system occur along the Mogollon Rim (Blasch and others, 2006; Pool and others, 2011). Additional recharge can occur from streams where water levels in the streams are above the groundwater table and sediments are sufficiently permeable.

Groundwater flows through four aquifers within the study area (fig. 3). The deepest aquifer is the Redwall aquifer (sometimes called the R aquifer; Cooley and others, 1969), which is primarily a limestone aquifer resting on Proterozoic crystalline bedrock. The Redwall aquifer underlies almost all of the study area. The Coconino aquifer (or C aquifer; Cooley and others, 1969) is stratigraphically above the Redwall aquifer and its major water-bearing unit is the Coconino Sandstone. Other geologic formations within the Coconino aquifer include the Kaibab Formation, Toroweap Formation, Schnebly Hill Formation, and the upper and middle Supai Formations (Pool and others, 2011). The geologic formations associated with the Coconino aquifer are not saturated everywhere within the study area. Within the Verde Valley, the Verde Formation is stratigraphically above the Coconino and Redwall aquifers. The Verde Formation has variable lithology because it consists of the weathering products of diverse parent rocks, its depositional environment varied between fluvial and lacustrine (Twenter and Metzger, 1963, p. 76), and intermittent volcanic activity during deposition produced interbedded volcanic and sedimentary rocks (Owen-Joyce and Bell, 1983). In general, in the Verde Formation coarse-grained facies produce useable amounts of water for wells, and fine-grained facies yield little water. Finally, narrow stringers of Quaternary alluvium are located along major stream channels in the Verde Valley and may contain localized aquifers that can produce economically important quantities of water (Twenter and Metzger, 1963). These alluvial deposits can be pathways for discharge of groundwater from underlying aquifers, and they also can be locations of recharge from streams and ditch diversions (Garner and Bills, 2012).

Groundwater also flows into and out of the study area in the subsurface, as study-area boundaries do not necessarily coincide with groundwater divides associated with each aquifer. This subsurface flow is described as underflow, and its magnitude and direction can be affected by human stresses, similar to other water-budget components.

Figure 2. Physiographic map of Arizona. Modified from Fenneman (1931); original drawing by Dr. Guy-Harold Smith (1895–1976), cartographer and emeritus professor of geography, Ohio State University.

Human Development of Water Resources

The Verde Valley has grown in population in recent decades (U.S. Census Bureau, 2011). In 2000, about 63,000 people lived in the Verde Valley. By 2010, about 71,000 lived in the Verde Valley, a 13-percent increase in 10 years. The Verde Valley is considered to be a rural part of Arizona, and it is not within any of the State water-resource management areas known as Active Management Areas (which were identified and designated by the State as historically having heavy reliance on mined groundwater; Arizona Department of Water Resources, 2012).

Residents of the Verde Valley use a combination of groundwater and surface water to meet their water demands (Blasch and others, 2006). Groundwater generally has been the source of water for domestic and municipal water uses since 1940 (Tadayon, 2005; also see the "Northern Arizona Regional Groundwater Flow Model" section). Residents in outlying areas commonly rely on private wells or community water suppliers as their source of domestic water. Municipalities such as Camp Verde, Clarkdale, Cottonwood, and Sedona (fig. 1) use public-supply wells for their municipal water-supply needs.

Surface water from perennial streams is used mostly to irrigate cultivated fields. More than 67 diversions in the Verde Valley deliver surface water to agricultural fields and residential customers (Garner and Bills, 2012). 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 half of the year or longer. Ditch diversions have altered the hydrology of the Verde Valley considerably, and many of these have been diverting water for more than 120 years. Ditch diversions present a substantial complication for the understanding of hydrologic processes in the Verde Valley (Garner and Bills, 2012). For the purposes of this study, the many and varied hydrologic processes comprised in the operation of ditch diversions are lumped together, with only the net effect of diversions on surface-water flow being considered. This is necessary because the hydrology of these ditch diversions, to date, has not been studied comprehensively.

Previous Water-Budget Studies

Twenter and Metzger (1963) provided a broad overview of Verde Valley hydrology, including measurements of streamflow and base flow of the Verde River and tributary streams, some documentation of the effects that diversions and ET have on streamflow, and a partial water budget. Some of their numerical methods were not documented in detail, making comparisons with their values difficult. Owen-Joyce and Bell (1983) described water resources in an area generally coincident with the Verde Valley subbasin; they included a water budget for the area and calculations of seasonal base flow at the Clarkdale gage and Camp Verde gage. Owen-Joyce (1984) described the hydrology of the stream-aquifer system near Camp Verde, included a water budget for the alluvial

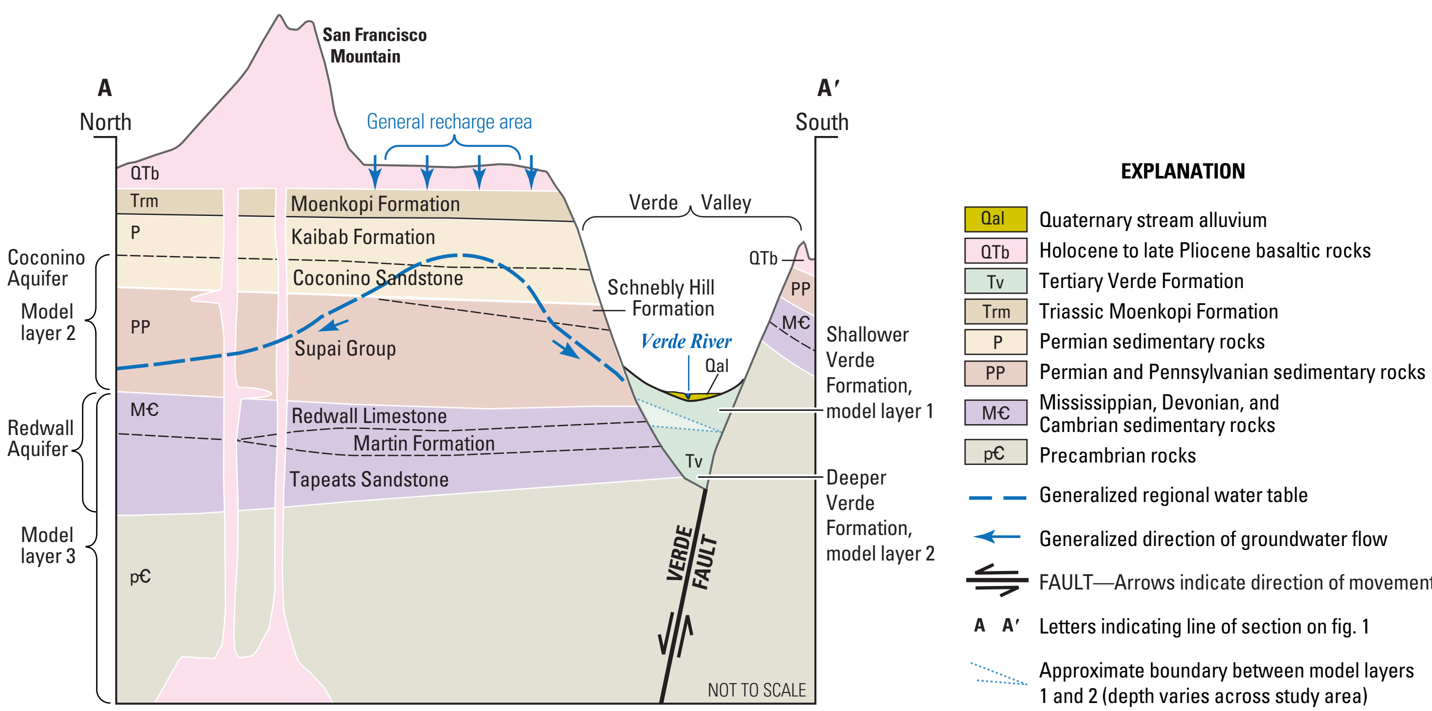

Figure 3. Schematic drawing of generalized hydrogeologic cross sections from the Verde River to San Francisco Mountain, central Arizona. Modified from Blasch and others (2006). Correspondence between geological layers and modeled layers in the Northern Arizona Regional Groundwater Flow Model is indicated.

aquifer hydraulically connected to the river, and estimated base flow for the Camp Verde gage.

Arizona Department of Water Resources (2000, 2009) compiled extensive water-resource data for the upper and middle Verde River subbasins, including tables of groundwater withdrawals that constitute partial water-budget information. Hart and others (2002) published base flow and spring-discharge rates for the Coconino aquifer, which also constitute partial water-budget information for the Verde River watershed. Blasch and others (2006) presented annual average water budgets for the entire Verde Valley subbasin, an area larger than the study area of this report (fig. 1).

Leake and Pool (2010) examined how groundwater withdrawals and incidental recharge can affect connected surface-water features in the Verde Valley. The methods of Leake and Pool (2010) were used in appendix 4 of this report to develop figures that encompass a longer time period and an additional aquifer. Pool and others (2011) presented predevelopment and 2005 water budgets for an area nearly coincident with the Verde Valley as defined in this report. The regional groundwater-flow model documented by Pool and others (2011) is the central analysis tool used in this report.

Methods and Approach

The full water budget for the Verde Valley was produced using NARGFM version 1.1, the groundwater-flow model documented in Pool and others (2011) that included simulation of natural and human stresses for 1910–2005. Three profiles of hypothetical future human stresses for 2005–2110 were posed to the NARGFM by creating new input files. The NARGFM was then executed several times for the complete 1910–2110 period, with water budgets being extracted from model-output files. Water budgets were added and subtracted from one another so as to isolate only the relative changes in their values that were attributable to human stresses.

The Northern Arizona Regional Groundwater Flow Model

The NARGFM is a computer simulation of groundwater and surface-water flow implemented in MODFLOW–2005 (Harbaugh, 2005). The model is considered to be an ideal tool for generating water budgets for the Verde Valley, because it synthesizes numerous and disparate pieces of hydrologic information into a single and cohesive view of the hydrologic systems in northern Arizona. The alternative approach—estimation of water-budget components independently of one another—would have been less effective for evaluating the effects of human stresses on the hydrologic system.

The NARGFM covers an area considerably larger than the Verde Valley (fig. 4). This section provides a brief summary only of the NARGFM; complete documentation of the NARGFM is available in Pool and others (2011). All of the water simulated as flowing within the NARGFM domain originates from applied recharge; there are no constant-head boundaries. Internal groundwater divides are generated in the model by solving groundwater flow equations, not from boundary conditions.

The model was horizontally discretized into a 600-row by 400-column grid of cells 0.62 miles in length on each side, rotated to align with directions of greatest regional hydraulic conductivity. Three vertical layers simulated the various aquifers within and near the study area (figs. 3 and 5). Layer 3 is the lowest and most spatially extensive layer in the Verde Valley and represents the Redwall aquifer and older crystalline and sedimentary rocks. Layer 2 represents the sand and gravel facies of the Verde Formation in the Verde Valley, and the Coconino aquifer on the Colorado Plateau. Layer 1 represents

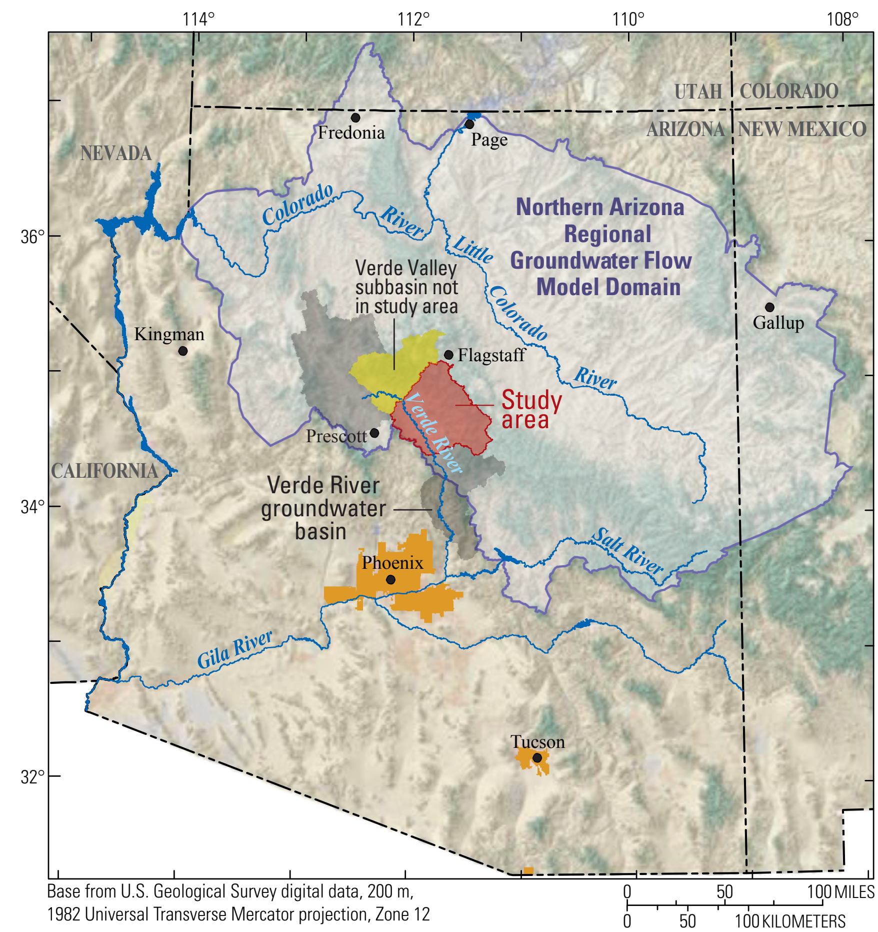

Figure 4. Map of the spatial extent of the Northern Arizona Regional Groundwater Flow Model and study area of this report.

the unconfined fluviolacustrine facies of the Verde Formation and shallow Quaternary stream alluvium.

Time was discretized into nine stress periods of varying length for the 1910–2005 simulation period (fig. 6). Stress periods in MODFLOW represent blocks of time in which constant stresses are applied. In model runs for the period 2005–2110, five stress periods of varying length were defined. Every stress period contained five timesteps, with each timestep after the first one being 20 percent longer than the preceding timestep. Timesteps are used to obtain higher temporal resolution for model responses.

The NARGFM was calibrated by adjusting several model parameters within hydrologically reasonable limits so that the model matched observations of water levels in wells and discharge to streams and springs. Rates of natural recharge were calculated and calibrated in a separate process, as described in Pool and others (2011), with the goal of matching simulated runoff and base-flow rates to observed and estimated rates.

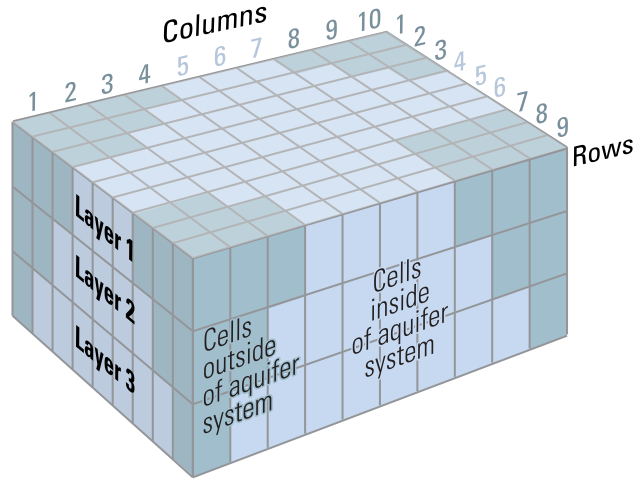

Figure 5. Conceptual diagram showing a 3-layer grid representing a groundwater-flow model's spatial discretization. Figure modified from Leake (1997).

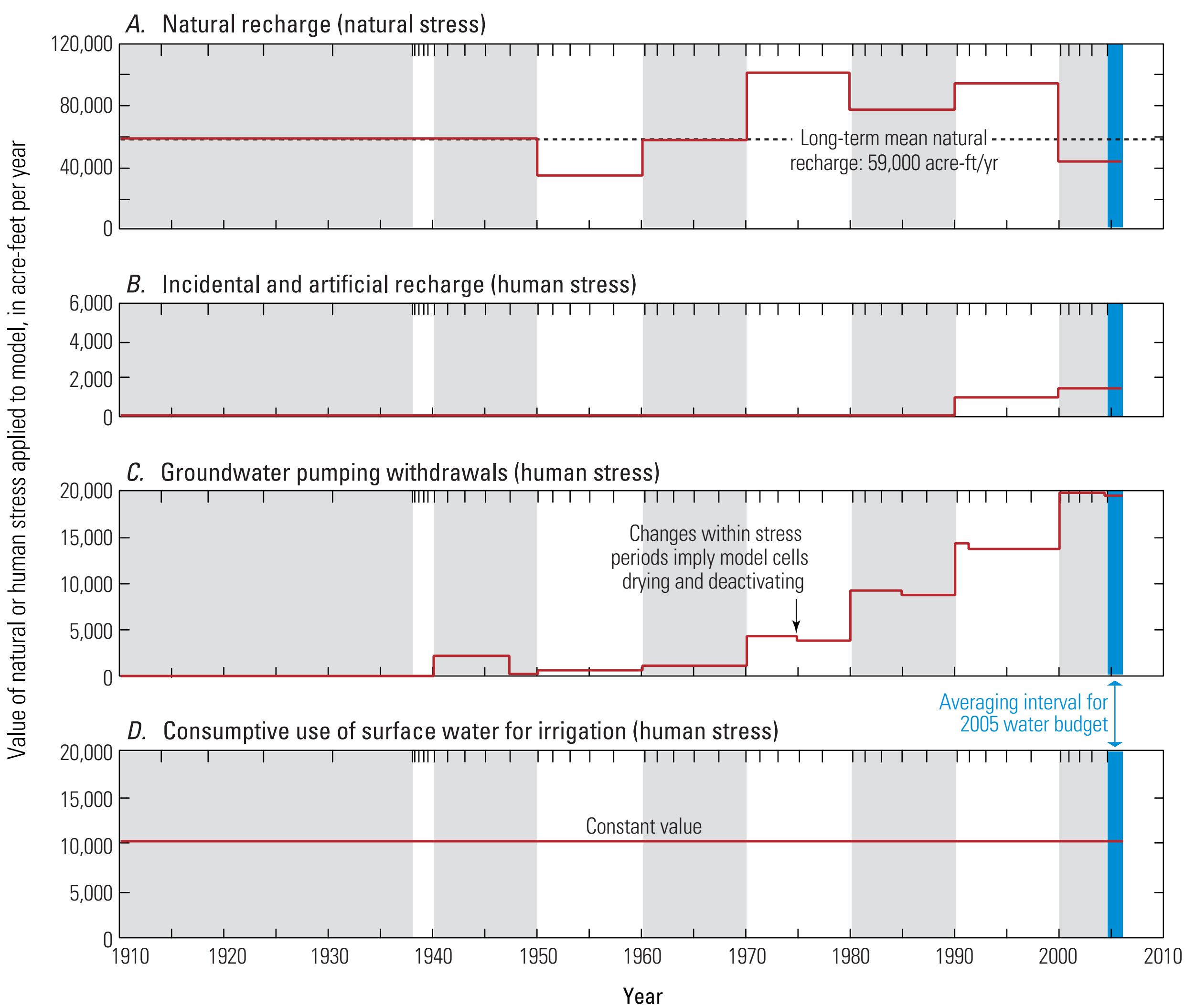

Figure 6. Plots showing natural and human stresses in the Verde Valley through time, applied to the Northern Arizona Regional Groundwater Flow Model over the period 1910–2005. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote timesteps within modeled stress periods.

Table 1. Description of five instances of running the Northern Arizona Regional Groundwater Flow Model for this study.

Name of model run	Time period of model run	Nature of natural stresses	Nature of human stresses	Variable name[1]
Full transient run	1910–2005	As published in Pool and others (2011)	As published in Pool and others (2011)	S_t
Forward-looking increased human stresses	2005–2110	Held at long-term average values[2]	Increased 3 percent per decade for 50 years, then held constant	S_t
Forward-looking decreased human stresses	2005–2110	Held at long-term average values[2]	Decreased 3 percent per decade for 50 years, then held constant	S_t
Forward-looking unchanged human stresses	2005–2110	Held at long-term average values[2]	Maintained at 2005 levels	S_t
Natural-conditions run	1910–2110	1910–2005: as published in Pool and others (2011); 2005–2110: held at long-term average values[2]	No human stresses	N_t

[1]As used in the "Calculation of relative changes in water budgets" section of this report.
[2]Long-term average values for natural stresses calculated as the weighted mean of 1910–2005 natural-stress values.

Creation of Forward-Looking Model Runs

The NARGFM was used to investigate how a simulated hydrologic system that models a real-world hydrologic system responds to changes in future human stresses. Numerous complex scenarios that consider variable future human stresses can be conceived and tested. Such scenarios, however, require considerable and wide-ranging data, such as population and per-capita water-use projections, and presently are not practical to be developed for the Verde River groundwater basin.

Instead, three hypothetical scenarios were developed for the 2005–2110 time period, wherein human stresses are changed at varying rates (fig. 7). The purpose of these hypothetical future scenarios was *not to predict any specific reality*, but to demonstrate and quantify the relative response of the hydrologic system to varying human stresses. The three scenarios were developed as follows:

- **Unchanged human stresses, 2005–2110.** The distribution and amount of human stresses that existed in 2005 are continued unchanged at those same rates and locations into the future.
- **Increased human stresses, 2005–2110.** This model run begins with human stresses as they existed in 2005, maintains these human-stress levels until 2010, increases them by 3 percent of the 2005 value for each of the next five decades (for a total of up to 15 percent increase over 2005 levels by the year 2060), and then holds them unchanged at the increased level for the following 50 years.
- **Decreased human stresses, 2005–2110.** This model run is the inverse of the increased-human-stresses model run. It begins with human stresses as they existed in 2005, maintains these levels until 2010, decreases them by a total of 15 percent over the subsequent 50 years, and then holds them unchanged at the decreased level for the following 50 years.

Human stresses were changed or maintained in these ways *across the entire model domain*, not just within the Verde Valley. The human stresses that were varied in the model runs were groundwater withdrawals and incidental and artificial recharge. Consumptive use of surface water for irrigation was not varied despite being a human stress; there has been insufficient hydrologic investigation of this process (Garner and Bills, 2012), and reasonable rates by which to vary it were not able to be determined.

Natural stresses (namely, natural recharge) were held constant at long-term average values for all three forward-looking model runs. These runs did not, for example, incorporate natural-recharge values derived from global-climate model forecasts. Regardless, the values actually chosen for natural stresses were irrelevant—the effects that natural stresses have on the hydrologic system *are independent of and superimposed upon* the human stresses imposed on the hydrologic system. The reason for this is the assumed linearity of model response. This assumed independence is centrally important to understanding the findings in this report.

As the groundwater model simulation proceeded into the future, wells in some model cells were not deep enough to access groundwater. Any wells that went dry in this manner were turned off (as opposed to, for example, moving or deepening those wells). The full attempted rate of pumping in these forward-looking model runs, therefore, was not realized. Turning off dry model cells is a simplification that likely would not happen in the real world, but there was no reasonable alternative that did not require making assumptions about complex water-resource management decisions.

Running the Groundwater-Flow Model

The NARGFM was run five times for the purposes of this study (table 1). The first model run was identical to the transient 1910–2005 model run documented in Pool and others (2011). The next three model runs were the execution of the forward-looking model runs. The final natural-conditions model run excluded all human stresses over all time—this was needed in order to calculate the relative changes attributable solely to human stresses.

In areas such as the Verde Valley where groundwater is connected to surface-water resources, stresses imposed

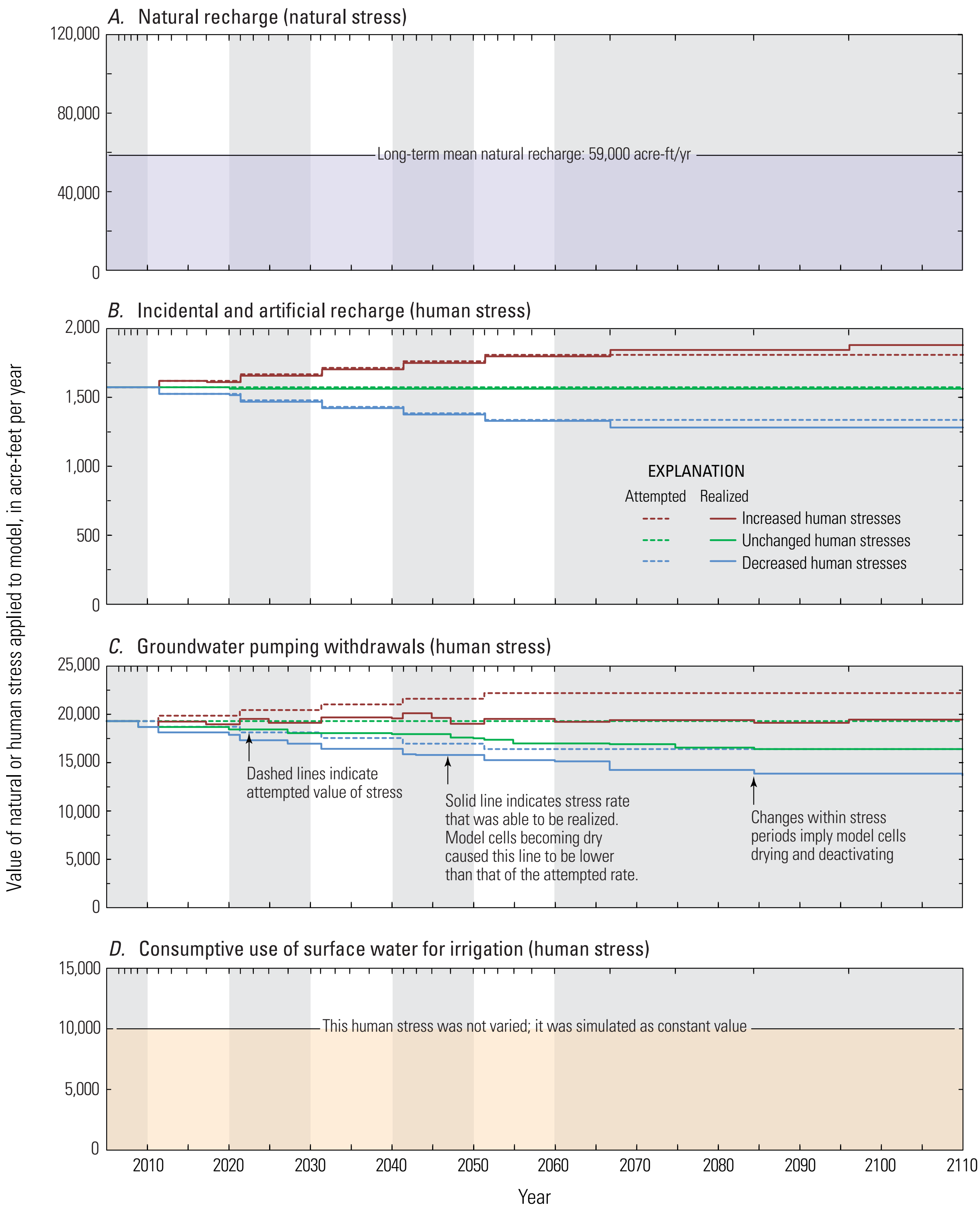

Figure 7. Plots showing rates of natural and human stresses, 2005–2110, applied to the Northern Arizona Regional Groundwater Flow Model under three scenarios for Verde Valley, Arizona. Shown are both the attempted rates of stresses and the realized rates that could be supported by the model simulation; the two differ because some model cells went dry. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote timesteps within modeled stress periods.

outside of the study area can cause responses in water-budget components within the study area. For this reason, an area much larger than the Verde Valley was simulated by the NARGFM (fig. 4).

Extraction of Water Budgets

Water budgets were extracted from the NARGFM by running ZONEBUDGET, a computer code that processes MODFLOW output files to generate water budgets for groupings of model cells known as zones (Harbaugh, 1990). One zone was defined to coincide with the study area. Adjacent zones were delineated so that surface-water and groundwater fluxes into and out of the study area could be quantified individually.

Values in water budgets are fluxes—volumes per unit of time—and in this report are presented in acre-feet per year (acre-ft/yr) and cubic feet per second (ft^3/s). Values greater than 10,000 acre-ft are rounded to the nearest 1,000 acre-ft, all others to the nearest 100 acre-ft. Values in ft^3/s are rounded to the nearest whole number, and correspond to the amount of water that would have to flow at a constant rate for a year to equal the equivalent acre-ft/yr value. Because of rounding, water budgets may appear not to perfectly balance.

Water budgets in this report are presented in several ways. Visual diagrams use boxes and arrows to represent reservoirs and conveyances, respectively. Each arrow corresponds to a value in a water budget. Tables list water-budget components on rows, grouped by inflows, outflows, and changes in storage. Maps are used to show the spatial distribution of some water-budget components. Finally, equations are defined in order to explain how water budgets are subtracted from one another when investigating changes attributable to human stresses.

Calculation of Relative Changes in Water Budgets

As published, the NARGFM simulates both natural and human stresses and the responses of the hydrologic system to those stresses. To investigate human stresses by themselves, a simple set of equations was employed to subtract the effects that natural stresses have on water-budget components, leaving as a residual only the relative changes in water-budget components attributable to human stresses. This approach requires an assumption of linearity in the simulated systems, which is a common technique of groundwater-flow investigation (Leake and Reeves, 2008; Barlow and Leake, 2012). This method for calculating relative changes attributable to human stresses can be described by the following equations:

$$A_t = S_t - (N_t - N_0), \qquad (1)$$

$$\Delta A_t = A_t - A_0, \qquad (2)$$

where

A_t is a water budget that has been adjusted to show only the effects of human stresses;

S_t is a water budget for a full model run at time t;

N_t is a natural-conditions water budget at time t (derived from a model run containing no human stresses, see the "Running the Groundwater-Flow Model" section);

N_0 is a natural-conditions water budget for a baseline year, either 1910 or 2005, depending on the period of analysis;

A_0 is an adjusted water budget for a baseline year, either 1910 or 2005 depending on the period of analysis; and

ΔA_t is the relative change in water-budget values, relative to either 1910 or 2005, that can be attributed to human stresses.

Substituting equation (1) into equation (2):

$$\Delta A_t = (S_t - N_t + N_0) - (S_0 - N_0 + N_0),$$

$$\Delta A_t = S_t - N_t + N_0 - S_0,$$

$$\Delta A_t = (S_t - N_t) - (S_0 - N_0), \qquad (3)$$

where

S_0 is a full water budget for a baseline year, either 1910 or 2005.

In this report, any discussion of relative changes in water budgets attributable to human stresses refers to the term ΔA_t. Full numeric results may be found in appendix 1, with values for S_t in table 1.1 and values for ΔA_t in tables 1.2 through 1.5.

Human Effects on the Hydrologic System of the Verde Valley, 1910–2005 and 2005–2110

Human stresses between 1910 and 2005 were found to have affected the hydrologic system of the Verde Valley, and human stresses likely will continue to affect the hydrologic system between 2005 and 2110. Effects on water-budget components mostly were associated with capture (Barlow and Leake, 2012), which is discussed in the "Discussion" section.

In the ensuing sections, the hydrologic system is evaluated with respect to its water-budget components in as many as three ways:

1. The magnitude of the component as of 2005 conditions (fig. 8; table 2);
2. The relative change from 1910–2005 attributable to human stresses (table 2); and
3. The relative changes from 2005–2110 attributable to human stresses, under three varying human-stress conditions (table 3).

Because the NARGFM was not designed to simulate all of the water-budget components discussed in this report, some water-budget components may appear as if they are not affected by human stresses, even though conceptually they could be (for example, natural recharge).

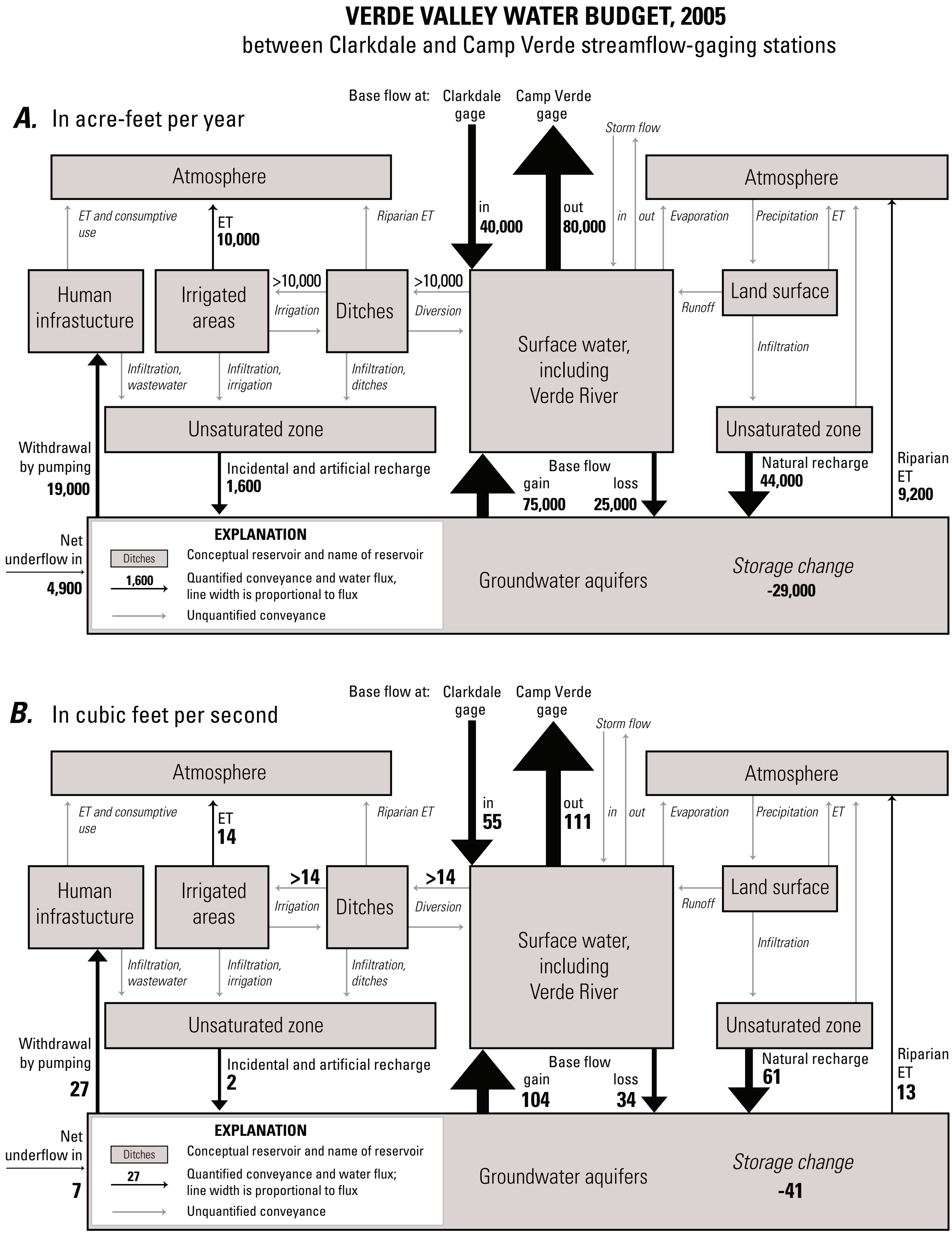

Figure 8. Diagrams showing water budget for Verde Valley, central Arizona, 2005. *A*, Fluxes given in acre-feet per year. *B*, Fluxes given in cubic feet per second. ET, evapotranspiration; infras., infrastructure; >, unquantified but larger than indicated amount.

Table 2. Groundwater and surface-water budgets (2005) and relative changes of water-budget values attributable to human stresses (1910–2005), Verde Valley, central Arizona.

		Water-budget values, 2005 (acre-feet per year)		Relative change in water-budget values because of human stresses, 1910–2005[1] (acre-feet per year)	
Water-budget component	**Category of component**	**Inflow**	**Outflow**	**Inflow**	**Outflow**
	Groundwater system				
Natural recharge from precipitation	Stress, natural	44,000		20	
Incidental and artificial recharge	Stress, human	1,600		[3]+1,600	
Net underflow	Response	4,900		[4]-200	
Withdrawal of groundwater by pumping	Stress, human		19,000		[3]+19,000
Net discharge of groundwater as base flow	Response		51,000		-5,400
Riparian evapotranspiration	Response		9,200		-200
Total:		[5]50,000	[5]79,000	[5]+1,400	[5]+14,000
Change in groundwater storage	Response	[5]-29,000		[5]-12,000	
	Surface-water system				
Base flow entering study area (at Clarkdale gage[6])	Response	[7]40,000		-4,900	
Net discharge of groundwater as base flow[8]	Response	51,000		-5,400	
Crop use of diverted surface water	Stress, human		10,000		[9]0
Base flow exiting study area (at Camp Verde gage[6])	Response		[8]80,000		-10,000

		Water-budget values, 2005 (cubic feet per second)		Relative change in water-budget values because of human stresses, 1910–2005 (cubic feet per second)	
Water-budget component	**Category of component**	**Inflow**	**Outflow**	**Inflow**	**Outflow**
	Groundwater system				
Natural recharge from precipitation	Stress, natural	61		0	
Incidental and artificial recharge	Stress, human	2		+2	
Net underflow	Response	7		-0.3	
Withdrawal of groundwater by pumping	Stress, human		27		+27
Net discharge of groundwater as base flow	Response		70		-7
Riparian evapotranspiration	Response		13		-0.3
Total:		70	110	+2	+19
Change in groundwater storage	Response	-40		-17	
	Surface-water system				
Base flow entering study area (at Clarkdale gage)	Response	55		-7	
Net discharge of groundwater as base flow	Response	70		-7	
Crop use of diverted surface water	Stress, human		14		0
Base flow exiting study area (at Camp Verde gage)	Response		111		-14

[1]That is, water-budget values are this much higher (+) or lower (-) because of human stresses that occurred between 1910 and 2005.

[2]Expected to be zero, as human activites were assumed to not affect natural precipitation-derived recharge.

[3]This human stress began after 1910, so the amount of relative change in the water budget is the same as the value itself.

[4]Human activities caused underflow in from the Colorado Plateau to decrease by 300 acre-ft/yr and underflow in from the upper Verde Valley subbasin to increase by 100 acre-ft/yr.

[5]Values do not sum exactly because of rounding.

[6]The Clarkdale gage is Verde River near Clarkdale, USGS streamflow-gaging station 09504000. The Camp Verde gage is Verde River near Camp Verde, USGS streamflow-gaging station 09506000.

[7]Differs from other published long-term estimates of baseflow (see table 4).

[8]Equal to corresponding row in groundwater system section of this table.

[9]Use of surface water for crop irrigation predates 1910 and is simulated as a constant value. Hence, this value.

Water-budget components are presented in two groupings: the groundwater systems and the surface-water systems. These two perspectives affect the sense of direction for “inflow” and “outflow.” The frame of reference for any water budget is arbitrary. In areas with a high degree of stream-aquifer interaction (such as the Verde Valley), a water budget can be expressed with respect to either the groundwater or surface-water system.

Groundwater System

From the perspective of the groundwater system, water enters aquifers through the processes of precipitation-derived natural recharge, underflow, incidental and artificial recharge, and infiltration of stream base flow. Water flows out of the aquifers through the processes of underflow, net discharge to streams as base flow, riparian ET, and withdrawals by pumping.

Natural Recharge (Inflow, Natural Stress)

Natural recharge to groundwater aquifers in the Verde Valley was about 44,000 acre-ft/yr (61 ft^3/s) in 2005. This value is an average for 2000–2005 conditions and is about 25 percent less than the long-term average of 59,000 acre-ft/yr (fig. 6), reflecting the dry conditions prevalent during the 2000–2005 time period. Other natural-recharge estimates have been published (for example, Arizona Department of Water Resources, 2000; Blasch and others, 2006; Pool and others, 2011; Tillman and others, 2011), but generally not for the study area as defined precisely for the present report. As such, those other published values are not directly comparable to the values in this report.

Human stresses, for the purposes of this study, cannot affect this natural recharge water-budget component. This is because the NARGFM does not vary natural recharge because of human activities. Speaking generally, however, global climate models indicate that human activities that affect global climate will increase aridity in the southwestern United States (Williams and others, 2010; deBuys, 2011). Increased aridity would likely decrease natural recharge.

Incidental and Artificial Recharge (Inflow, Human Stress)

Under 2005 conditions, incidental and artificial recharge in the Verde Valley together were about 1,600 acre-ft/yr (2 ft^3/s). This might be an underestimate, however, because not all processes that lead to incidental recharge have been studied and quantified. Surface-water ditch diversions and associated irrigation activities in the Verde Valley, for example, likely allow additional surface water to become recharge (Garner and Bills, 2012), but this effect was not simulated in the NARGFM.

Between 1910 and 2005, incidental and artificial recharge increased in the study area from 0 to 1,600 acre-ft/yr, and they were simulated as zero before 1990 (fig. 6). All of this increase was attributable to human activities, as incidental and artificial recharge inherently are human-driven processes.

Forward-looking model runs for 2005–2110 simulated small changes in the human stresses of incidental and artificial recharge—between a decrease of 300 acre-ft/yr and an increase of 300 acre-ft/yr (fig. 7). These decreases and increases are small in comparison to the overall Verde Valley water budget. Values for these components were scaled up and down in direct proportion with groundwater withdrawal rates.

Net Underflow (Inflow, Human Stress)

A total of about 4,900 acre-ft/yr (7 ft^3/s) of groundwater entered the study area from adjoining areas during 2005 (fig. 9). This is a net value, not a gross value; small-scale back-and-forth movement of water along study-area boundaries can produce much larger gross values that are not helpful for understanding the overall Verde Valley water budget. Study-area boundaries could have been delineated so as to minimize underflow, but they were not. Groundwater divides move during the transient simulation of the NARGFM, making it unlikely to find one boundary delineation that always maintains zero underflow.

Almost no change in net underflow between 1910 and 2005 was attributable to human stresses—a decrease of only about 200 acre-ft/yr was estimated to have occurred during that period. In the three forward-looking model runs for 2005–2110, however, net underflow into the study area increased in each case. Even in the case of decreased human stresses—wherein groundwater withdrawals in the Verde Valley decreased by 5,600 acre-ft/yr over 105 years—net underflow still increased by 1,000 acre-ft/yr (1 ft^3/s). This can be explained by aquifer-gradient changes imparted by pre-2005 pumping (a human stress) propagating outward from wells. Hydraulic gradient changes take time to travel through the aquifer. If these changes reach the study-area boundary only after 2005, then rates of underflow at the boundaries would change in response to these human stresses only during the forward-looking model runs. Unchanged and increased human-stress model runs showed additional increases of net underflow (up to 1,300 acre-ft/yr by year 2110). These results suggest that groundwater withdrawals in the Verde Valley—both those that have occurred to date and those that may yet occur—will induce additional groundwater inflow from adjacent areas.

Withdrawal of Groundwater by Pumping (Outflow, Human Stress)

As of 2005, groundwater withdrawals in the Verde Valley amounted to about 19,000 acre-ft/yr (27 ft^3/s) and supported municipal, domestic, and industrial water uses. Groundwater withdrawals have increased over time within the study area (fig. 6), as well as across the entire NARGFM domain of northern Arizona (Pool and others, 2011).

Table 3. Relative change of groundwater and surface-water budgets between 2005 and 2110 attributable to human stresses, Verde Valley, central Arizona.

		Water-budget values, 2005 (acre-feet per year)		Human stresses, relative changes 2005–2110[1] (acre-feet per year)					
				Decreased		Unchanged		Increased	
Water-budget component	Category of component	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Groundwater system									
Natural recharge from precipitation[2]	Stress, natural	44,000		[3]0		[3]0		[3]0	
Incidental and artificial recharge	Stress, human	1,600		-300		0		+300	
Net underflow	Response	4,900		+1,000		+1,200		+1,300	
Withdrawal of groundwater by pumping	Stress, human		19,000		-5,600		[4]-2,900		[5]+200
Net discharge of groundwater as base flow	Response		51,000		-2,700		-3,900		-4,800
Riparian evapotranspiration	Response		9,200		-300		-400		-500
Total:		[6]50,000	[6]79,000	[6]+800	[6]-8,600	[6]+1,100	[6]-7,100	[6]+1,600	[6]-5,000
Change in groundwater storage	Response	[6]-29,000		[6]+9,300		[6]+8,200		[6]+6,600	
Surface-water system									
Base flow entering study area (at Clarkdale gage[7])	Response	[8]40,000		-2,700		-3,300		-3,800	
Net discharge of groundwater as base flow[9]	Response	51,000		-2,700		-3,900		-4,800	
Crop use of diverted surface water	Stress, human		10,000		[10]0		100		100
Base flow exiting study area (at Camp Verde gage[7])	Response		[8]80,000		-5,400		-7,200		-8,600

		Water-budget values, 2005 (cubic feet per second)		Human stresses, relative changes 2005–2110 (cubic feet per second)					
				Decreased		Unchanged		Increased	
Water-budget component	Category of component	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Groundwater system									
Incidental and artificial recharge	Stress, human	2		-0.4		0		+0.4	
Net underflow	Response	7		+1		+2		+2	
Withdrawal of groundwater by pumping	Stress, human		27		-8		-4		+0.2
Net discharge of groundwater as base flow	Response		70		-4		-5		-7
Riparian evapotranspiration	Response		13		-0.4		-0.5		-0.6
Total:		70	110	+1	-11	+2	-10	+5	-7
Change in groundwater storage	Response	-40		+13		+11		+9	
Surface-water system									
Base flow entering study area (at Clarkdale gage)	Response	55		-4		-5		-5	
Net discharge of groundwater as base flow	Response	70		-4		-5		-7	
Crop use of diverted surface water	Stress, human		14		0		0		0
Base flow exiting study area (at Camp Verde gage)	Response		111		-7		-10		-12

[1]That is, water-budget values are this much higher (+) or lower (-) because of human stresses that occurred between 2005 and 2100.

[2]Simluated as an unvarying rate equal to the long-term (1910-2005) average natural-recharge rate.

[3]Expected to be zero, as human activites were assumed to not affect natural precipitation-derived recharge.

[4]Although withdrawals were simulated as unchanged 2005-2110, some cells with wells in them went dry and were unable to continue pumping.

[5]Because of drying cells, this value was not increased as much as was specified to the model.

[6]Values do not sum exactly, because of rounding.

[7]The Clarkdale gage is Verde River near Clarkdale, USGS streamflow-gaging station 09504000. The Camp Verde gage is Verde River near Camp Verde, USGS streamflow-gaging station 09506000.

[8]Differs from other published long-term estimates of baseflow (see table 4).

[9]Equal to corresponding row in groundwater system section of this table.

[10]Use of surface water for crop irrigation is simulated as a constant value. Hence, this value.

The three forward-looking model runs attempted to decrease, hold steady, and increase groundwater withdrawals between 2005 and 2110. Model runs, however, were unable to achieve their full attempted changes in groundwater withdrawal rate—some of the simulated wells in the NARGFM went dry. Compared with 2005 groundwater withdrawal rates, by the year 2110 the model runs attempted to (a) decrease withdrawals by about 3,000 acre-ft/yr, (b) maintain withdrawals at 2005 rates, and (c) increase withdrawals by about 3,000 acre-ft/yr. Instead, by the year 2110 the model runs respectively (a) decreased withdrawals by 5,600 acre-ft/yr, (b) decreased withdrawals by 2,900 acre-ft/yr, and (c) increased withdrawals by 200 acre-ft/yr (fig. 7).

Model cells that went dry were considered acceptable for two reasons. First, the model runs produced three variable withdrawal conditions, which in turn meant they produced three variable conditions of human stresses on the groundwater system. Creation of variable human-stress

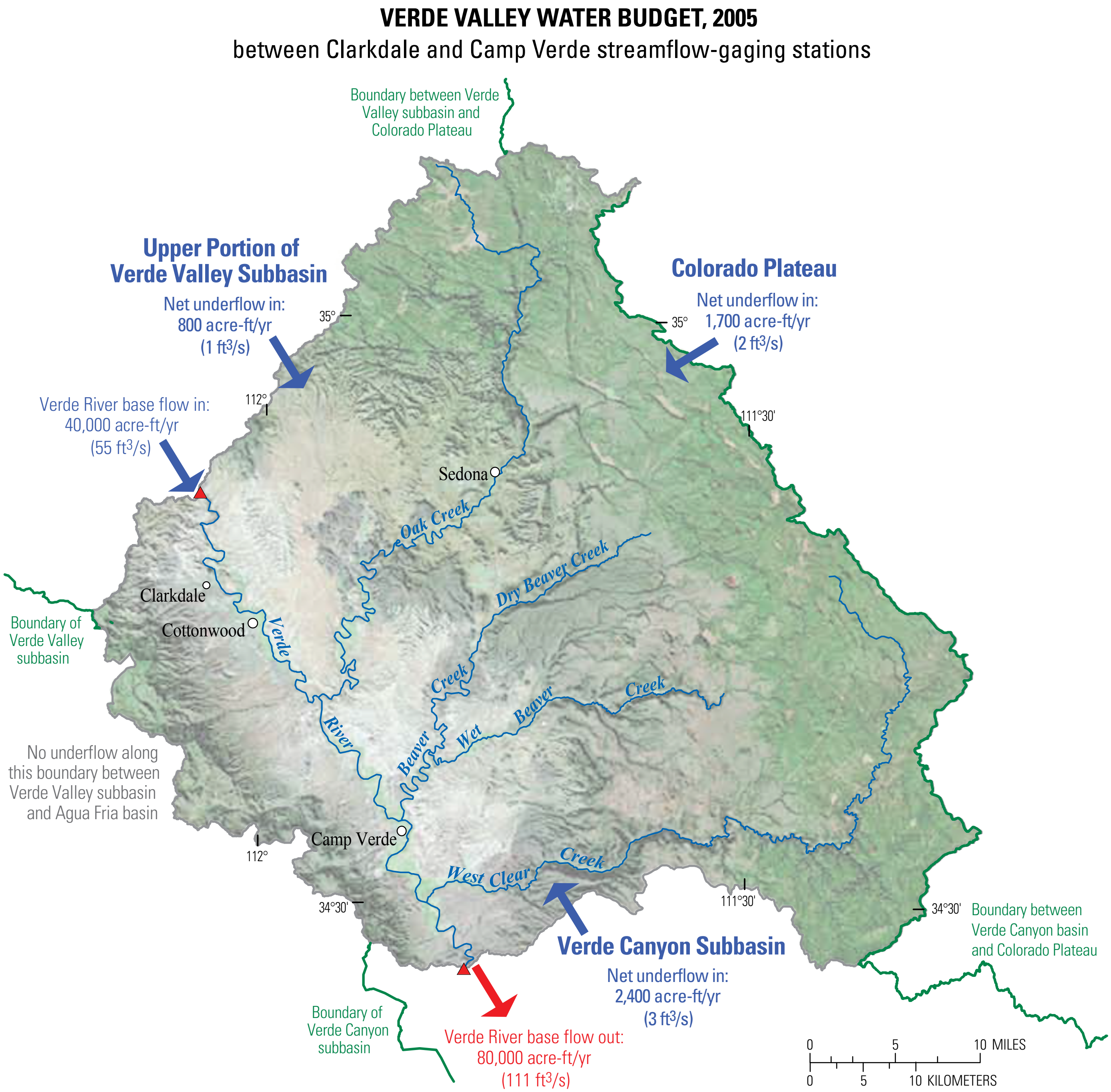

Figure 9. Map showing underflow and base flow into and out of the Verde Valley, central Arizona, 2005.

conditions was the goal of these model runs, and this goal was achieved. Second, human stresses were altered not only within the study area, but also throughout the entire NARGFM domain; most other areas of the model domain did not contain such a large number of dry wells in the simulations.

Riparian Evapotranspiration (Outflow, Response)

As of 2005, about 9,200 acre-ft/yr (13 ft^3/s) of groundwater was estimated to return to the atmosphere through riparian ET in the Verde Valley. The major riparian zones in the study area are the near-stream environments of the Verde River, Oak Creek, Beaver Creek, and West Clear Creek (fig. 1).

Values for riparian ET decreased because of human stresses, both from 1910 to 2005 and from 2005 to 2110, but only by small amounts. Riparian ET values decreased by about 500 acre-ft/yr (less than 1 ft^3/s) during the 2005–2110 time period because of increased human stresses; in model runs for the 1910–2005 time period, riparian ET decreases were less than 500 acre-ft/yr (tables 2 and 3). The maximum decrease in riparian ET was about 5 percent of total riparian ET in the Verde Valley. Among the three forward-looking model runs, decreases in riparian ET differed, indicating that Verde Valley riparian ET is variably sensitive to human stresses. Decreased riparian ET in response to groundwater withdrawals is one of the possible sources of captured water (Webb and others, 2007; Leake and Pool, 2010; Barlow and Leake, 2012); the results of this study indicate that such a phenomenon has occurred in the Verde Valley and could continue to occur.

Change in Groundwater Storage

In 2005, groundwater storage in aquifers within the study area was decreasing by about 29,000 acre-ft/yr. This 2005 rate of decrease was larger than groundwater withdrawal rates ever have been in the study area, but only about 12,000 acre-ft/yr of this storage decrease in 2005 was attributable to human stresses. The remaining 17,000 acre-ft/yr of storage decrease was the result of below-average natural recharge in years preceding 2005 (fig. 6; see also Pool and others, 2011, p. 79). The effects of human stresses on groundwater storage are independent of effects caused by natural stresses, and the two are superimposed on one another (Leake, 2011; Pool and others, 2011).

For the forward-looking model runs in the period 2005–2110, the rate of decrease in groundwater storage was lessened in all three cases. That is, while groundwater storage still decreased during this hypothetical future period, the rate of its annual decrease became slower. For the increased human-stress condition, the decreased rate of groundwater storage decrease is offset precisely by increases in inflow components (incidental and artificial recharge and net underflow into the study area) and decreases in outflow components (net discharge as base flow and riparian ET; table 3). This is

An Independent Estimate of Riparian Evapotranspiration

Riparian ET is challenging to quantify accurately. One approach to improving understanding of the accuracy of any one riparian ET estimate is to verify it by developing an estimate through an alternative and independent method. An exercise was undertaken in this study wherein riparian ET was estimated by using remotely sensed satellite data, which is reasonably independent of the method employed in the NARGFM.

This independent method of riparian ET estimation used a regression model that related measured ET to data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite's Enhanced Vegetation Index (EVI) grid data. Image datasets were produced from this satellite every 16 days. Data from 2000 to 2010 (across all seasons and variations in hydrologic condition) were averaged to obtain a range of values.

The riparian ET estimates calculated in this way (table A1) were at least 50 percent larger than the water-budget value calculated by the NARGFM. Lower values of riparian ET estimates, about 14,000 acre-ft/yr, were calculated by subtracting model-derived precipitation estimates from the value derived from this remote-sensing approach; the reasoning was that even when phreatophytes (plants whose roots may reach the water table) have access to groundwater, they will use some of the precipitation that falls around them. The amount of precipitation they use is not known, and therefore a reasonable upper bound for riparian ET, where no precipitation is used, was 22,000 acre-ft/yr. The NARGFM estimated that, as of 2005, only about 9,200 acre-ft/yr of groundwater was used for riparian ET within the Verde Valley.

A more complete explanation of this method and its limitations and assumptions, as well as another approach to summarizing its data, is provided in appendix 2.

Table A1. Riparian evapotranspration estimated using remotely sensed satellite data, 2000–2010, Verde Valley, central Arizona.

Buffer area	Delineation type[1]	Annual mean ET (acre-feet per year)	
		Minus precipitation	Riparian
Woody wetlands	Landcover	3,883	5,276
Oak Creek	Stream proximity	2,912	4,707
Verde River	Stream proximity	2,889	4,224
West Clear Creek	Stream proximity	2,056	4,319
Emergent herbaceous wetlands	Landcover	1,214	1,621
Wet Beaver Creek	Stream proximity	1,138	1,908
TOTAL		14,000	22,000

[1]See appendix 2 for description of this column.

consistent with the concept of capture: as a well withdraws water over time, the source of that water increasingly shifts away from depletion of groundwater storage and toward the capture of natural discharge (Theis, 1940).

Another approach to evaluating changes in groundwater storage is to map changes in groundwater-table altitude. Lowered water-table altitudes can result in having to deepen, augment, or even relocate wells. As simulated under the condition of unchanged human stress for the 2005–2110 time period, water-table altitudes in the Verde Valley decreased because of human stresses (fig. 10). The largest decreases were more than 100 ft, near the city of Cottonwood. Modeled water-table altitudes also decreased in areas adjacent to but outside of the Verde Valley. Maps for the decreased-human-stress and increased-human-stress conditions demonstrated a spatial pattern very similar to that for the unchanged-human-stress condition and are, therefore, not presented in this report.

Net Discharge of Groundwater as Base Flow (Outflow, Response)

The net discharge of groundwater as base flow is the water-budget component that represents the connection between the groundwater and surface-water systems. As

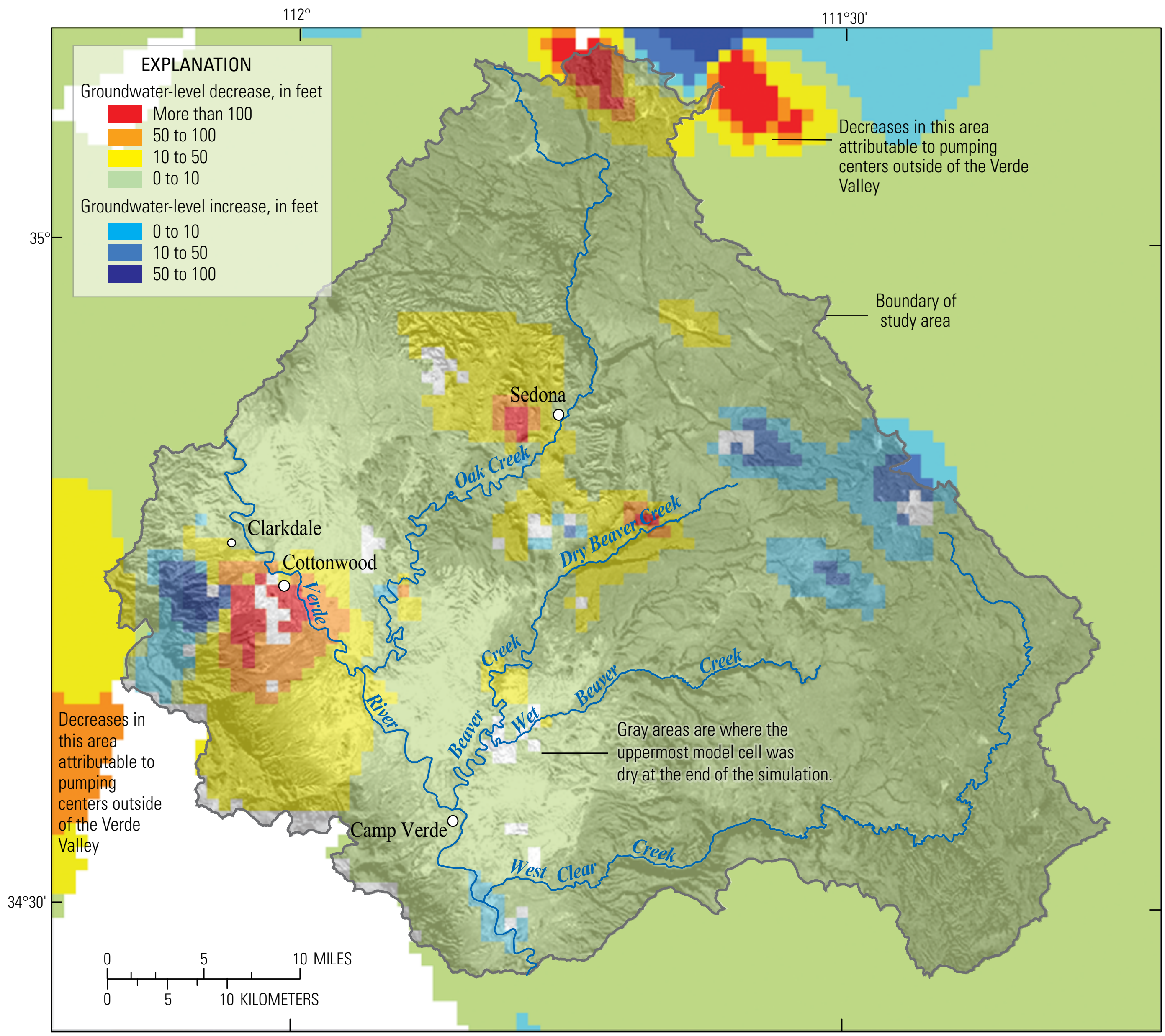

Figure 10. Map showing relative changes in groundwater-table altitude attributable to unchanged human stresses, simulated by the Northern Arizona Regional Groundwater Flow Model, Verde Valley, central Arizona, 2005–2110. Values used to produce this map are from the uppermost layer of the model.

such, it is listed in both the groundwater and surface-water groupings of this discussion, and is numerically identical in both. To avoid repetition, it is discussed only in the "Net Discharge of Groundwater as Base Flow" subsection of the "Surface-Water System" section.

Surface-Water System

From the perspective of the water flowing in and through streams and irrigated areas, water enters and exits through the processes of net groundwater discharge to the stream network, ET from fields irrigated with surface water, and base flow entering and exiting the study area by way of the Verde River.

Base Flow Entering the Verde Valley (Inflow, Response)

In 2005, the Verde River conveyed about 40,000 acre-ft/yr (55 ft^3/s) of base flow past the Clarkdale gage, at the upstream end of the study area (fig. 11). There are no other perennial streams that flow into the study area.

The NARGFM-simulated value for base flow entering the Verde Valley is less than previously published values of base flow at the Clarkdale gage (table 4) for several possible reasons. Measurement or calculation of base flow in other studies used methods that differed from the present study (for example, hydrograph separation). Differing time ranges for averaging were used among various studies, and some studies (for example, Blasch and others, 2006) used only selected seasons for base-flow calculations. In any case, any apparent underestimation of the absolute magnitude of base flow at the Clarkdale or Camp Verde gage does not affect the ability of the present study to evaluate the relative changes in base flow attributable to human stresses.

Base flow entering the study area at the Clarkdale gage in 2005 was estimated to have decreased by about 4,900 acre-ft/yr (7 ft^3/s) because of human stresses during the 1910–2005 time period (fig. 11). Although the human stresses that caused this decrease likely are mostly located in areas of the Verde River groundwater basin upgradient from the Clarkdale gage, some could have been located in other groundwater basins. This possibility could include basins downgradient from the Clarkdale gage, because the process of capture occurs irrespective of directions of groundwater flow (Leake and Pool, 2010; Leake, 2011; Barlow and Leake, 2012). Any capture from downgradient basins is probably minimal in the case of the Clarkdale gage, because the major downgradient pumping centers are many miles from this gage and likely capture their water from more proximal sources.

The three forward-looking model runs each indicate additional decreases in base flow at the Clarkdale gage between 2005 and 2110 (fig. 12). These decreases range from 2,700 to 3,800 acre-ft/yr (4 to 5 ft^3/s), depending on the degree of change in human stresses across the NARGFM domain. The model run with decreased human stresses produced the smallest decrease in base flow, while the model run with increased human stresses produced the largest decrease in base flow. On the basis of the methods of this report, therefore, human stresses will continue to capture stream base flow at the Clarkdale gage during the 2005–2110 time period.

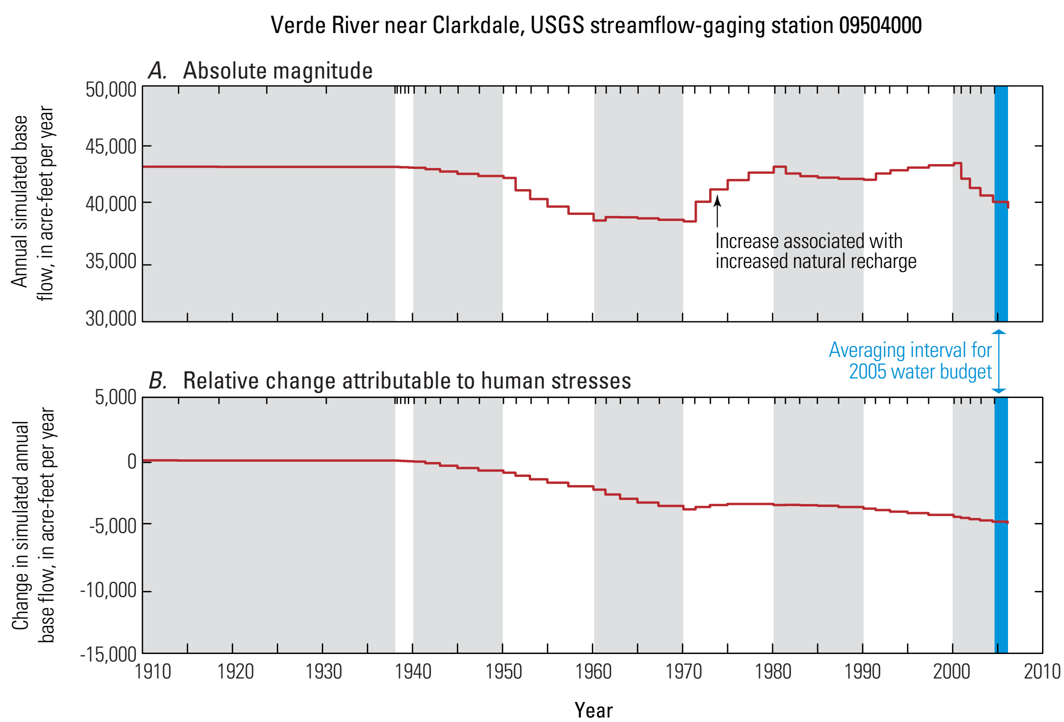

Figure 11. Plots of base flow simulated by the Northern Arizona Regional Groundwater Flow Model in the Verde River at Clarkdale, USGS streamflow-gaging station 09504000, during 1910–2005 model run. *A,* Absolute magnitude of base flow. *B,* Relative change in base flow attributable to human stresses. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote timesteps within modeled stress periods.

Table 4. Summary of annual, winter, and summer base-flow values at USGS streamflow-gaging stations from this and related studies, Verde Watershed, central Arizona.

[NARGFM, Northern Arizona Regional Groundwater Flow Model; acre-ft/yr, acre-feet per year; ft^3/s, cubic feet per second]

Publication source	Base flow, acre-ft/yr			Base flow, ft^3/s			Computation period	Computation method
	Annual average	Winter only	Summer only	Annual average	Winter only	Summer only		
Verde River near Paulden (USGS streamflow-gaging station 09503700)[1]								
This study	17,000	-	-	23	-	-	2005	NARGFM
Pool and others (2011)	21,700	-	-	30	-	-	predevelopment	NARGFM
Blasch and others (2006), table 6	[2]17,700	-	-	[2]24.5	-	-	1963–2004	HYSEP[3]
Blasch and others (2006), table 8	17,600	[2]18,200	-	24.4	25.1	-	1964–2003	HYSEP[3]
Owen-Joyce and Bell (1983)	16,000–17,000	-	-	22–24	-	-	1965–1978	visual inspection[4]
Verde River near Clarkdale (USGS streamflow-gaging station 09504000)								
This study	40,000	-	-	55	-	-	2005	NARGFM
Garner and Bills (2012)	-	52,000	46,000	-	72	64	6/2007, 2/2011	synoptic baseflow
Pool and others (2011)	43,300	-	-		-	-	predevelopment	NARGFM
Blasch and others (2006), table 6	[2]57,200	-	-	[2]79	-	-	1965–2004	HYSEP[3]
Blasch and others (2006), table 8	[2]57,200	260,400	-	79	83.5	-	1966–2003	HYSEP[3]
Owen-Joyce and Bell (1983)	49,000–60,000	-	-	68–83	-	-	1966–1978	visual inspection[4]
Verde River near Camp Verde (USGS streamflow-gaging station 09506000)								
This study	80,000	-	-	111	-	-	2005	NARGFM
Garner and Bills (2012)	-	152,000	33,000	-	209	45	6/2007, 2/2011	synoptic baseflow
Pool and others (2011)	[5]72,700	-	-	[5]100	-	-	predevelopment	NARGFM
Blasch and others (2006), table 6	-	[2]138,800	-	-	192	-	1934–1945, 1988–2004	HYSEP[3]
Blasch and others (2006), table 8	-	154,900; 144,100	-	-	214; 199	-	1934–1945; 1989–2003	HYSEP[3]
Owen-Joyce and Bell (1983)	48,000–145,000	145,000	31,000–70,000	66–200	200	43–96	1935–1945, 1976–1979	visual inspection[4]
Twenter and Metzger (1963)	-	163,000	-	-	225	-	not specified[6]	not specified[6]
Owen-Joyce (1984)	-	118,000	66,000	-	163	[7]91	11/1980, 6/1981	synoptic baseflow

[1]Station is outside of study area, but is a widely used location for reporting of baseflow. The groundwater-flow model in this report can calculate this using the same methods as other stations.

[2]Unclear whether these are annual or winter values; they are placed in columns that seem most likely. From Blasch and others (2006), p. 24: "Most of the base-flow separations use winter base-flow data because these are the least affected by diversions and ET."

[3]HYSEP software (Sloto and Crouse, 1996) using the fixed-interval method for hydrograph separation.

[4]Method employed was visual hydrograph separation, followed by summary statistic computations on monthly and annual base-flow components.

[5]Delineation of the location of this stream-gaging station differed slightly from that of the present report, which resulted in the exclusion of some groundwater discharge.

[6]Methods for calculating the reported value were not described. Reported value is assumed to be winter base flow because it is similar to other winter base-flow values.

[7]Value is the mean of 92.8 and 89.4 ft^3/s measured on June 8 and June 11, 1981, respectively.

Net Discharge of Groundwater as Base Flow (Inflow, Response)

In 2005, there was a net discharge of about 51,000 acre-ft/yr (70 ft^3/s) of groundwater to streams in the Verde Valley. This is a single value that represents an annual and spatial total. Net groundwater discharge in the Verde Valley differs between summer and winter (Garner and Bills, 2012) and occurs not only in the mainstem Verde River but also within perennial reaches of tributary streams. Although the NARGFM can report gross values of groundwater discharge and infiltration of base flow on a 0.62-mi spatial scale, the model is best suited to reporting a net value (discharge minus infiltration) at the scale of a groundwater basin (Pool and others, 2011, p. 89).

From 1910 to 2005, human stresses led to a decrease in net discharge of base flow in the study area (fig. 13). As of 2005, net base-flow discharge was about 5,400 acre-ft/yr (7 ft^3/s) less than it would have been if there never had been any human stresses. By 2110, relative to 2005, conditions of the forward-looking model runs estimated an additional decrease in net base flow discharge between 2,700 and 4,800 acre-ft/yr (4 to 7 ft^3/s). The decreased-human-stress model run caused the smallest amount of base-flow decrease, while the increased-human-stress model run caused the largest amount of base-flow decrease.

Ditch Diversions and Crop Irrigation (Outflow, Human Stress)

The NARGFM simulated the amount of surface water consumed by crop irrigation and ET as a constant 10,000 acre-ft/yr (14 ft^3/s) through all simulation periods (figs. 6 and 7). This simplified consumptive-use rate was calculated from a geographic information system dataset describing areal distribution of crops and average values of annual water consumption for various crop types (Pool and others, 2011, p. 37).

Ditch diversions represent a major human alteration to the hydrologic system in the Verde Valley, but they have not yet been studied comprehensively. The design and operation of a ditch diversion is far more complex than was modeled in the NARGFM (fig. 14). Because consumptive use was simulated as a constant rate, this study was unable to assess how varying human stresses might affect it (although they surely do), and conclusions therefore should not be drawn regarding streamflow at the reach-level (mile) scale of the Verde River or its perennial tributaries. Considerable additional research—enumerated to some degree in Blasch and others (2006) and Garner and Bills (2012)—would be necessary to understand reach-level changes in base flow attributable to ditch diversions, particularly regarding how these diversions affect the shallow groundwater-flow system that supplies base flow to streams.

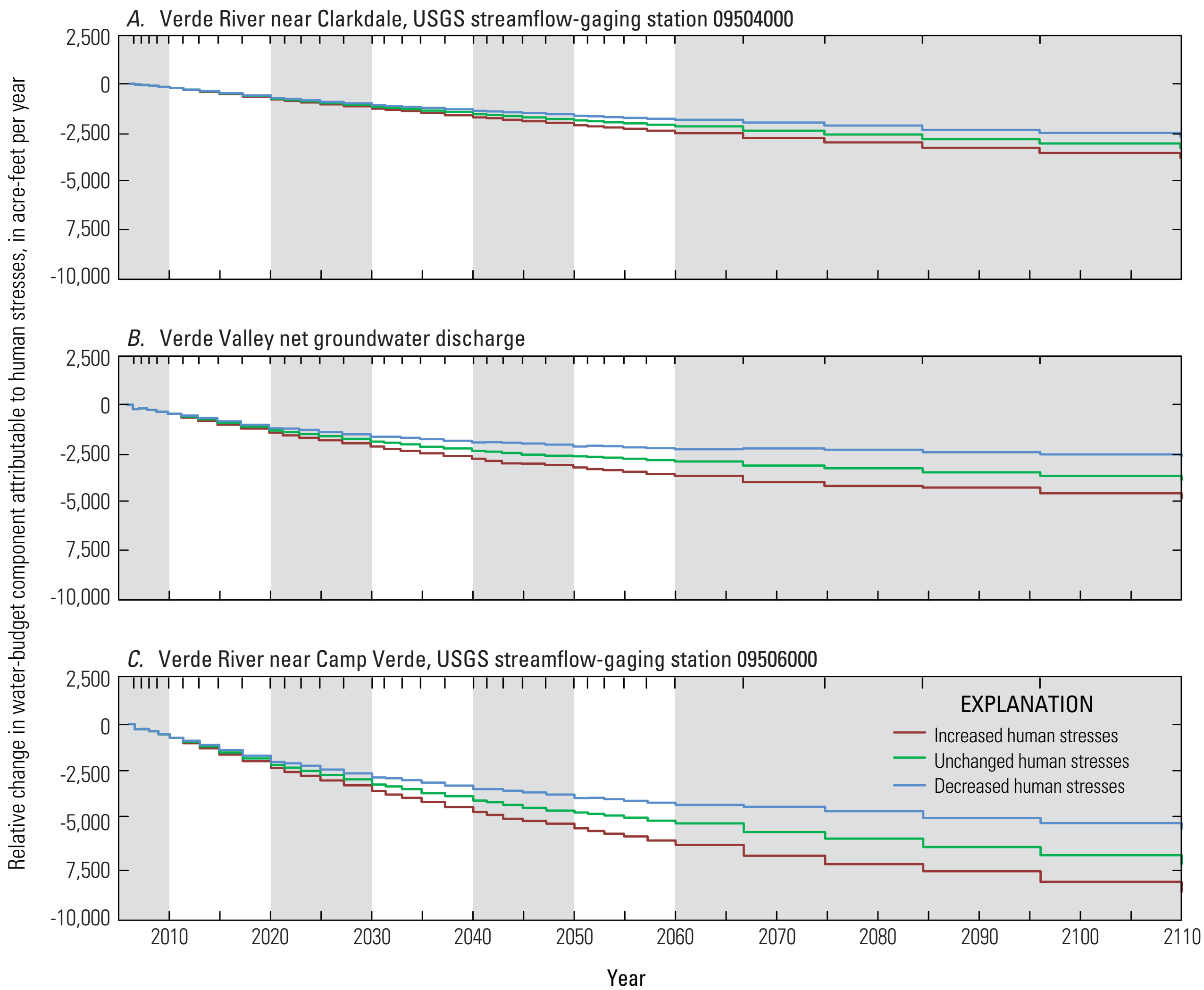

Figure 12. Plots showing changes in base flow and net groundwater discharge attributable to human stresses, 2005–2110, simulated by the Northern Arizona Regional Groundwater Flow Model in the Verde Valley, central Arizona, under three scenarios of increased, unchanged, and decreased human stresses. *A,* Change to base flow in the Verde River at Clarkdale, USGS streamflow-gaging station 09504000. *B,* Net change to groundwater discharge in the Verde Valley. *C,* Change to base flow in the Verde River near Camp Verde, USGS streamflow-gaging station 09506000. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote timesteps within modeled stress periods.

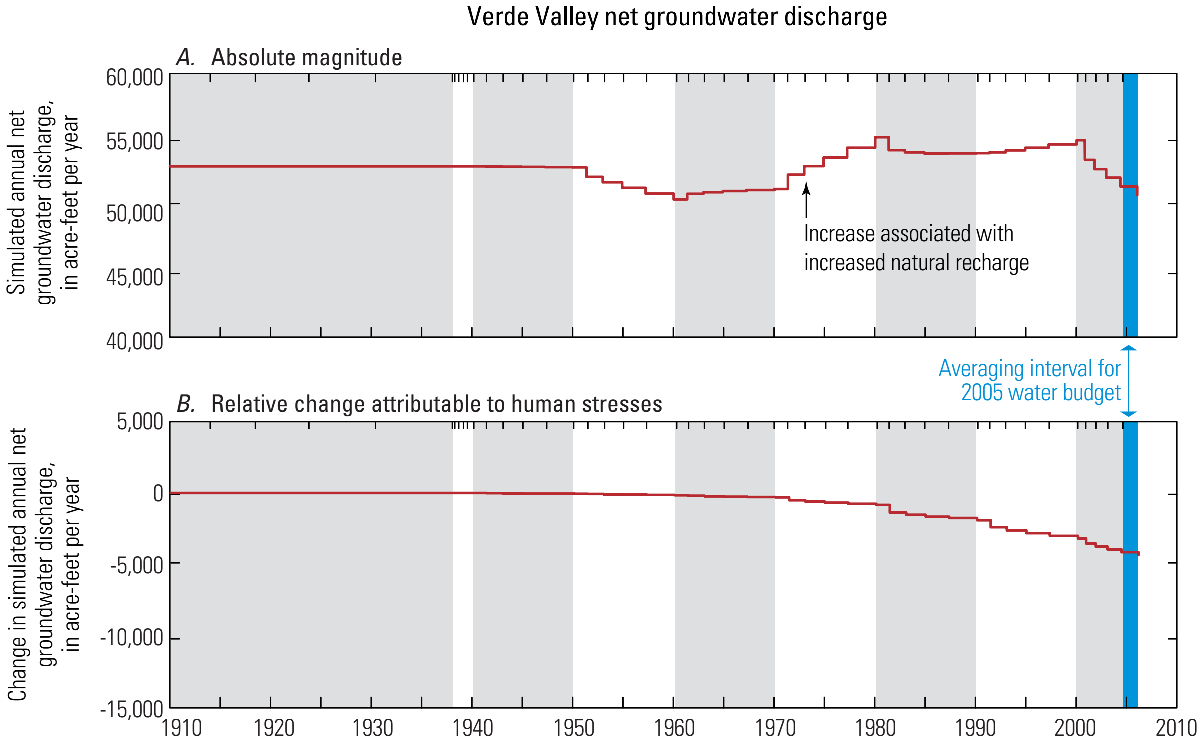

Figure 13. Plots showing net groundwater discharge for 1910–2005, as simulated by the Northern Arizona Regional Groundwater Flow Model, Verde Valley, central Arizona. *A,* Absolute magnitude of net groundwater discharge, in acre-feet per year. *B,* Relative change in net groundwater discharge attributable to human stresses, given in acre-feet per year. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote timesteps within modeled stress periods.

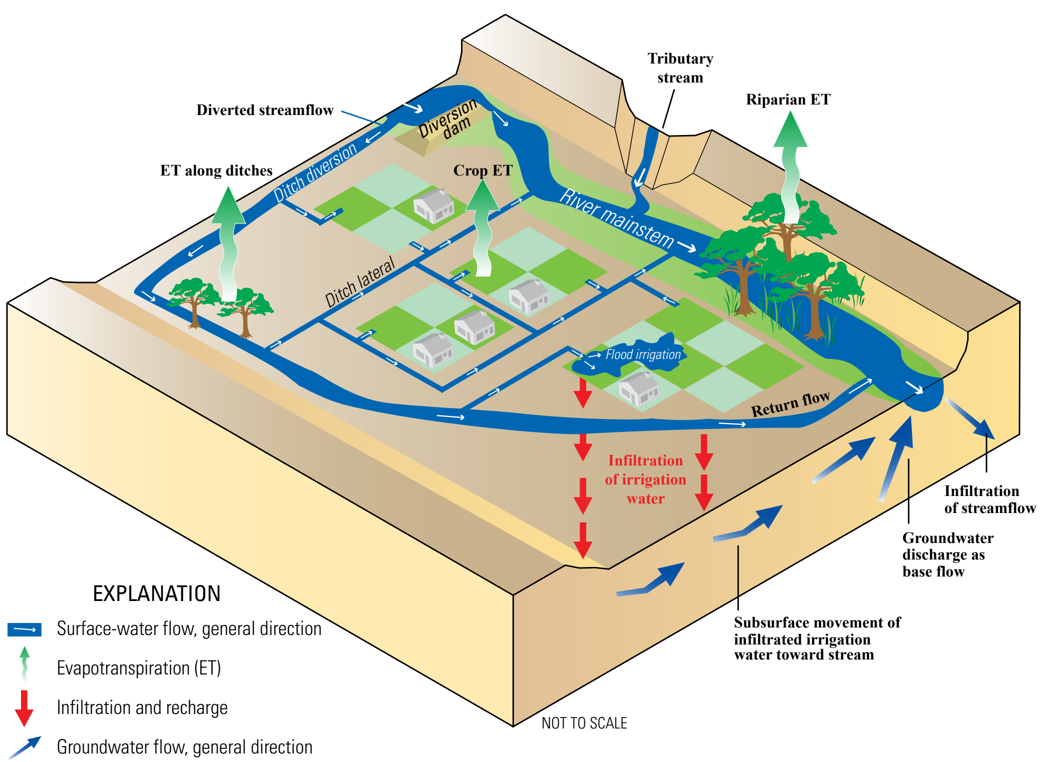

Figure 14. Conceptual diagram of an idealized perennial stream with an active irrigation system of ditch diversions and irrigation. Modified from Garner and Bills (2012).

An Independent Estimate of Crop Irrigation Consumptive Use

The simulation of ditch diversions and crop irrigation within the NARGFM is of necessity greatly simplified relative to the actual operation of these systems and processes. To evaluate the reasonableness of the value used in the NARGFM, an independent estimate of this water-budget component was calculated by conducting a survey of irrigated fields within the Verde Valley during 2010–2011. Although irrigation and growing conditions could have been different in 2010–2011 as compared with 2005, general agreement between the numbers might be expected.

Total planted irrigated acreage was calculated by using a combination of aerial photography, field inspection, and a geographic information system. The crop being grown in each field was recorded, and average values for total water consumption for the various crop types were obtained from published reports. Irrigation is not a perfectly efficient process in that some amount of water in excess of plant needs is diverted because of losses within the irrigation system; published values for irrigation-method efficiencies (Dickens and others, 2011, p. 22) were used to determine that, overall in the Verde Valley, irrigation methods were about 50 percent efficient.

On the basis of these methods, about 10,500 acre-ft of surface water was needed to meet the water demands of crops in the Verde Valley during the 2010 growing season (table B1). This value is virtually identical to the constant consumptive-use rate (10,000 acre-ft/yr) used in the NARGFM. Because of system inefficiencies in irrigation infrastructure and application methods, 20,800 acre-ft of water was estimated to be needed to be diverted from streams.

A more complete discussion of these methods and their results can be found in appendix 3.

Table B1. Irrigated acreage and estimates of consumptive water use for the summer 2010 growing season in the Verde Valley, central Arizona.

[No irrigated agriculture was observed in February 2011; all units acre-feet per growing season unless otherwise specified; dashes indicate values of zero]

		Water consumptively used		Total water needed, given inefficiencies	
Type of irrigation-water use	Irrigated acreage (acres)[1]	Surface water	Groundwater	Surface water	Groundwater
Agricultural crop	850	2,300	50	4,400	50
Alfalfa	360	1,300	-	2,700	-
Corn	250	520	-	1,000	-
Nut orchards	120	300	-	600	-
Vegetables	50	60	-	80	-
Nursery plants	20	50	-	60	-
Grape orchards	50	-	50	-	50
Industrial irrigation	650	-	2,400	-	3,100
Golf courses	600	-	2,200	-	2,800
Athletic fields	50	-	200	-	250
Other (grasses, lawns, horse property)	2,300	8,300	120	16,400	150
Totals	3,800	10,500	2,600	20,800	3,300

[1]Value obtained by survey and inventory in July 2010. Inventory in February 2011 found no evidence of active irrigation.

Base Flow Exiting the Verde Valley (Outflow, Response)

The Verde River exits the study area at the Camp Verde gage, and in 2005 it conveyed about 80,000 acre-ft/yr (111 ft^3/s) past this station (fig. 15). This NARGFM-simulated value is intermediate between other published values (table 4), which is consistent with the NARGFM value being an annual total. The NARGFM approach to calculating this value simply is a water balance of all other surface-water components: base flow entering the study area, plus net discharge of groundwater as base flow, minus crop use of surface water by irrigation.

As of 2005, annual base flow at the Camp Verde gage had decreased by about 10,000 acre-ft/yr (14 ft^3/s) since 1910 because of human stresses (fig. 15). Coincidentally, this value is the same as the amount consumed by irrigated crops. Although some of this decrease theoretically could be attributable to downgradient human stresses on the groundwater system, that is unlikely, because very few (and no major) human stresses exist downgradient of this gage. This 10,000-acre-ft/yr decrease represents the combined effects on base flow at the Camp Verde gage resulting from all human activities upstream and upgradient of this gage that have occurred between 1910 and 2005. Although this is a back-calculated value based on a complex, regional-scale computer simulation, it supports the interpretation that human stresses up to 2005 have affected annual base-flow discharge rates in the Verde River.

The three forward-looking model runs indicated that base flow at the Camp Verde gage could continue to decrease between 2005 and 2110 because of human stresses (fig. 12). These decreases ranged from 5,400 to 8,600 acre-ft/yr (7 to 12 ft^3/s) relative to 2005 rates, depending on how each forward-looking model run represented human stresses. While these model runs did not attempt to predict any specific future reality with respect to human stresses, they do support the interpretation that base flow in the Verde River at the Camp Verde gage will continue to be affected by human stresses.

Water-Budget Components not Simulated

The NARGFM did not simulate all possible hydrologic processes. On figure 8, gray arrows with no numbers indicate water-budget components considered to be potentially significant in terms of water volume but that were not simulated.

Quantitative precipitation estimates were used as part of the NARGFM development, but these estimates are used as tools for model development rather than as true inputs or outputs. Also, the vast majority of precipitation returns to the atmosphere through ET and does not enter the groundwater and surface-water hydrologic systems discussed in this report.

Runoff is precipitation that neither becomes recharge to an aquifer nor returns to the atmosphere through ET (it also is known as event flow or storm flow). The NARGFM did not simulate runoff, therefore, runoff estimates are excluded from this report. Blasch and others (2006) estimated annual runoff of 64,900 acre-ft/yr (90 ft^3/s) at the Clarkdale gage, and 156,600 acre-ft/yr (216 ft^3/s) at the Camp Verde gage. These values were calculated by hydrograph separation using a long record, which means that they are not necessarily directly comparable to water-budget values in this report.

Although the NARGFM simulated incidental and artificial recharge, the model did not simulate the human infrastructure that removes, treats, conveys, holds, and returns such water to the environment. The model instead calculated incidental recharge simply as a percentage of withdrawn groundwater, which was returned to the model in the same grid cell from which it was withdrawn. Similarly, and as discussed in the "Ditch Diversions and Crop Irrigation" section, the NARGFM did not simulate the numerous potential pathways for incidental recharge within the process of diverting surface water and applying it to fields for irrigation.

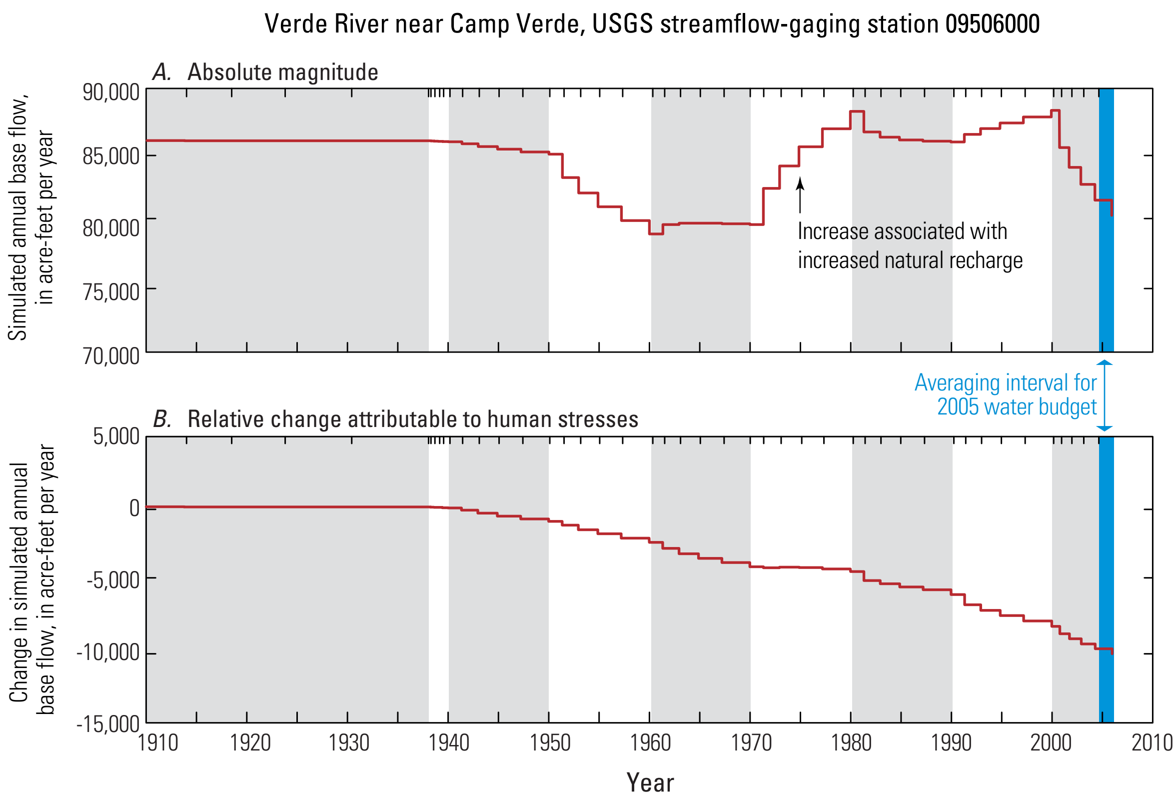

Figure 15. Plots of base flow simulated by the Northern Arizona Regional Groundwater Flow Model in the Verde River near Camp Verde, USGS streamflow-gaging station 09506000, during the 1910–2005 model run. *A,* Absolute magnitude of base flow. *B,* Relative change in base flow attributable to human stresses. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote timesteps within modeled stress periods.

Not all sources of ET in the Verde Valley were simulated. Riparian ET was simulated, and to some degree the ET associated with irrigation of fields and crops was taken into account, but other instances of ET, such as in upland areas or along ditch diversions, were not simulated.

Discussion

Streamflow Capture

Withdrawing groundwater from a well intrinsically alters the hydrologic system: “all water discharged by wells is balanced by a loss of water somewhere” (Theis, 1940, p. 280). Water withdrawn from a well is derived from one or more of these sources: (1) decrease in groundwater storage; (2) reduction in natural discharge; and (3) increase in natural recharge. The sum of components 2 and 3 is known as capture (Barlow and Leake, 2012). The relative fraction that each of these three sources supplies to a pumped well varies through time (fig. 16), and varies solely on the basis of the hydraulic properties of the aquifer(s) and the distance between the pumping location and the connected surface-water features (Leake and Pool, 2010).

When a well first withdraws groundwater, 100 percent of the water is derived from a decrease in groundwater storage. As pumping continues, the source of water to the well transitions from a storage-dominated supply to a capture-dominated supply. Eventually, a new equilibrium may be reached where 100 percent of the withdrawn water is supplied by capture. This is the case only as long as there is sufficient water available for capture. If total pumping exceeds total capturable water, then a new equilibrium is not possible and aquifers will continue to be depleted of their storage as time proceeds.

The analyses in this report indicate that human stresses to the groundwater system have affected base flow in the Verde River through the process of streamflow capture. As of 2005, annual base flow at the Clarkdale gage was estimated to have decreased 4,900 acre-ft/yr (7 ft^3/s) because of human stresses between 1910 and 2005. Although some of this decrease at the Clarkdale gage could be attributable to human stresses in downgradient areas such as the Verde Valley—capture of streamflow by pumping wells occurs irrespective of hydraulic gradients (Leake, 2011; Barlow and Leake, 2012)—most was considered attributable to groundwater withdrawals upstream and upgradient of the Clarkdale gage. At the Camp Verde gage, data in this report indicated a decrease of 10,000 acre-ft/yr (14 ft^3/s) between 1910 and 2005 attributable to human stresses.

Ideally, the base-flow decreases simulated by the NARGFM would be independently and easily verifiable with streamflow records. Unfortunately, periods of record at streamflow-gaging stations throughout the Verde River groundwater basin generally are not long enough to see such effects (table 5). Another complication is that runoff is superimposed on base flow in a hydrograph, and hydrograph separation to disentangle the two (for example, Sloto and Cruse, 1996) is an interpretive method subject to uncertainty arising from decisions made by the data analyst. Also, any changes in base flow resulting from variable natural stresses (notably, natural recharge) are superimposed upon the streamflow record. These complicating factors are precisely why computer simulations of hydrologic systems can be helpful: they provide a means for investigating the effects of these factors independently of each other.

Base flow at the Clarkdale and Camp Verde gages may continue to decrease into the future (2005–2110). Results in this report indicate that this would be the case even if groundwater-withdrawal rates were decreased over time, because streamflow capture continues for some time even after pumping stops (Barlow and Leake, 2012).

Winter and others (1998) suggested that surface water and groundwater are “a single resource.” The findings of the present study—that groundwater withdrawals have decreased base flow in the Verde River—indicate that a single-resource (or conjunctive-use) view is appropriate for the Verde River groundwater basin.

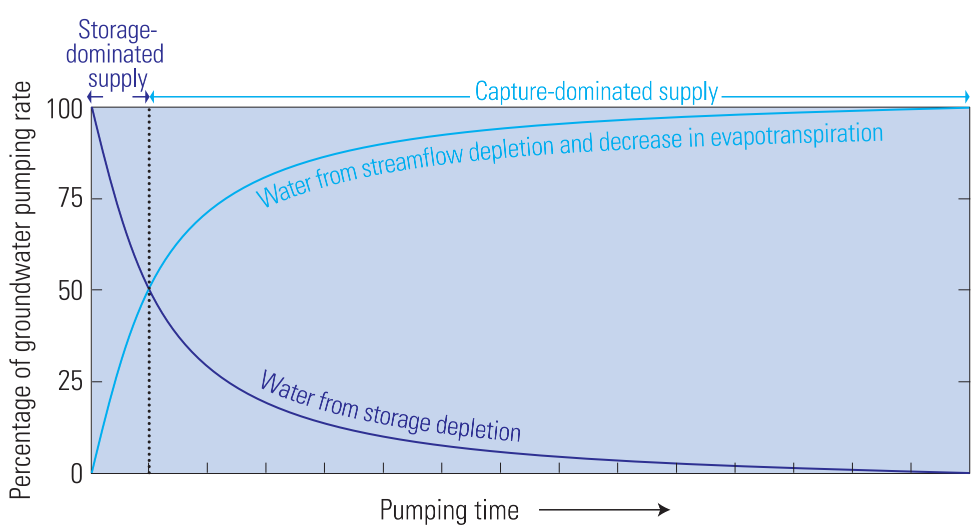

Figure 16. Conceptual plot showing the sources of water to a pumped well through time. Modified from Leake and Pool (2010).

Table 5. Inventory of USGS streamflow-gaging stations within the Verde River groundwater basin, central Arizona.

Station identifier[1]	Station name	Time period of gage operation
	Streamgages upstream of Verde Valley	
09502800	Williamson Valley Wash near Paulden	1965–85; 2001–present
09502900	Del Rio Springs near Chino Valley	1996–present
09502960	Granite Creek at Prescott	1994–present
09503000	Granite Creek near Prescott	1932–47; 1994–present
09503300	Granite Creek below Watson Lake near Prescott	1999–present
09503700	Verde River near Paulden	1963–present
	Streamgages within Verde Valley	
09504000	Verde River near Clarkdale[2,3]	1965–present
09504420	Oak Creek near Sedona	1981–present
09504500	Oak Creek near Cornville	1940–present
09505200	Wet Beaver Creek near Rimrock	1961–present
09505350	Dry Beaver Creek near Rimrock	1960–present
09505400	Beaver Creek near Lake Montezuma	[4]
09505800	West Clear Creek near Camp Verde	1964–present
09506000	Verde River near Camp Verde[5]	1934–45; 1988–present

[1]Excludes streamgages no longer in operation as of 2011. For a comprehensive list, see Blasch and others (2006, appendix 4).
[2]Also has streamflow data for 1915–1921.
[3]Referred to as the Carkdale gage in the present report.
[4]2004–present.
[5]Referred to as the Camp Verde gage in this report.

Causes of Changes in Verde Valley Base Flow

Base flow "is the portion of stream flow that is derived from persistent, slowly varying sources" (Dingman, 2002, p. 373). Base flow sometimes is assumed to be constant, which is not true in the general sense, nor do the results of this study show it to be true in the Verde Valley. Several factors, both natural- and human-driven, affect base flow in the Verde Valley:

- Diverting water from a stream into a ditch (fig. 17) reduces flow downstream of the diversion.
- Ditch diversions likely affect base flow in more complex ways as well (Garner and Bills, 2012). Ditch diversions cause base flow and runoff to be distributed across a broader area of the alluvial valley floor than might have occurred under predevelopment conditions. Such water has many complex pathways through which it may flow after being redistributed, including subsurface pathways (fig. 14).
- Short-term changes in base flow can be caused by groundwater gradient changes imparted by individual storm events (Sophocleous, 2002).
- Changes in riparian-vegetation distribution can alter base flow over both short and long time scales. Natural forces can alter such vegetation, but in the Verde Valley human activity also has altered near-stream riparian ecology (for example, increased riparian vegetation directly downstream of long-term ditch diversion points).
- Groundwater withdrawals in and around the Verde Valley eventually will be offset by capture (decreased base flow and riparian ET). The question is not if this will happen, but when. Results in this report indicate that capture of base flow occurred during 1910–2005 and will continue during 2005–2110. If groundwater withdrawals exceed total capturable water, additional capture may occur from adjacent basins.
- Incidental and artificial recharge can increase base flow in connected surface-water features (Leake and Pool, 2010).
- Base flow changes in response to cyclic variations in natural recharge (Pool, 2005) over decades or longer. Although the aquifers that supply base flow to perennial streams in the Verde River watershed are large, they are not so large as to entirely dampen varying natural-recharge stresses over long time periods (Pool and others, 2011).
- Climate change may cause long-term changes in base flow. Climate forecasts project increased aridity in the southwest (Williams and others, 2010; deBuys, 2011), which implies decreased natural recharge and therefore decreased base flow.

With so many factors able to cause changes in it, Verde River base flow varies on seasonal, weekly, daily, and hourly time scales (fig. 18). Nonetheless, despite its inconstancy, Verde Valley base flow is considered quantifiable, provided that studies select an appropriate time scale and provide sufficient context and qualification.

Capture Maps—Another Approach to Understanding Streamflow Capture

Capture maps (Leake and Pool, 2010) are a technique used for exploring the spatial aspects of streamflow capture at the expense of temporal aspects. This is converse (and complementary) to the technique of water budgets, which generally explore temporal aspects at the expense of spatial ones. Capture maps indicate, for a given location, what fraction of water from a well would be derived from capture—the reduction in natural discharge and (or) increase in natural recharge—after a fixed period of time for a given layer of a groundwater-flow model. Locations on these maps with larger values for this fraction (redder colors, up to a fraction of 1.0) indicate a greater amount of water would be obtained by capture than areas with smaller values of this fraction (bluer colors, as low as a fraction of 0.0).

Employing the methods of Leake and Pool (2010) on the NARGFM, capture maps were developed for a 100-year interval in each of the three model layers in the Verde Valley. The capture map from the deepest layer (layer 3) is shown below (fig. C1).

The 100-year capture map for layer 3 indicates that a wide swath surrounding the Verde River, Oak Creek, and West Clear Creek would exhibit capture of over 90 percent after 100 years. The aquifer that would be accessed in layer 3 is the Redwall aquifer, which is regionally extensive and generally is recharged at higher elevations along the Mogollon Rim (Blasch and others, 2006). Despite its regional extent and limited surface exposure in the Verde Valley, these capture maps confirm that the Redwall aquifer is connected to surface-water features in the Verde Valley. Even when the geologic formations of the Redwall aquifer are not in direct contact with Verde Valley streams, these capture maps are consistent with the concept that Redwall-aquifer groundwater moves upward through shallower formations to discharge into streams in the Verde Valley. This concept also is consistent with geochemical studies in Blasch and others (2006) and Zlatos (2008).

A more complete discussion of this analysis, as well as capture maps for model layers 1 and 2, can be found in appendix 4.

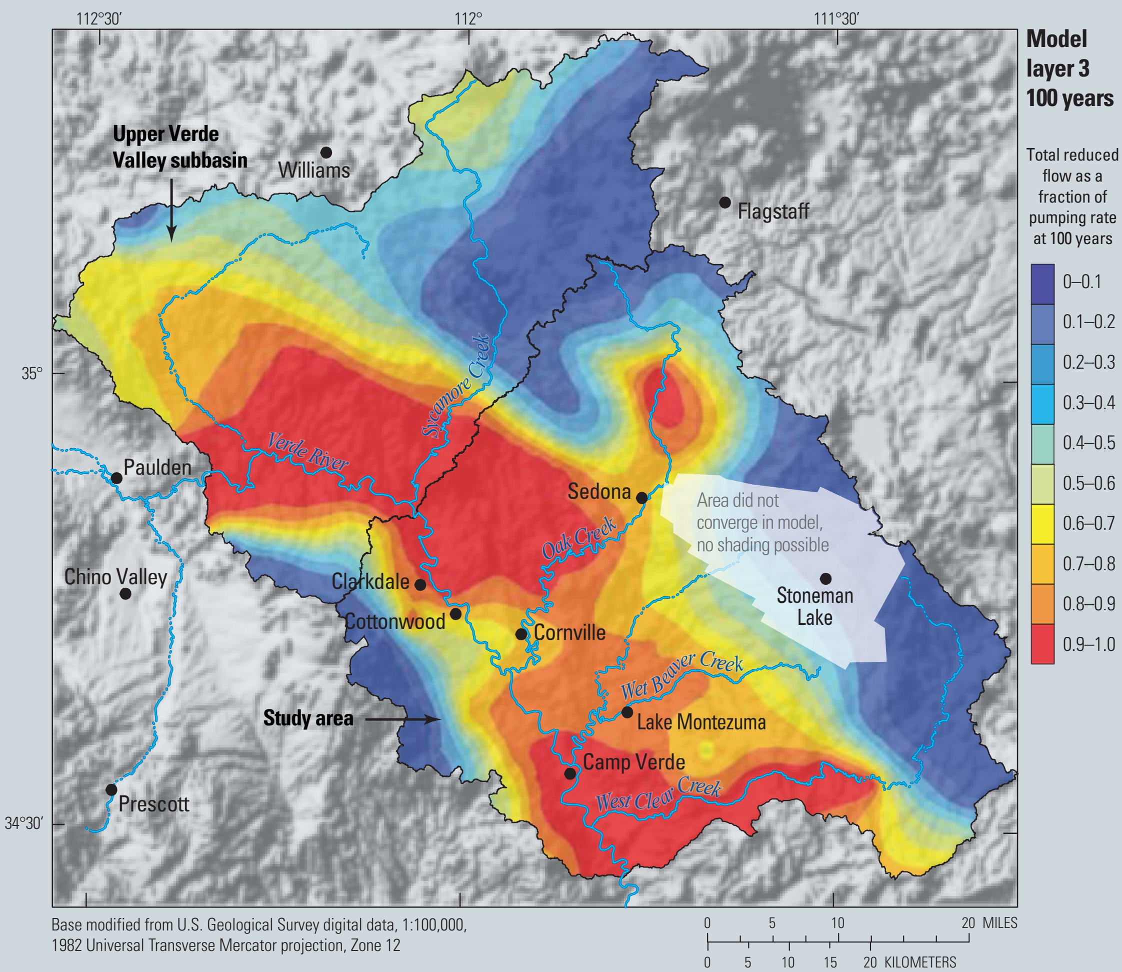

Figure C1. Map showing computed reduction in flow of streams and springs and reduction in riparian evapotranspiration as a fraction of pumping rate that would result from pumping groundwater from NARGFM layer 3 (the deepest layer in the model) at a constant rate for 100 years. The color at any location represents the fraction of the pumping rate that can be attributed to changes in outflow from or inflow to the aquifer.

Figure 17. Photograph of surface-water diversion dam typical of Verde Valley ditch diversion systems. Modified from Garner and Bills (2012).

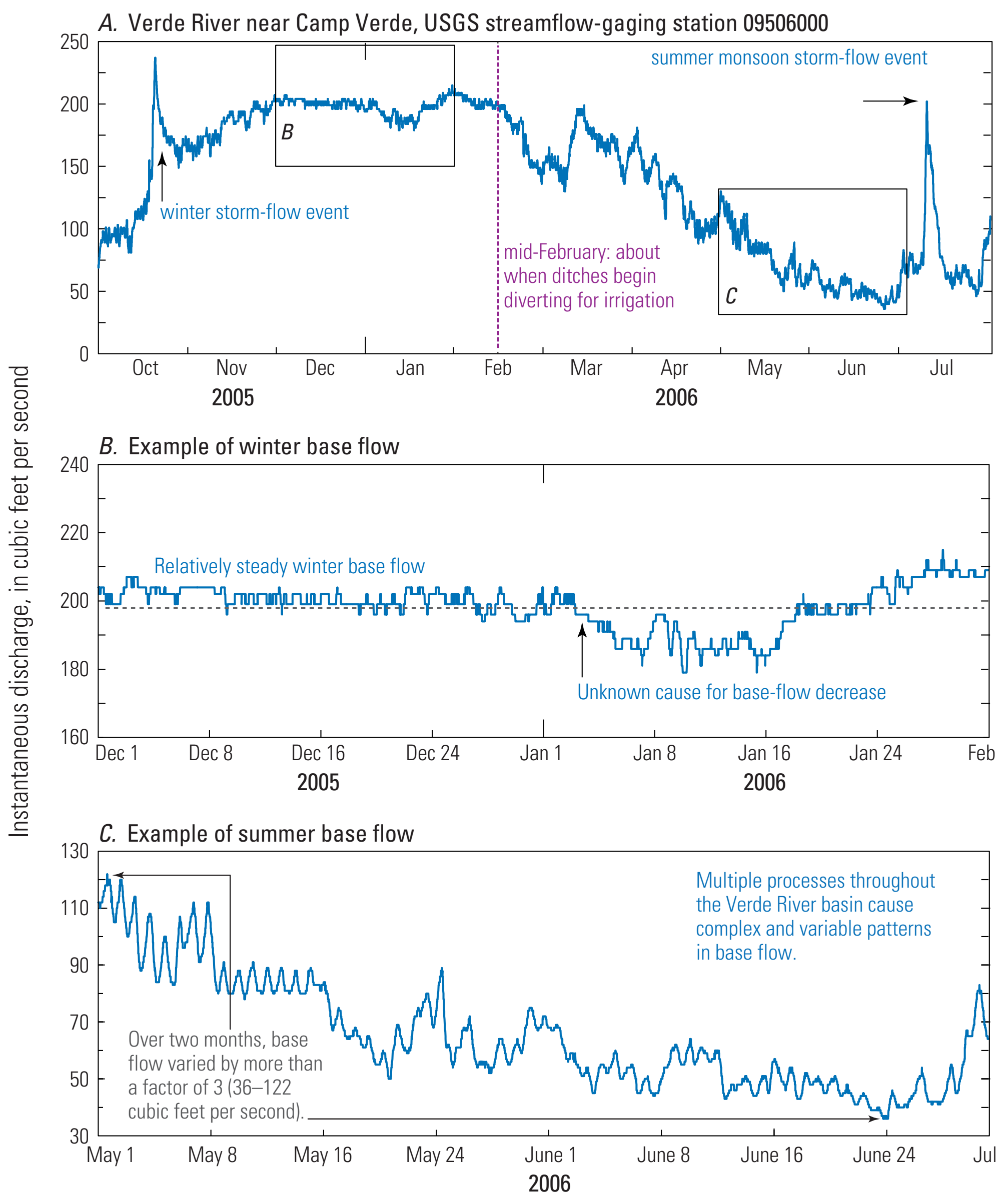

Figure 18. Time-series plots showing discharge at Verde River near Camp Verde, USGS streamflow-gaging station 09506000, central Arizona, given in cubic feet per second. *A*, October 2005 through July 2006. *B*, Characteristic winter base flow December 2005 through January 2006. *C*, Characteristic summer base flow May through June 2006.

Restatement of Central Questions

This study addressed three central questions (see the “Introduction” section). This section restates those questions and summarizes the findings of this study with respect to each topic.

How have human stresses on the hydrologic system affected Verde River base flow?—As of 2005, human stresses that occurred between 1910 and 2005 were estimated to have decreased base flow in the Verde River (fig. 15). At the downstream Camp Verde gage, base flow as of 2005 was about 10,000 acre-ft/yr (14 ft^3/s) less than it would have been in the absence of any human stresses (see fig. 15*B*).

How have human stresses outside the Verde Valley affected base flow within the Verde Valley?—As of 2005, base flow at the Clarkdale gage (at the upstream end of the Verde Valley) was estimated to have decreased by about 4,900 acre-ft/yr (7 ft^3/s) because of human stresses that occurred between 1910 and 2005 (fig. 11*B*). The most probable human stresses that caused this decrease were considered to be those occurring in upgradient areas of the Verde River groundwater basin, although conceptually some human stresses in other groundwater basins (even those downgradient of the Clarkdale gage) could have accounted for some of this decrease.

How might future human stresses to the hydrologic system affect Verde River base flow?—On the basis of three hypothetical forward-looking model runs, base flow at the Clarkdale gage could decrease by an additional 2,700 to 3,800 acre-ft/yr (4 to 5 ft^3/s) between 2005 and 2110 (fig. 12; table 3). Over the same time period, base flow at the Camp Verde gage could decrease by an additional 5,400 to 8,600 acre-ft/yr (7 to 12 ft^3/s). These human-stress induced decreases are in addition to decreases that were estimated already to have occurred at the gages as of 2005.

Summary

This report describes the results of an investigation into the degree to which human stresses have affected and might in the future affect the hydrologic system of the Verde Valley, using water budgets as the central analytical tool. For the purposes of this report, the Verde Valley is the 1,500-mi^2 area of the Verde Valley subbasin located between USGS streamflow-gaging stations Verde River near Clarkdale, Arizona (the Clarkdale gage) and Verde River near Camp Verde (the Camp Verde gage). Residents in the Verde Valley use a combination of groundwater and surface water to meet their water demands.

The Northern Arizona Regional Groundwater Flow Model (NARGFM) was used in this study, including the 1910–2005 human and natural stresses provided with the model. Three profiles of hypothetical future human stresses for the period 2005–2110 were executed by the NARGFM—increased, decreased, and unchanged human stresses. The NARGFM was run as needed for the full 1910–2110 period, including a special version of the model that included no human stresses whatsoever. The resulting water budgets were then extracted from model-output files. Finally, water budgets were added and subtracted to isolate only the relative changes in their values that were attributable to human stresses.

The model demonstrates that human stresses between 1910 and 2005 have affected the hydrologic system of the Verde Valley, and likely will continue to affect the hydrologic system between 2005 and 2110 through groundwater withdrawals by pumping and through incidental and artificial recharge.

Natural recharge as of 2005 was about 44,000 acre-ft/yr (61 ft^3/s) in the Verde Valley. Incidental and artificial recharge together were about 1,600 acre-ft/yr (2 ft^3/s), although this could be an underestimate. A net of about 4,900 acre-ft/yr (7 ft^3/s) of groundwater entered the study area from adjoining areas (underflow) as of 2005. Simulations indicated that net underflow changed very little between 1910 and 2005, but underflow could increase between 2005 and 2110. Groundwater withdrawals in 2005 were about 19,000 acre-ft/yr (27 ft^3/s). Riparian evapotranspiration (ET) was about 9,200 acre-ft/yr (13 ft^3/s) in 2005; riparian ET was shown to be capable of being decreased by human stresses by as much as 500 acre-ft/yr between 2005 and 2110, which is consistent with the concept of capture. Groundwater storage in aquifers within the Verde Valley was decreasing at about 29,000 acre-ft/yr as of 2005, although only 12,000 acre-ft/yr of this was attributable to human stresses. As time proceeded in the simulated 2005–2110 period, the rate of groundwater-storage decrease slowed down, which is consistent with the concept that the source of water to a well changes over time—from depletion of groundwater storage toward the capture of natural discharge.

At the upstream Clarkdale gage, base flow was about 40,000 acre-ft/yr (55 ft^3/s) in 2005, which is less than other published values of base flow at this gage. Base flow at the Clarkdale gage, as of 2005, was estimated to have decreased by about 4,900 acre-ft/yr (7 ft^3/s) as a result of human stresses between 1910 and 2005. During the 2005–2110 period, the model showed that base flow at the Clarkdale gage may decrease an additional 2,700 to 3,800 acre-ft/yr (4 to 5 ft^3/s) because of human stresses. Net groundwater discharge (equivalent to net surface-water inflow from groundwater) throughout the Verde Valley was about 51,000 acre-ft/yr (70 ft^3/s), and as of 2005 had decreased by about 5,400 acre-ft/yr (7 ft^3/s) because of human stresses. At the downstream Camp Verde gage, base flow was about 80,000 acre-ft/yr (111 ft^3/s) as of 2005, and had decreased by about 10,000 acre-ft/yr (14 ft^3/s) between 1910 and 2005 because of human stresses. This 10,000 acre-ft/yr decrease represents the combined effects on base flow at the Camp Verde gage of all human activities upstream and upgradient of this gage that occurred between 1910 and 2005. Model simulations indicated that base flow at the Camp Verde gage could continue to decrease during the 2005–2110 period by 5,400 to 8,600 acre-ft/yr (7 to 12 ft^3/s) because of human stresses.

Withdrawing groundwater from a well intrinsically alters the hydrologic system: “All water discharged by wells is balanced by a loss of water somewhere" (Theis, 1940, p. 280). Water withdrawn from a well is derived from one or more of these sources: (1) decrease in groundwater storage; (2) reduction in natural discharge; and (3) increase in natural recharge. The sum of components 2 and 3 is known as capture. The results presented in this report indicate that human stresses to the groundwater system have affected base flow in the Verde River through the process of streamflow capture and can continue to do so into the future.

Base flow in the Verde Valley is not constant over time, as sometimes is (incorrectly) assumed. Many factors contribute to the variability of base flow at varying time scales. Ditch diversions that are prevalent in the Verde Valley reduce base flow directly by diverting water and change it in more complex ways by redistributing water across the floodplain. Groundwater withdrawals capture streamflow and decrease base flow. Variations in natural recharge driven by climate and climate change also can change base flow.

In summary, human stresses were found to have decreased base flow in the Verde River between 1910 and 2005, and under hypothetical forward-looking scenarios, human stresses were capable of causing continued and additional decreases in base flow. These findings are consistent with (a) the concept of capture, (b) previous studies that have found surface-water and groundwater systems in the Verde River groundwater basin to be connected, and (c) the characterization of groundwater and surface water as a single resource.

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Glossary

***Artificial recharge*—**Water used by humans that deliberately is infiltrated into the subsurface to become recharge. Means by which this is accomplished include infiltration basins and discharge to a stream. Similar to incidental recharge, except that artificial recharge is deliberate and actively managed.

***Base flow net groundwater discharge*—**The total amount of groundwater discharge to a stream that occurs where the water-table altitude is higher than the altitude of the stream-water surface. Conversely, if a water table is below the elevation of water in a stream and streambed sediments are sufficiently permeable, stream water enters the subsurface and may become recharge.

***Consumptive use*—**The use of applied irrigation water by plants.

***Groundwater storage*—**Water located within the intergranular pore spaces, fractures, and (possibly) larger void spaces within an aquifer.

***Human infrastructure*—**The dams, canals, pipes, tanks, and treatment systems used to withdraw, treat, convey, store, and deliver water to customers, as well as the canals and pipes that convey used water and wastewater away from customers. At various points within human infrastructure, there exists potential for incidental recharge.

***Human stresses*—**Stresses applied to the hydrologic system that exist solely because of the presence of humans. For this report, these were defined as groundwater withdrawals by pumping, incidental recharge, artificial recharge, and consumptive use of surface water through irrigation. The lattermost of these, however, was not varied under any modeled conditions, as it is not well quantified.

***Incidental recharge*—**Water used by humans that infiltrates the subsurface and becomes recharge in an unmanaged way. Common examples include discharge from septic-system drain fields, water that leaks from pressurized water-supply pipes, and water applied to irrigated lands that infiltrates past the root zone.

***Natural recharge*—**Precipitation that falls on the land surface, infiltrates the unsaturated zone, percolates downward, and reaches the water table.

***Natural stresses*—**Stresses applied to the hydrologic system because of natural forces. For this study, the term natural stresses was defined to be natural recharge derived from precipitation.

***Riparian evapotranspiration*—**A processes whereby groundwater either is incorporated into plant tissues or returned to the atmosphere through surface evaporation or transpiration through plant stomata (Hillel, 1998; Mauseth, 1991).

***Underflow*—**Groundwater that flows entirely in the subsurface across boundaries that are not coincident with groundwater divides.

Appendix 1. Results of Water Budgets for Model Runs, 1910–2005 and 2005–2110

Table 1.1. Results of groundwater-flow model simulation, 1910–2005, Verde Valley, central Arizona.

[GW, groundwater; SW, surface water; all values in acre-feet per year; values are described by variable S_t in equation (1) in main body of text]

Simluated date	Groundwater inflow						Groundwater outflow		
	Incidental recharge	Baseflow infiltration	Natural recharge	Underflow from			Withdrawals	Discharge as base flow	Evapo-transpiration
				Upper Verde Valley subbasin	Colorado Plateau	Verde Canyon			
1/1/1910	0	21929	58550	860	1702	1746	2	75002	9400
10/6/1913	0	21929	58550	860	1702	1746	2	75005	9400
4/12/1918	0	21933	58550	860	1702	1746	2	75008	9400
9/12/1923	0	21930	58550	860	1702	1746	2	75005	9400
3/14/1930	0	21929	58550	860	1702	1746	2	75005	9400
1/1/1938	0	21932	58550	860	1702	1746	2	75008	9400
4/9/1938	0	21928	58550	860	1702	1746	2	75002	9400
8/4/1938	0	21932	58550	860	1702	1746	2	75008	9400
12/24/1938	0	21933	58550	860	1702	1746	2	75010	9400
6/11/1939	0	21928	58550	860	1702	1746	2	75008	9400
1/1/1940	0	21927	58550	860	1702	1746	2	75005	9400
5/5/1941	0	21930	58550	860	1702	1746	2040	74987	9399
12/15/1942	0	21936	58550	860	1702	1746	2040	74978	9399
11/21/1944	0	21936	58550	860	1702	1746	2040	74963	9398
3/20/1947	0	21940	58550	860	1702	1746	2040	74960	9397
12/31/1949	0	21943	58535	860	1702	1746	227	74948	9396
5/6/1951	0	21985	35121	952	1602	1687	596	74261	9394
12/15/1952	0	22025	35121	996	1509	1608	596	73882	9391
11/22/1954	0	22072	35121	1038	1427	1518	596	73518	9388
3/19/1957	0	22135	35121	1080	1354	1427	596	73142	9384
12/31/1959	0	22186	35121	1122	1288	1337	596	72754	9379
5/5/1961	0	22197	58535	1048	1350	1335	1106	73183	9375
12/15/1962	0	22207	58535	1023	1404	1354	1106	73316	9372
11/21/1964	0	22210	58535	1002	1448	1380	1106	73405	9369
3/20/1967	0	22213	58535	981	1480	1410	1106	73488	9367
12/31/1969	0	22211	58535	961	1504	1441	1106	73559	9365
5/6/1971	46	22199	100678	788	1678	1551	4274	74637	9361
12/15/1972	46	22190	100678	698	1843	1712	4274	75283	9359
11/22/1974	46	22177	100678	616	1996	1917	4274	75929	9359
3/19/1977	0	22163	100678	535	2136	2157	3818	76648	9359
12/31/1979	0	22128	100678	457	2271	2438	3818	77415	9359
5/5/1981	39	22394	76094	525	2224	2471	9108	76693	9351
12/15/1982	39	22504	76094	539	2188	2488	9108	76642	9344
11/21/1984	39	22602	76094	548	2164	2505	9108	76657	9338
3/20/1987	39	22667	76094	559	2150	2524	8696	76737	9331
12/31/1989	39	22749	76094	571	2146	2550	8696	76832	9325
5/6/1991	1014	23051	93656	504	2213	2646	14231	77187	9314
12/15/1992	1014	23161	93656	475	2277	2773	13529	77448	9303
11/22/1994	1014	23241	93656	449	2336	2885	13529	77732	9294
3/19/1997	1014	23325	93656	424	2392	3005	13529	78076	9285
1/1/2000	1014	23402	93656	399	2445	3130	13529	78473	9276
10/21/2000	1573	23810	43902	569	2287	2979	19625	77380	9266
10/10/2001	1573	24003	43902	632	2124	2824	19625	76864	9257
12/8/2002	1573	24202	43902	687	1972	2698	19625	76408	9246
4/30/2004	1573	24389	43902	743	1831	2553	19625	75937	9234
1/1/2006	1573	24589	43902	801	1703	2417	19290	75472	9221

Table 1.1. Results of groundwater-flow model simulation, 1910–2005, Verde Valley, central Arizona.—Continued

Simluated date	Net				SW outflow, irrigation consumptive use	Net base flow, Camp Verde gage	Groundwater withdrawals above gage at		Incidental recharge above gage at	
	Ground-water storage change	Streamflow produced in Verde Valley	Base flow (gage) at							
			Paulden	Clarkdale			Clarkdale	Camp Verde	Clarkdale	Camp Verde
1/1/1910	0	53072	21694	43191	10200	86064	0	2	2018	2018
10/6/1913	0	53076	21679	43176	10200	86052	186	188	2018	2018
4/12/1918	0	53074	21674	43172	10200	86047	186	188	2018	2018
9/12/1923	0	53074	21673	43171	10200	86046	186	188	2018	2018
3/14/1930	0	53075	21671	43170	10200	86045	186	188	2018	2018
1/1/1938	0	53076	21670	43168	10200	86044	186	188	2018	2018
4/9/1938	0	53074	21660	43157	10200	86031	3368	3370	2720	2720
8/4/1938	-1	53075	21648	43146	10200	86021	3368	3370	2720	2720
12/24/1938	-1	53078	21634	43132	10200	86010	3368	3370	2720	2720
6/11/1939	-1	53079	21616	43114	10200	85993	3368	3370	2720	2720
1/1/1940	-2	53077	21592	43091	10200	85968	3368	3370	2720	2720
5/5/1941	-2018	53056	21460	42966	10200	85822	14722	16762	7514	7514
12/15/1942	-2004	53042	21262	42767	10200	85610	14722	16762	7514	7514
11/21/1944	-1992	53027	21072	42579	10200	85406	14722	16762	7514	7514
3/20/1947	-1979	53020	20890	42388	10200	85208	14722	16762	7514	7514
12/31/1949	-168	53005	20722	42228	10200	85034	14722	14949	7514	7514
5/6/1951	-23243	52276	20282	41179	10200	83255	28437	29033	12297	12297
12/15/1952	-22934	51858	19926	40440	10200	82097	28437	29033	12297	12297
11/22/1954	-22642	51446	19585	39797	10200	81043	28437	29033	12297	12297
3/19/1957	-22324	51006	19250	39194	10200	80000	28437	29033	12297	12297
12/31/1959	-21969	50568	18915	38617	10200	78985	28437	29033	12297	12297
5/5/1961	504	50987	18700	38906	10200	79693	31247	32353	13263	13263
12/15/1962	425	51109	18413	38895	10200	79804	31247	32353	13263	13263
11/21/1964	382	51196	18138	38807	10200	79802	31247	32353	13263	13263
3/20/1967	343	51275	17881	38686	10200	79761	31247	32353	13263	13263
12/31/1969	305	51349	17635	38542	10200	79691	31247	32353	13263	13263
5/6/1971	38318	52438	18183	40204	10200	82443	31462	35736	12717	12762
12/15/1972	37889	53093	18500	41253	10200	84146	31462	35736	12717	12762
11/22/1974	37484	53751	18701	42041	10200	85593	31462	35736	12717	12762
3/19/1977	37447	54485	18817	42677	10200	86962	31442	35260	12717	12717
12/31/1979	36986	55287	18858	43191	10200	88278	31442	35260	12717	12717
5/5/1981	8232	54298	18718	42613	10200	86712	26938	36047	9902	9941
12/15/1982	8402	54139	18682	42387	10200	86326	26938	36047	9902	9941
11/21/1984	8467	54055	18634	42259	10200	86115	26938	36047	9902	9941
3/20/1987	8905	54070	18563	42150	10200	86020	26938	35634	9902	9941
12/31/1989	8918	54083	18475	42074	10200	85958	26938	35634	9902	9941
5/6/1991	21955	54136	18534	42603	10200	86539	25677	39908	9916	10930
12/15/1992	22666	54287	18505	42887	10200	86975	25677	39205	9916	10930
11/22/1994	22601	54491	18467	43108	10200	87399	25677	39205	9916	10930
3/19/1997	22501	54751	18427	43305	10200	87856	25677	39205	9916	10930
1/1/2000	22351	55071	18380	43487	10200	88358	25677	39205	9916	10930
10/21/2000	-31541	53570	17967	42169	10200	85539	29172	48797	11154	12727
10/10/2001	-31056	52861	17759	41376	10200	84037	29172	48797	11154	12727
12/8/2002	-30605	52206	17598	40744	10200	82750	29172	48798	11154	12727
4/30/2004	-30172	51549	17447	40198	10200	81547	29172	48798	11154	12727
1/1/2006	-29361	50884	17299	39705	10200	80389	29172	48463	11154	12727

Table 1.2. Relative changes in water-budget components attributable to human stresses, 1910–2005, based on a groundwater-flow model, Verde Valley, central Arizona.

[GW, groundwater; SW, surface water; all values in acre-feet per year; values are described by variable ΔA_t in equation (3) in main body of text]

Simluated date	Groundwater inflow						Groundwater outflow		
	Incidental recharge	Baseflow infiltration	Natural recharge	Underflow from			Withdrawals	Discharge as base flow	Evapo-transpiration
				Upper Verde Valley sub-basin	Colorado Plateau	Verde Canyon			
1/1/1910	0	0	0	0	0	0	0	0	0
10/6/1913	0	4	0	0	0	0	0	6	0
4/12/1918	0	5	0	0	0	0	0	6	0
9/12/1923	0	2	0	0	0	0	0	3	0
3/14/1930	0	2	0	0	0	0	0	6	0
1/1/1938	0	5	0	0	0	0	0	9	0
4/9/1938	0	1	0	0	0	0	0	3	0
8/4/1938	0	5	0	0	0	0	0	9	0
12/24/1938	0	3	0	0	0	0	0	9	0
6/11/1939	0	1	0	0	0	0	0	9	0
1/1/1940	0	0	0	0	0	0	0	6	0
5/5/1941	0	1	0	0	0	0	2038	-15	-1
12/15/1942	0	7	0	0	0	0	2038	-24	-1
11/21/1944	0	8	0	0	0	0	2038	-39	-2
3/20/1947	0	12	0	0	0	0	2038	-41	-2
12/31/1949	0	16	-15	0	0	0	225	-50	-3
5/6/1951	0	15	-9	1	0	0	594	-71	-4
12/15/1952	0	30	-9	1	-1	0	594	-92	-6
11/22/1954	0	34	-9	0	-1	0	594	-98	-7
3/19/1957	0	59	-9	1	-1	0	594	-110	-8
12/31/1959	0	71	-9	2	-3	0	594	-116	-10
5/5/1961	0	94	-15	2	-9	0	1104	-142	-14
12/15/1962	0	121	-15	2	-16	0	1104	-166	-17
11/21/1964	0	140	-15	3	-24	0	1104	-172	-19
3/20/1967	0	155	-15	4	-33	0	1104	-187	-21
12/31/1969	0	172	-15	5	-42	0	1104	-201	-24
5/6/1971	46	249	-27	7	-56	0	4272	-370	-30
12/15/1972	46	307	-27	8	-73	1	4272	-424	-34
11/22/1974	46	368	-27	11	-89	1	4272	-468	-39
3/19/1977	0	424	-27	15	-107	1	3816	-512	-44
12/31/1979	0	466	-27	20	-124	1	3816	-560	-49
5/5/1981	39	731	-21	23	-121	1	9106	-945	-59
12/15/1982	39	848	-21	26	-116	1	9106	-1028	-68
11/21/1984	39	949	-21	31	-110	0	9106	-1093	-76
3/20/1987	39	1006	-21	37	-105	-1	8694	-1146	-84
12/31/1989	39	1086	-21	46	-102	-3	8694	-1262	-92
5/6/1991	1014	1424	-24	50	-118	-4	14229	-1528	-107
12/15/1992	1014	1558	-24	54	-137	-7	13527	-1667	-119
11/22/1994	1014	1669	-24	59	-155	-9	13527	-1795	-131
3/19/1997	1014	1785	-24	66	-173	-20	13527	-1913	-144
1/1/2000	1014	1896	-24	73	-190	-27	13527	-2032	-158
10/21/2000	1573	2247	-9	81	-204	-18	19623	-2109	-167
10/10/2001	1573	2417	-9	82	-221	-12	19623	-2200	-176
12/8/2002	1573	2578	-9	86	-238	-12	19623	-2295	-186
4/30/2004	1573	2725	-9	88	-256	-12	19623	-2384	-197
1/1/2006	1573	2885	-9	91	-272	-10	19288	-2470	-209

Table 1.2. Relative changes in water-budget components attributable to human stresses, 1910–2005, based on a groundwater-flow model, Verde Valley, central Arizona.—Continued

Simluated date	Net				SW outflow, irrigation consumptive use	Net base flow, Camp Verde gage	Groundwater withdrawals above gage at		Incidental recharge above gage at	
	Ground-water storage change	Streamflow produced in Verde Valley	Base flow (gage) at							
			Paulden	Clarkdale			Clarkdale	Camp Verde	Clarkdale	Camp Verde
1/1/1910	0	0	0	0	0	0	0	0	0	0
10/6/1913	0	2	-15	-6	0	-4	186	186	0	0
4/12/1918	0	1	-19	-10	0	-9	186	186	0	0
9/12/1923	0	1	-20	-10	0	-9	186	186	0	0
3/14/1930	0	4	-22	-12	0	-8	186	186	0	0
1/1/1938	0	4	-23	-13	0	-9	186	186	0	0
4/9/1938	0	2	-33	-24	0	-21	3367	3367	701	701
8/4/1938	-1	4	-44	-35	0	-31	3367	3367	701	701
12/24/1938	-1	6	-59	-49	0	-43	3367	3367	701	701
6/11/1939	-1	8	-77	-67	0	-60	3367	3367	701	701
1/1/1940	-2	6	-100	-90	0	-84	3367	3367	701	701
5/5/1941	-2018	-16	-232	-215	0	-231	14722	16760	5495	5495
12/15/1942	-2004	-31	-430	-413	0	-444	14722	16760	5495	5495
11/21/1944	-1992	-46	-621	-602	0	-648	14722	16760	5495	5495
3/20/1947	-1979	-54	-802	-792	0	-846	14722	16760	5495	5495
12/31/1949	-168	-67	-970	-952	0	-1018	14722	14947	5495	5495
5/6/1951	-496	-86	-1216	-1199	0	-1284	28437	29031	10279	10279
12/15/1952	-470	-122	-1488	-1470	0	-1592	28437	29031	10279	10279
11/22/1954	-444	-132	-1763	-1743	0	-1875	28437	29031	10279	10279
3/19/1957	-419	-169	-2035	-2017	0	-2186	28437	29031	10279	10279
12/31/1959	-396	-186	-2304	-2286	0	-2472	28437	29031	10279	10279
5/5/1961	-803	-236	-2681	-2657	0	-2893	31247	32351	11245	11245
12/15/1962	-765	-286	-3016	-2990	0	-3277	31247	32351	11245	11245
11/21/1964	-729	-312	-3315	-3278	0	-3590	31247	32351	11245	11245
3/20/1967	-704	-342	-3584	-3549	0	-3891	31247	32351	11245	11245
12/31/1969	-677	-373	-3840	-3808	0	-4181	31247	32351	11245	11245
5/6/1971	-3580	-619	-3641	-3631	0	-4250	31462	35734	10698	10744
12/15/1972	-3473	-731	-3476	-3474	0	-4205	31462	35734	10698	10744
11/22/1974	-3379	-836	-3392	-3395	0	-4231	31462	35734	10698	10744
3/19/1977	-2880	-936	-3393	-3397	0	-4333	31442	35258	10698	10698
12/31/1979	-2789	-1026	-3471	-3482	0	-4508	31442	35258	10698	10698
5/5/1981	-7373	-1676	-3460	-3465	0	-5140	26938	36044	7884	7922
12/15/1982	-7154	-1875	-3477	-3488	0	-5363	26938	36044	7884	7922
11/21/1984	-6970	-2041	-3525	-3539	0	-5580	26938	36044	7884	7922
3/20/1987	-6382	-2152	-3615	-3632	0	-5783	26938	35632	7884	7922
12/31/1989	-6201	-2348	-3738	-3763	0	-6110	26938	35632	7884	7922
5/6/1991	-10175	-2952	-3842	-3876	0	-6827	25676	39906	7898	8912
12/15/1992	-9197	-3225	-3957	-3993	0	-7219	25676	39203	7898	8912
11/22/1994	-8966	-3463	-4073	-4114	0	-7577	25676	39203	7898	8912
3/19/1997	-8737	-3698	-4202	-4250	0	-7948	25676	39203	7898	8912
1/1/2000	-8500	-3928	-4348	-4406	0	-8333	25676	39203	7898	8912
10/21/2000	-13607	-4356	-4448	-4488	0	-8844	29172	48795	9136	10709
10/10/2001	-13356	-4617	-4541	-4581	0	-9198	29172	48795	9136	10709
12/8/2002	-13120	-4874	-4632	-4681	0	-9554	29172	48795	9136	10709
4/30/2004	-12889	-5109	-4726	-4779	0	-9888	29172	48795	9136	10709
1/1/2006	-12315	-5355	-4826	-4882	0	-10238	29172	48460	9136	10709

Table 1.3. Relative changes in water-budget components attributable to human stresses, 2005–2110, based on a condition of decreased human stresses, Verde Valley, central Arizona.

[GW, groundwater; SW, surface water; all values in acre-feet per year; values are described by variable ΔA_t in equation (3) in main body of text]

Simluated date	Groundwater inflow						Groundwater outflow		
	Incidental recharge	Baseflow infiltration	Natural recharge	Underflow from			Withdrawals	Discharge as base flow	Evapo-transpiration
				Upper Verde Valley sub-basin	Colorado Plateau	Verde Canyon			
1/1/2006	0	0	0	0	0	0	0	0	0
7/16/2006	0	50	-6	7	-18	-7	-1	-168	-6
3/8/2007	0	72	-6	11	-23	-5	-1	-111	-9
12/16/2007	0	128	-6	15	-28	-5	-1	-129	-14
11/19/2008	0	188	-6	20	-32	-5	-596	-165	-20
1/1/2010	0	256	-6	26	-36	-6	-596	-209	-26
5/6/2011	-47	313	-6	33	-39	-6	-1157	-236	-33
12/15/2012	-47	384	-6	42	-41	-6	-1157	-292	-41
11/22/2014	-47	480	-6	52	-40	-5	-1157	-363	-51
3/19/2017	-47	588	-6	65	-38	-5	-1157	-437	-62
12/31/2019	-57	684	-6	79	-32	-4	-1414	-520	-74
5/5/2021	-104	692	-6	86	-28	-4	-1967	-535	-79
12/15/2022	-104	735	-6	94	-23	-4	-1967	-558	-84
11/21/2024	-104	788	-6	103	-15	-4	-1967	-609	-91
3/19/2027	-104	842	-15	114	-5	-4	-2327	-674	-99
12/30/2029	-104	907	-15	127	9	-4	-2327	-727	-108
5/5/2031	-150	899	-15	132	17	-4	-2868	-736	-112
12/14/2032	-150	909	-15	139	27	-4	-2868	-784	-116
11/21/2034	-150	944	-15	147	39	-3	-2868	-816	-122
3/18/2037	-150	985	-15	155	55	-2	-2868	-858	-129
12/30/2039	-150	1022	-15	165	76	-2	-2868	-917	-137
5/4/2041	-197	998	-15	169	86	-3	-3409	-914	-140
12/14/2042	-197	1016	-15	175	98	-3	-3480	-935	-143
11/20/2044	-197	1029	-15	181	115	-3	-3480	-964	-147
3/19/2047	-197	1057	-15	188	137	-2	-3480	-994	-151
12/30/2049	-197	1091	-15	195	166	-2	-3480	-1056	-157
5/5/2051	-244	1078	-15	200	181	-2	-4019	-1026	-158
12/14/2052	-244	1074	-15	204	200	-2	-4019	-1050	-160
11/21/2054	-244	1094	-15	209	227	-2	-4019	-1083	-163
3/18/2057	-244	1117	-15	215	263	-2	-4019	-1112	-166
12/30/2059	-244	1140	-15	222	317	-2	-4146	-1136	-169
9/19/2066	-291	1037	-15	234	592	-2	-5046	-1207	-234
10/11/2074	-291	1047	-15	246	615	-2	-5046	-1269	-240
6/14/2084	-291	1071	-15	256	675	-2	-5425	-1370	-246
1/24/2096	-291	1097	-15	267	723	-1	-5425	-1450	-252
12/30/2109	-291	1123	-15	277	770	0	-5586	-1539	-313

Table 1.3. Relative changes in water-budget components attributable to human stresses, 2005–2110, based on a condition of decreased human stresses, Verde Valley, central Arizona.—Continued

Simluated date	Net Ground-water storage change	Net Streamflow produced in Verde Valley	Net Base flow (gage) at Paulden	Net Base flow (gage) at Clarkdale	SW outflow, irrigation consumptive use	Net base flow, Camp Verde gage	Groundwater withdrawals above gage at Clarkdale	Groundwater withdrawals above gage at Camp Verde	Incidental recharge above gage at Clarkdale	Incidental recharge above gage at Camp Verde
1/1/2006	0	0	0	0	0	0	0	0	0	0
7/16/2006	216	-218	-29	-43	0	-261	-17	-18	-39	-39
3/8/2007	194	-183	-61	-67	0	-250	-17	-18	-39	-39
12/16/2007	276	-257	-104	-98	0	-356	-17	-18	-39	-39
11/19/2008	971	-352	-153	-159	0	-511	-17	-613	-39	-39
1/1/2010	1097	-465	-213	-225	0	-689	-17	-613	-39	-39
5/6/2011	1703	-548	-274	-297	0	-845	-892	-2049	-372	-419
12/15/2012	1845	-675	-348	-378	0	-1053	-892	-2049	-372	-419
11/22/2014	2012	-843	-433	-478	0	-1321	-892	-2049	-372	-419
3/19/2017	2202	-1026	-536	-592	0	-1617	-892	-2049	-372	-419
12/31/2019	2663	-1204	-656	-728	0	-1931	-892	-2306	-372	-429
5/5/2021	3225	-1227	-708	-781	0	-2008	-1766	-3734	-706	-809
12/15/2022	3322	-1294	-767	-840	0	-2133	-1766	-3734	-706	-809
11/21/2024	3440	-1397	-831	-926	0	-2322	-1768	-3735	-706	-809
3/19/2027	3933	-1516	-902	-1005	0	-2521	-1768	-4094	-706	-809
12/30/2029	4096	-1634	-984	-1097	0	-2731	-1768	-4094	-706	-809
5/5/2031	4606	-1635	-1018	-1136	0	-2771	-2642	-5510	-1039	-1190
12/14/2032	4678	-1693	-1058	-1179	0	-2872	-2642	-5510	-1039	-1190
11/21/2034	4772	-1760	-1106	-1238	0	-2998	-2642	-5510	-1039	-1190
3/18/2037	4888	-1843	-1161	-1303	0	-3145	-2646	-5514	-1039	-1190
12/30/2039	5024	-1939	-1233	-1384	0	-3322	-2657	-5525	-1085	-1236
5/4/2041	5509	-1912	-1264	-1419	0	-3331	-3531	-6940	-1417	-1615
12/14/2042	5639	-1950	-1299	-1457	0	-3407	-3531	-7010	-1417	-1615
11/20/2044	5715	-1993	-1340	-1506	0	-3500	-3531	-7010	-1417	-1615
3/19/2047	5808	-2051	-1391	-1560	0	-3611	-3531	-7010	-1417	-1615
12/30/2049	5931	-2147	-1459	-1644	0	-3792	-3534	-7014	-1417	-1615
5/5/2051	6418	-2105	-1485	-1670	0	-3774	-4408	-8427	-1749	-1994
12/14/2052	6474	-2125	-1519	-1715	0	-3839	-4408	-8427	-1749	-1994
11/21/2054	6557	-2177	-1556	-1753	0	-3930	-4598	-8616	-1749	-1994
3/18/2057	6646	-2229	-1598	-1795	0	-4024	-4600	-8619	-1749	-1994
12/30/2059	6900	-2276	-1650	-1852	0	-4129	-4600	-8746	-1749	-1994
9/19/2066	8005	-2244	-1767	-1989	0	-4233	-5488	-10534	-2139	-2430
10/11/2074	8171	-2316	-1905	-2139	0	-4455	-5488	-10534	-2139	-2430
6/14/2084	8723	-2441	-2086	-2358	0	-4799	-5495	-10920	-2191	-2482
1/24/2096	8908	-2547	-2253	-2523	0	-5070	-5496	-10920	-2191	-2482
12/30/2109	9293	-2661	-2432	-2716	0	-5378	-5612	-11198	-2378	-2669

Table 1.4. Relative changes in water-budget components attributable to human stresses, 2005–2110, based on a condition of unchanged human stresses, Verde Valley, central Arizona.

[GW, groundwater; SW, surface water; all values in acre-feet per year; values are described by variable ΔA_t in equation (3) in main body of text]

Simluated date	Groundwater inflow						Groundwater outflow		
	Incidental recharge	Baseflow infiltration	Natural recharge	Underflow from			Withdrawals	Discharge as base flow	Evapo-transpiration
				Upper Verde Valley sub-basin	Colorado Plateau	Verde Canyon			
1/1/2006	0	0	0	0	0	0	0	0	0
7/16/2006	0	50	-6	7	-18	-7	-1	-168	-6
3/8/2007	0	72	-6	11	-23	-5	-1	-111	-9
12/16/2007	0	128	-6	15	-28	-5	-1	-129	-14
11/19/2008	0	188	-6	20	-32	-5	-596	-165	-20
1/1/2010	0	256	-6	26	-36	-6	-596	-209	-26
5/6/2011	0	349	-6	33	-39	-5	-596	-256	-34
12/15/2012	0	434	-6	42	-42	-6	-596	-319	-43
11/22/2014	0	540	-6	52	-42	-5	-596	-399	-53
3/19/2017	0	655	-6	65	-40	-5	-596	-473	-65
12/31/2019	-10	758	-6	80	-35	-4	-861	-561	-78
5/5/2021	-10	803	-6	87	-31	-4	-861	-597	-84
12/15/2022	-10	864	-6	95	-25	-4	-861	-633	-91
11/21/2024	-10	925	-6	105	-17	-4	-861	-689	-99
3/19/2027	-10	993	-15	116	-7	-4	-1244	-754	-108
12/30/2029	-10	1064	-15	129	9	-4	-1244	-828	-118
5/5/2031	-10	1101	-15	135	17	-4	-1244	-852	-123
12/14/2032	-10	1129	-15	143	29	-3	-1244	-908	-129
11/21/2034	-10	1178	-15	151	44	-3	-1244	-973	-136
3/18/2037	-10	1231	-15	161	65	-3	-1244	-1012	-144
12/30/2039	-10	1279	-15	171	92	-2	-1324	-1080	-154
5/4/2041	-10	1295	-15	176	106	-3	-1324	-1106	-158
12/14/2042	-10	1340	-15	182	126	-3	-1324	-1139	-162
11/20/2044	-10	1379	-15	190	153	-3	-1324	-1180	-167
3/19/2047	-10	1389	-15	198	190	-2	-1685	-1234	-173
12/30/2049	-10	1367	-15	207	248	-2	-1769	-1281	-238
5/5/2051	-10	1382	-15	212	281	-2	-1919	-1287	-241
12/14/2052	-10	1390	-15	217	328	-3	-1919	-1317	-244
11/21/2054	-10	1412	-15	223	401	-2	-2300	-1352	-248
3/18/2057	-10	1442	-15	230	526	-2	-2300	-1397	-252
12/30/2059	-10	1457	-15	237	589	-3	-2300	-1447	-256
9/19/2066	-10	1535	-15	252	624	-3	-2381	-1577	-264
10/11/2074	-10	1595	-15	269	685	-3	-2731	-1663	-270
6/14/2084	-10	1646	-15	286	734	-3	-2886	-1814	-332
1/24/2096	-10	1693	-15	304	785	-2	-2886	-1947	-341
12/30/2109	-10	1777	-15	322	837	-1	-2895	-2098	-353

Table 1.4. Relative changes in water-budget components attributable to human stresses, 2005–2110, based on a condition of unchanged human stresses, Verde Valley, central Arizona.—Continued

Simluated date	Net				SW outflow, irrigation consumptive use	Net base flow, Camp Verde gage	Groundwater withdrawals above gage at		Incidental recharge above gage at	
	Ground-water storage change	Streamflow produced in Verde Valley	Base flow (gage) at							
			Paulden	Clarkdale			Clarkdale	Camp Verde	Clarkdale	Camp Verde
1/1/2006	0	0	0	0	0	0	0	0	0	0
7/16/2006	216	-218	-29	-43	0	-261	-17	-18	-39	-39
3/8/2007	194	-183	-61	-67	0	-250	-17	-18	-39	-39
12/16/2007	276	-257	-104	-98	0	-356	-17	-18	-39	-39
11/19/2008	971	-352	-153	-159	0	-511	-17	-613	-39	-39
1/1/2010	1097	-465	-213	-225	0	-689	-17	-613	-39	-39
5/6/2011	1238	-606	-281	-304	0	-910	-17	-613	-39	-39
12/15/2012	1401	-752	-362	-392	0	-1144	-17	-613	-39	-39
11/22/2014	1583	-939	-457	-502	0	-1441	-17	-613	-39	-39
3/19/2017	1797	-1128	-570	-624	0	-1752	-17	-613	-39	-39
12/31/2019	2280	-1319	-698	-770	0	-2089	-17	-878	-39	-49
5/5/2021	2385	-1400	-758	-829	0	-2230	-17	-878	-39	-49
12/15/2022	2508	-1496	-826	-900	0	-2396	-18	-880	-39	-49
11/21/2024	2648	-1614	-897	-994	0	-2608	-18	-880	-39	-49
3/19/2027	3190	-1747	-976	-1072	0	-2819	-18	-1262	-39	-49
12/30/2029	3371	-1892	-1075	-1201	0	-3093	-18	-1262	-39	-49
5/5/2031	3451	-1952	-1116	-1235	0	-3187	-18	-1262	-39	-49
12/14/2032	3554	-2037	-1169	-1288	0	-3325	-18	-1262	-39	-49
11/21/2034	3673	-2151	-1234	-1382	0	-3533	-31	-1274	-90	-100
3/18/2037	3823	-2242	-1301	-1441	0	-3684	-34	-1278	-90	-100
12/30/2039	4069	-2358	-1391	-1553	0	-3911	-34	-1358	-90	-100
5/4/2041	4127	-2401	-1435	-1599	0	-4001	-34	-1358	-90	-100
12/14/2042	4231	-2478	-1486	-1653	0	-4132	-34	-1358	-90	-100
11/20/2044	4352	-2559	-1546	-1727	0	-4286	-257	-1581	-90	-100
3/19/2047	4799	-2623	-1617	-1805	0	-4428	-261	-1946	-90	-100
12/30/2049	5093	-2648	-1692	-1873	0	-4521	-261	-2030	-90	-100
5/5/2051	5301	-2669	-1736	-1926	0	-4595	-261	-2180	-90	-100
12/14/2052	5412	-2707	-1781	-1977	0	-4684	-264	-2183	-90	-100
11/21/2054	5930	-2764	-1835	-2031	0	-4795	-264	-2564	-90	-100
3/18/2057	6140	-2838	-1900	-2101	0	-4939	-264	-2564	-90	-100
12/30/2059	6296	-2904	-1974	-2183	0	-5087	-264	-2564	-90	-100
9/19/2066	6596	-3112	-2164	-2411	0	-5523	-289	-2670	-160	-170
10/11/2074	7197	-3258	-2344	-2599	0	-5857	-289	-3020	-160	-170
6/14/2084	7645	-3461	-2540	-2840	0	-6300	-298	-3184	-188	-198
1/24/2096	7915	-3641	-2751	-3066	0	-6707	-839	-3725	-333	-343
12/30/2109	8218	-3875	-2956	-3298	0	-7173	-983	-3878	-525	-535

Table 1.5. Relative changes in water-budget components attributable to human stresses, 2005–2110, based on a condition of increased human stresses, Verde Valley, central Arizona.

[GW, groundwater; SW, surface water; all values in acre-feet per year; values are described by variable ΔA_t in equation (3) in main body of text]

Simluated date	Groundwater inflow						Groundwater outflow		
	Incidental recharge	Baseflow infiltration	Natural recharge	Underflow from			Withdrawals	Discharge as base flow	Evapo-transpiration
				Upper Verde Valley sub-basin	Colorado Plateau	Verde Canyon			
1/1/2006	0	0	0	0	0	0	0	0	0
7/16/2006	0	50	-6	7	-18	-7	-1	-168	-6
3/8/2007	0	72	-6	11	-23	-5	-1	-111	-9
12/16/2007	0	128	-6	15	-28	-5	-1	-129	-14
11/19/2008	0	188	-6	20	-32	-5	-596	-165	-20
1/1/2010	0	256	-6	26	-36	-6	-596	-209	-26
5/6/2011	47	384	-6	33	-40	-5	-35	-277	-35
12/15/2012	47	482	-6	42	-44	-6	-35	-348	-45
11/22/2014	47	597	-6	53	-44	-5	-35	-431	-56
3/19/2017	37	715	-6	65	-43	-5	-309	-511	-68
12/31/2019	37	829	-6	80	-37	-4	-309	-597	-82
5/5/2021	84	909	-6	87	-33	-4	244	-659	-89
12/15/2022	84	989	-6	96	-28	-4	244	-701	-97
11/21/2024	84	1063	-15	106	-20	-4	-161	-763	-105
3/19/2027	84	1137	-15	118	-8	-4	-161	-840	-116
12/30/2029	84	1222	-15	132	10	-4	-161	-917	-127
5/5/2031	131	1288	-15	138	20	-3	381	-973	-133
12/14/2032	131	1336	-15	146	34	-3	381	-1032	-141
11/21/2034	131	1393	-15	155	53	-3	381	-1092	-149
3/18/2037	131	1465	-15	166	80	-2	381	-1169	-159
12/30/2039	131	1531	-15	178	119	-2	293	-1246	-169
5/4/2041	178	1596	-15	183	140	-3	832	-1284	-174
12/14/2042	178	1659	-15	190	172	-3	832	-1340	-180
11/20/2044	178	1636	-15	199	217	-3	333	-1391	-246
3/19/2047	178	1663	-15	208	288	-2	-261	-1432	-252
12/30/2049	178	1696	-15	219	414	-2	-261	-1512	-259
5/5/2051	225	1757	-15	224	499	-3	248	-1536	-262
12/14/2052	225	1784	-15	230	573	-3	248	-1577	-266
11/21/2054	225	1811	-15	236	583	-3	248	-1631	-269
3/18/2057	225	1856	-15	244	595	-3	248	-1693	-272
12/30/2059	225	1895	-15	253	611	-3	-69	-1758	-276
9/19/2066	272	2025	-15	274	672	-4	106	-1939	-285
10/11/2074	272	2072	-15	296	724	-3	106	-2090	-292
6/14/2084	272	1966	-15	320	777	-4	-162	-2282	-416
1/24/2096	307	2049	0	346	835	-3	175	-2486	-432
12/30/2109	307	2126	0	372	896	-2	175	-2673	-450

Table 1.5. Relative changes in water-budget components attributable to human stresses, 2005–2110, based on a condition of increased human stresses, Verde Valley, central Arizona.—Continued

Simluated date	Net				SW outflow, irrigation consumptive use	Net base flow, Camp Verde gage	Groundwater withdrawals above gage at		Incidental recharge above gage at	
	Ground-water storage change	Streamflow produced in Verde Valley	Base flow (gage) at Paulden	Base flow (gage) at Clarkdale			Clarkdale	Camp Verde	Clarkdale	Camp Verde
1/1/2006	0	0	0	0	0	0	0	0	0	0
7/16/2006	216	-218	-29	-43	0	-261	-17	-18	-39	-39
3/8/2007	194	-183	-61	-67	0	-250	-17	-18	-39	-39
12/16/2007	276	-257	-104	-98	0	-356	-17	-18	-39	-39
11/19/2008	971	-352	-153	-159	0	-511	-17	-613	-39	-39
1/1/2010	1097	-465	-213	-225	0	-689	-17	-613	-39	-39
5/6/2011	782	-662	-290	-313	0	-974	857	822	295	342
12/15/2012	965	-830	-378	-411	0	-1241	857	822	295	342
11/22/2014	1162	-1028	-481	-526	0	-1554	857	822	295	342
3/19/2017	1636	-1226	-605	-659	0	-1886	857	549	295	332
12/31/2019	1885	-1426	-738	-808	0	-2234	857	549	295	332
5/5/2021	1550	-1568	-807	-879	0	-2447	1731	1975	628	712
12/15/2022	1698	-1690	-883	-961	0	-2651	1731	1975	628	712
11/21/2024	2257	-1826	-961	-1056	0	-2882	1731	1570	628	712
3/19/2027	2439	-1977	-1053	-1153	0	-3130	1731	1570	628	712
12/30/2029	2641	-2139	-1162	-1285	0	-3423	1718	1557	574	658
5/5/2031	2302	-2261	-1216	-1339	0	-3600	2592	2973	906	1037
12/14/2032	2436	-2368	-1278	-1407	0	-3775	2592	2973	906	1037
11/21/2034	2584	-2485	-1358	-1496	0	-3981	2588	2969	906	1037
3/18/2037	2749	-2633	-1447	-1608	0	-4241	2588	2969	906	1037
12/30/2039	3045	-2776	-1550	-1724	0	-4501	2345	2639	906	1037
5/4/2041	2693	-2880	-1602	-1767	0	-4647	3213	4045	1238	1416
12/14/2042	2847	-3000	-1669	-1847	0	-4846	3213	4045	1238	1416
11/20/2044	3455	-3027	-1743	-1925	0	-4952	3208	3542	1238	1416
3/19/2047	4278	-3095	-1826	-2007	0	-5102	3208	2947	1238	1416
12/30/2049	4533	-3208	-1927	-2122	0	-5330	3208	2947	1238	1416
5/5/2051	4251	-3292	-1983	-2179	0	-5471	4073	4321	1570	1795
12/14/2052	4420	-3361	-2043	-2246	0	-5608	4073	4321	1570	1795
11/21/2054	4533	-3441	-2111	-2312	0	-5754	4073	4321	1570	1795
3/18/2057	4638	-3549	-2197	-2411	0	-5960	4073	4321	1570	1795
12/30/2059	5084	-3652	-2293	-2527	0	-6180	4067	3998	1570	1795
9/19/2066	5342	-3963	-2512	-2778	0	-6742	4910	5016	1902	2173
10/11/2074	5632	-4161	-2729	-3007	0	-7168	4900	5006	1785	2057
6/14/2084	6174	-4248	-2962	-3285	0	-7533	4259	4096	1698	1969
1/24/2096	6248	-4535	-3190	-3544	0	-8080	4251	4426	1656	1963
12/30/2109	6644	-4799	-3415	-3795	0	-8594	4091	4266	1471	1778

Appendix 2. Evapotranspiration by Riparian Vegetation, 2000–2010, Estimated Using Remote Sensing

This appendix provides an estimate of riparian evapotranspiration (ET) in the Verde Valley that is independent of the methods used by the Northern Arizona Regional Groundwater Flow Model. Advances in satellite-based remote-sensing technology have enabled the development of methods that use empirical regression models to estimate ET in the American Southwest (Nagler and Glenn, 2009; Nagler and others, 2009). This method was used at a regional scale for the determination of groundwater availability (Tillman and others, 2011), and the same method has been applied to the Verde Valley, with the results presented in this appendix. Average annual groundwater discharge by riparian vegetation was estimated for the study area for the period 2000 through 2010.

Methods

This method uses a regression model that relates measured ET to remotely sensed data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite's Enhanced Vegetation Index (EVI) grid data (Oak Ridge National Laboratory, 2008). Computation of final values consisted of four steps, described in the following sections.

Estimates of Monthly ET Across Entire Verde Valley

Enhanced Vegetation Index (EVI) is a measure of vegetation greenness to which evapotranspiration is directly correlated (Nagler and Glenn, 2009; Nagler and others, 2009). EVI raster data from the MODIS instrumentation aboard the Terra and Aqua satellites operated by the National Aeronautics and Space Administration (NASA) were obtained from the Oak Ridge National Laboratory (Oak Ridge National Laboratory, 2008) in multiple 171 × 115-mi bands and combined using a mosaic tool to cover the study area. Near-daily satellite passes provided 820 × 820-ft resolution EVI data composited over 16-day intervals for the 2000 through 2010 time period. ET (in millimeters per day; mm/day) was calculated in ArcGIS™ on 820 × 820-ft individual grid cells for the entire study area from EVI data using a relation developed previously by researchers with the USGS Southwest Biological Science Center and the University of Arizona (Nagler and Glenn, 2009; Nagler and others, 2009):

$$ET = 1.22\ ET_o \times EVI^* , \qquad (1)$$

where ET_o is the reference crop evapotranspiration (in millimeters per day) and EVI^* is scaled EVI. This relation between ET, ET_o, and EVI^* was developed by regressing actual ET data measured by sap flux sensors, moisture flux towers, and neutron hydroprobe water balance measurements in riparian and agricultural areas along the Lower Colorado River in Arizona, and it is validated in other publications (Nagler and Glenn, 2009; Nagler and others, 2009). Plants included in the regression model were alfalfa (the most common crop along the Lower Colorado River), saltcedar (the most common riparian species), cottonwoods, and arrowweed.

ET_o was estimated on a monthly basis using a modified Blaney-Criddle relation (Brouwer and Heibloem, 1986):

$$ET_o = p\ (0.46\ T_{mean} + 8) , \qquad (2)$$

where p is mean daily percentage of annual daytime hours (percent) obtained from published values for the study area (Brouwer and Heibloem, 1986) and T_{mean} is mean daily temperature. T_{mean} was calculated on a monthly basis from daily minimum and maximum temperature data (PRISM Climate Group, 2012). EVI is converted to a scaled value (EVI^*) following the relation of Nagler and others (2005):

$$EVI^* = 1–(0.542–EVI)/(0.542–0.091) , \qquad (3)$$

where 0.542 and 0.091 represent maximum and minimum EVI values, respectively, from a large data set of riparian plant communities in the Southwest (Nagler and others, 2005; Dennison and others, 2009). These same riparian plant communities are found throughout the Verde Valley, the study area of the present report.

Computed groundwater-discharge-by-vegetation grid cells of 820 × 820 ft using equations (1), (2), and (3) were downsampled in ArcGIS to 164 × 164-ft grids using nearest neighbor interpolation for further analyses. The 164 × 164-ft grid values that were spatially associated with the combined stream buffer and land cover areas were extracted for computation of summary statistics.

Subselect Areas Where ET is Likely from Groundwater

Geographic areas of presumed groundwater-using vegetation were defined using a combination of proximity to surface-water drainages and landcover types. First, a 164-ft (50-meter) buffer was created around all named surface-water drainages in the study area using geographic information system tools (Arizona State Land Department, 1993). The 164-ft buffer distance was selected to adequately encompass riparian vegetative areas based on analyses of satellite and aerial photography of the surface-water drainages in the study area. Areas within the 164-ft surface-drainage buffer that were defined in the 2001 National Land Cover Dataset (NLCD; Homer and others, 2004) as “hay/pasture” or “cultivated crops” were removed, because these areas are normally irrigated in the study area and do not use groundwater directly. All remaining vegetation within the buffer area was presumed to be using primarily groundwater for growth and maintenance.

Not all of the surface-water drainages identified in this analysis necessarily have riparian ET associated with them, particularly the smallest and most ephemeral streams. For the purposes of comparison, named streams were further subdivided into two groups. Oak Creek, Wet Beaver Creek, and West Clear Creek formed the first group, and are the major perennial streams in the Verde Valley. The second group comprised all remaining named surface-water drainages.

Specific land coverages within the NLCD were used to define additional areas of groundwater-using vegetation in the study area that were outside the 164-ft surface-drainage buffer. Land classifications of "herbaceous wetland" and "woody wetland" were selected to represent locations at which all or nearly all water extracted by plants comes from groundwater. Herbaceous wetland is defined in NLCD as land in which the soil or substrate is periodically saturated or inundated with water and which is covered by more than 80 percent perennial herbaceous vegetation; woody wetland is defined as land in which the soil or substrate is periodically saturated or inundated with water and which is covered by more than 20 percent forest or shrubland.

Adjustment for Possible Contributions of Direct Precipitation

Direct precipitation may potentially be at least a partial source of water for vegetation greenness and associated EVI in the subset areas defined above. Therefore, a lower bound on estimated groundwater discharge by vegetation for the study area was developed by subtracting monthly precipitation (PRISM Climate Group, 2012) from monthly riparian ET estimates developed in the preceding step.

Calculation of Summary Statistics

Monthly values of groundwater ET were summed to obtain annual values for the years 2000–2010. Annual mean values were then calculated from these annual values, and those are reported in the tables of this appendix and in the main body of this report.

All values calculated using these methods were converted from original metric units to the units used throughout this report. For example, cubic meters per year were converted to acre-feet per year.

Results

Annual average groundwater discharge by riparian vegetation in the Verde Valley for 2000–2010 was estimated to be 23,000–41,000 acre-ft/yr (table 2.1) if it is assumed that all named surface-water drainages have riparian ET. The variability between the low and high values in this range is accounted for by the amount of precipitation falling on the areas of presumed riparian ET.

Because Oak Creek, Wet Beaver Creek, and West Clear Creek are considered to be the only named surface-water drainages that likely have riparian ET, the estimated annual average groundwater discharge by riparian vegetation in the Verde Valley for 2000–2010 was reduced to 14,000–22,000 acre-ft/yr.

Cyclical seasonal patterns were evident in the temporal computed ET data, with high rates and volumes of ET during summer months and low rates and volumes during winter months. For most winter time periods, minimal ET rates combined with adequate precipitation resulted in little or no groundwater ET for the lower bound estimate. The woody wetland land-cover area produced the greatest volume of annual ET—as much as about 5,300 acre-ft/yr.

Table 2.1. Riparian evapotranspration estimated by using remotely sensed satellite data, 2000–2010, Verde Valley, central Arizona.

[acre-ft/yr, acre-feet per year]

Buffer area	Delineation type	Annual-mean ET minus precipitation (acre-ft/yr)[2]	Annual-mean riparian ET (acre-ft/yr)[1]
Land-use types and streams likely to have riparian evapotranspiration			
Woody wetlands	Landcover[3]	3,883	5,276
Oak Creek	Stream proximity[4]	2,912	4,707
Verde River	Stream proximity	2,889	4,224
West Clear Creek	Stream proximity	2,056	4,319
Emergent herbaceous wetlands	Landcover	1,214	1,621
Wet Beaver Creek	Stream proximity	1,138	1,908
Subtotal		14,000	22,000
Other streams that might or might not have riparian evapotranspiration			
Jacks Canyon	Stream proximity	787	1,817
Dry Beaver Creek	Stream proximity	601	1,277
Spring Creek	Stream proximity	581	1,281
West Fork Oak Creek	Stream proximity	580	1,214
Rarick Canyon	Stream proximity	577	1,320
Dry Creek	Stream proximity	532	1,177
Rattlesnake Canyon	Stream proximity	485	1,117
Cherry Creek	Stream proximity	468	902
Oak Wash	Stream proximity	408	683
Clover Creek	Stream proximity	368	831
Beaver Creek	Stream proximity	346	587
Toms Creek	Stream proximity	308	706
Wickiup Creek	Stream proximity	267	608
Walker Creek	Stream proximity	246	480
Coffee Creek	Stream proximity	229	542
Pumphouse Wash	Stream proximity	219	516
Walnut Creek	Stream proximity	207	444
Brady Canyon	Stream proximity	191	474
Corduroy Wash	Stream proximity	188	446
Long Canyon	Stream proximity	187	520
Blowout Creek	Stream proximity	145	295
Gaddis Wash	Stream proximity	140	255
Bitter Creek	Stream proximity	118	277
Woody Wash	Stream proximity	116	269
Soldier Wash	Stream proximity	113	226
Russell Wash	Stream proximity	111	222
Grief Hill Wash	Stream proximity	79	175
Schoolhouse Draw	Stream proximity	77	199
Grandpa Wash	Stream proximity	56	128
Turkey Creek	Stream proximity	43	101
Subtotal		8,800	19,000
Grand total		23,000	41,000

[1]Annual mean computed for calendar years 2000–2010.
[2]Gridded precipitation obtained from PRISM Climate Group (2012).
[3]Selected on the basis of National Land Cover Dataset (Homer and others, 2004).
[4]Selected on the basis of being within 164 feet of a named stream channel.

Appendix 3. Irrigation-Water Consumptive Use, 2010, Estimated Using a Crop Inventorying Approach

Irrigation water use in the Verde Valley historically has not been well characterized. To better understand this component of the water budget, an indirect method to estimate irrigation withdrawal was employed (Dickens and others, 2011). This calculates an estimate of irrigation consumptive use in the Verde Valley that is independent of the Northern Arizona Regional Groundwater Flow Model. Total irrigation water needs were estimated for each crop by using the equation:

$$W_c = (A_c \times C_c) / L_f$$

where

W_c is irrigation withdrawals per growing season for a particular crop in acre-feet per growing season,

A_c is total planted area of a given crop in acres,

C_c is the consumptive water requirement for a given crop in feet per growing season, and

L_f is a dimensionless irrigation-efficiency coefficient between 0 and 1 for the irrigation infrastructure used for each field of the given crop.

A_c (total planted acreage) was calculated for each crop using a combination of aerial photography, field inspection, and a geographic information system (fig. 3.1). For each nonfallow field, the crop type, irrigation-water source, irrigation system, irrigation-system efficiency, and any other observations regarding irrigation practices were recorded during both the summer and winter field inventories. Golf courses and athletic fields were assumed to obtain irrigation water from groundwater wells.

C_c (consumptive water requirement) was estimated by using the modified Blaney-Criddle ET method (U.S. Bureau of Reclamation, 1992). Local average temperature and rainfall data from the Montezuma Castle National Monument weather station (National Oceanic and Atmospheric Administration, 2010), which is located about 5 miles north of Camp Verde, Arizona, were applied in this method.

L_f (irrigation-efficiency coefficient) represents all water losses caused by inefficiencies in irrigation infrastructure and water-application method. The factors considered include: conveyance loss, irrigation system efficiency, overwatering, and irrigation-system age and condition, among others. Ranges for L_f were obtained from Howell (2003), and specific values were chosen through professional judgment. About 97 percent of all irrigated agricultural acres in the study area used flood

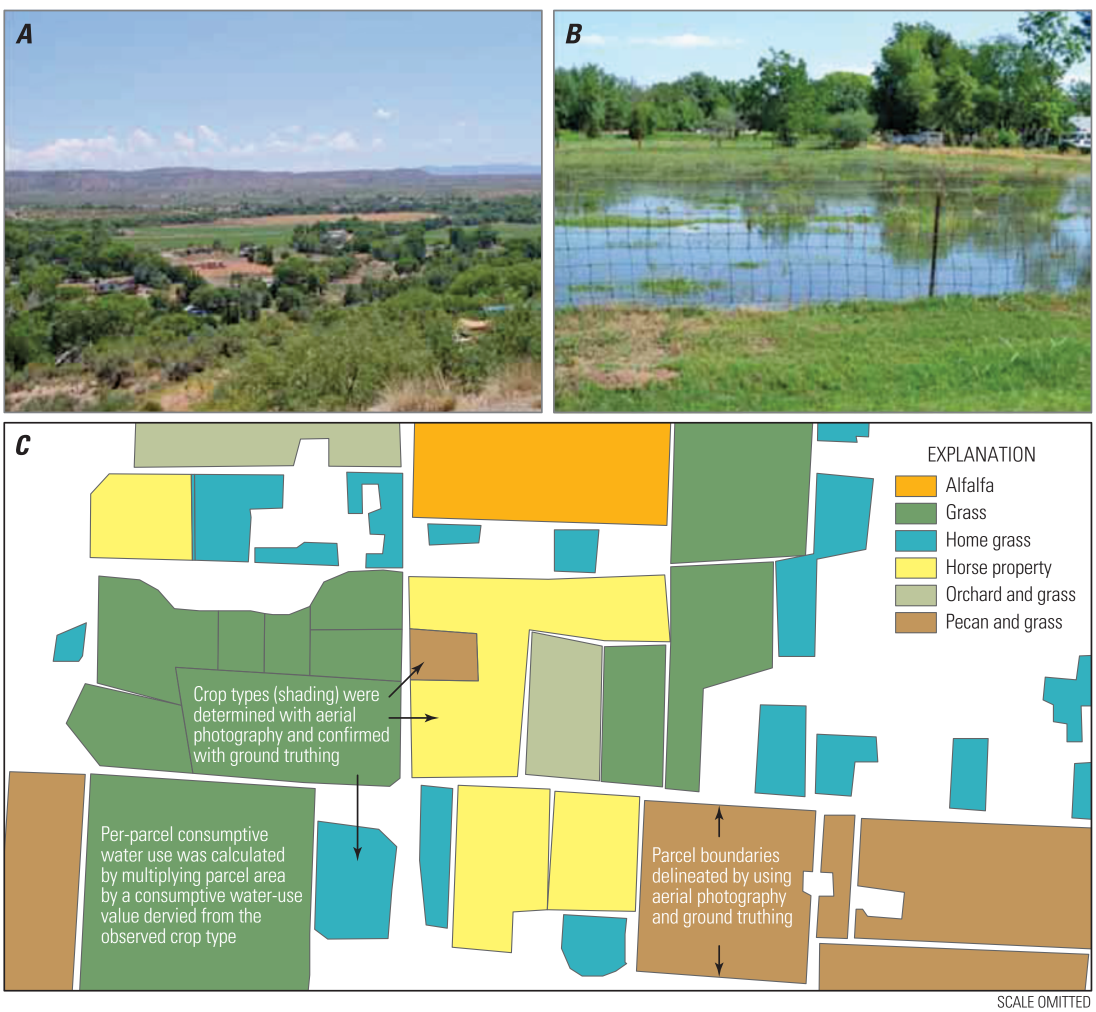


Figure 3.1. Consumptive use of irrigation water in the Verde Valley, central Arizona. *A,* Photograph of irrigated fields observed in July 2010. *B,* Photograph of horse property and pasture land being flooded with surface water. *C,* Conceptual map showing example of area inventoried in July 2010 for irrigation consumptive use.

irrigation, whose efficiency was estimated to be 0.5, or 50 percent. Two percent of irrigated acreage was watered with sprinklers, which were observed to have a system efficiency of 0.8 (that is, 80-percent efficient). Less than one percent of irrigated acreage was watered using drip irrigation, which has an efficiency of about 0.9.

In July 2010, about 10,500 acre-ft of irrigation surface water was estimated to be needed to meet the water demands of crops in the study area on the basis of these methods (see the table in the inset titles "An Independent Estimate of Crop Irrigation Consumptive Use" in the main body of this report). Because of system inefficiencies in irrigation infrastructure and application methods, 20,800 acre-ft of water was estimated to be needed to be diverted from streams. Discussion of the amount of water needed by irrigation systems but not used by crops (10,300 acre-ft) was beyond the scope of this report; possible pathways for such water include ditch leakage, evaporation, ET from vegetation along irrigation ditches, and irrigation excess or return flow (Healy and others, 2007) that either runs off fields or infiltrates past root zones and becomes groundwater recharge. Future studies, particularly ones producing a more complete view of the hydrology of the ditch diversions, could help researchers understand this better.

In February 2011, the same fields (inventoried in July 2010) were re-inventoried. No active use of irrigation water was observed. Although some ditch diversions continue to convey water during the winter months, no evidence was observed of this water being applied for winter irrigation. A small amount of diverted water in ditches may be used to maintain stock tanks or ponds in the winter months, but quantifying such use was beyond the scope of this report.

Appendix 4. One-Hundred-Year Capture Maps for the Verde Valley

The main body of this report evaluated basin-wide effects of human stresses by using water budgets, but did not generally discuss the spatial distribution of those stresses. However, there is value in exploring their spatial distribution. This appendix presents three maps produced by a technique known as capture-map development. Groundwater pumping removes water from storage in the aquifer, and with time, the effects of pumping will spread to greater distances and can reduce groundwater discharge to natural features. The timing of these effects is dependent on aquifer properties and on the proximity of pumping locations to streams, springs, wetlands, and riparian vegetation. Both of these factors in the timing of capture are spatial in nature.

Capture maps indicate, for a given location, what fraction of water from a well would be derived from capture—the reduction in natural discharge and (or) increase in natural recharge—after a fixed period of time for a given layer of a groundwater-flow model. Locations on these maps with larger values for this fraction (redder colors, as much as a fraction of 1.0) indicate that a larger amount of water would be obtained by capture than areas with smaller values of this fraction (bluer colors, as little as a fraction of 0.0). The maps were created by researchers assuming a well in a location pumps water at a constant rate for the period of time encompassed (100 years in this example), that the groundwater system responds linearly, and that changes in saturated thickness of aquifers (and therefore changes in transmissivity) are negligible. Capture maps can be used as guides for locating wells or artificial recharge infrastructure and to understand how soon such equipment might produce an effect on a connected feature such as a stream or wetland. Capture maps also can be used in the reverse sense to understand the timing of enhanced water availability to streams and vegetation by artificial recharge. For example, recharge in red map areas would enhance water availability much more quickly than recharge in blue map areas.

The method documented in Leake and others (2010) and Leake and Pool (2010) was used to create these maps. Leake and Pool (2010) published capture maps for the Verde Valley for 10- and 50-year intervals. This appendix presents maps for the 100-year interval, which corresponds to the amount of time used for forward-looking model runs in the main body of this report. The maps in this appendix were generated from raw tabular data associated with Leake and Pool (2010). Maps in this appendix are, therefore, visualizations of already-published data, employing the same method of visualization as used by Leake and Pool (2010).

The capture map for layer 1 (fig. 4.1) has only a small portion of the study area shaded in any color. This is because layer 1 of the underlying groundwater-flow model is not laterally extensive in the study area (layer 1 is used to simulate the fluviolacustrine facies of the Verde Formation and saturated stream alluvium). The pattern of coloration in this 100-year capture map generally is the same as the 10- and 50-year maps of Leake and Pool (2010), except that all colors are shaded more toward the red (more capture), and a larger area is fully red (90 to 100 percent capture).

The capture map for layer 2 (fig. 4.2) covers a larger portion of the Verde Valley; layer 2 is used to simulate the Supai Formation of the Colorado Plateau and the sand and gravel facies of the Verde Formation.

The capture map for layer 3 (fig. 4.3) covers almost all of the study area as well as the adjacent upper portion of the Verde Valley subbasin. This map expresses capture within the Redwall aquifer that underlies almost all of the study area; it also includes some areas of older crystalline and sedimentary rocks along the southern margins of the study area. One part of the map near Stoneman Lake could not be visualized because the method employed in developing capture maps failed to have the groundwater-flow model converge to a solution. This likely was caused by the dewatering of layer 2 in this area, which resulted in a change in hydraulic properties between layers 2 and 3. In this area, layer 2 (simulating the Supai Formation) has low saturated thickness (S. Leake, U.S. Geological Survey, oral commun., 2012).

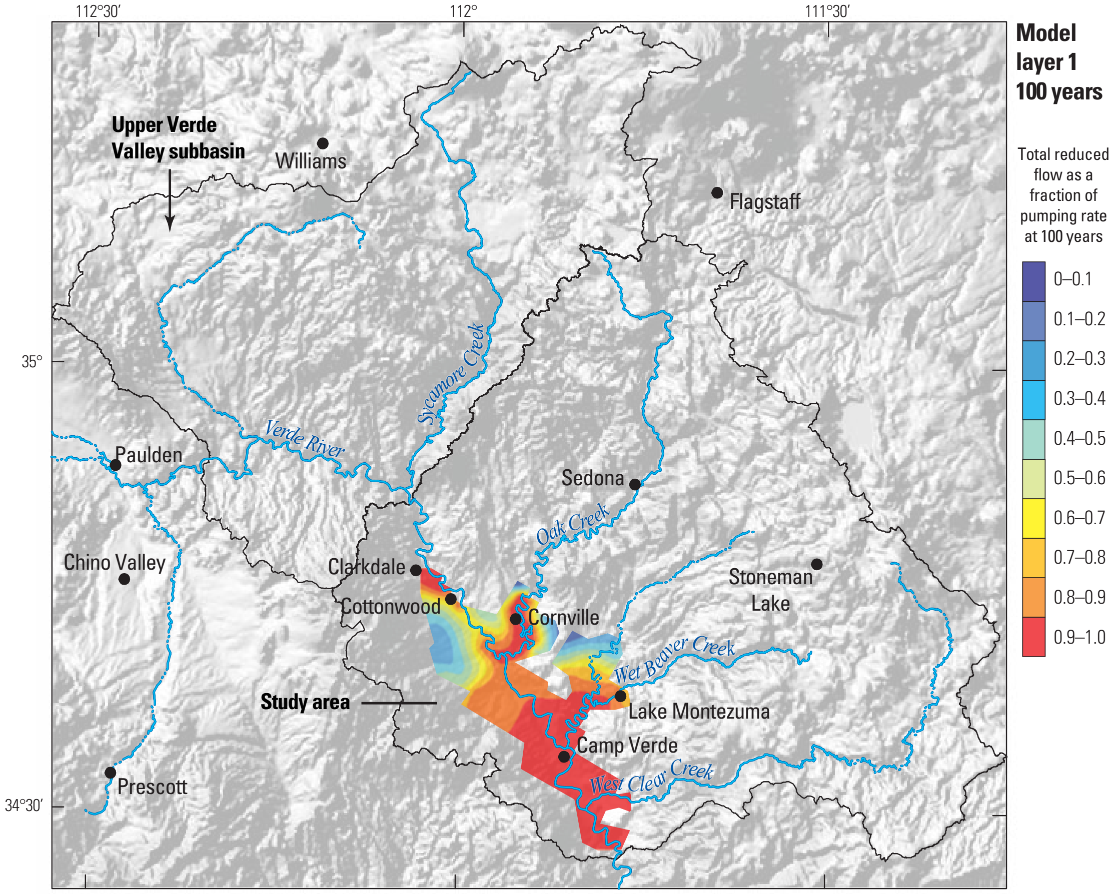


Figure 4.1 Map showing computed reduction in flow of streams and springs and reduction in riparian evapotranspiration as a fraction of pumping rate that would result from pumping groundwater from NARGFM layer 1 at a constant rate for 100 years. The color at any location represents the fraction of the pumping rate by a well at that location that can be attributed to changes in outflow from or inflow to the aquifer.

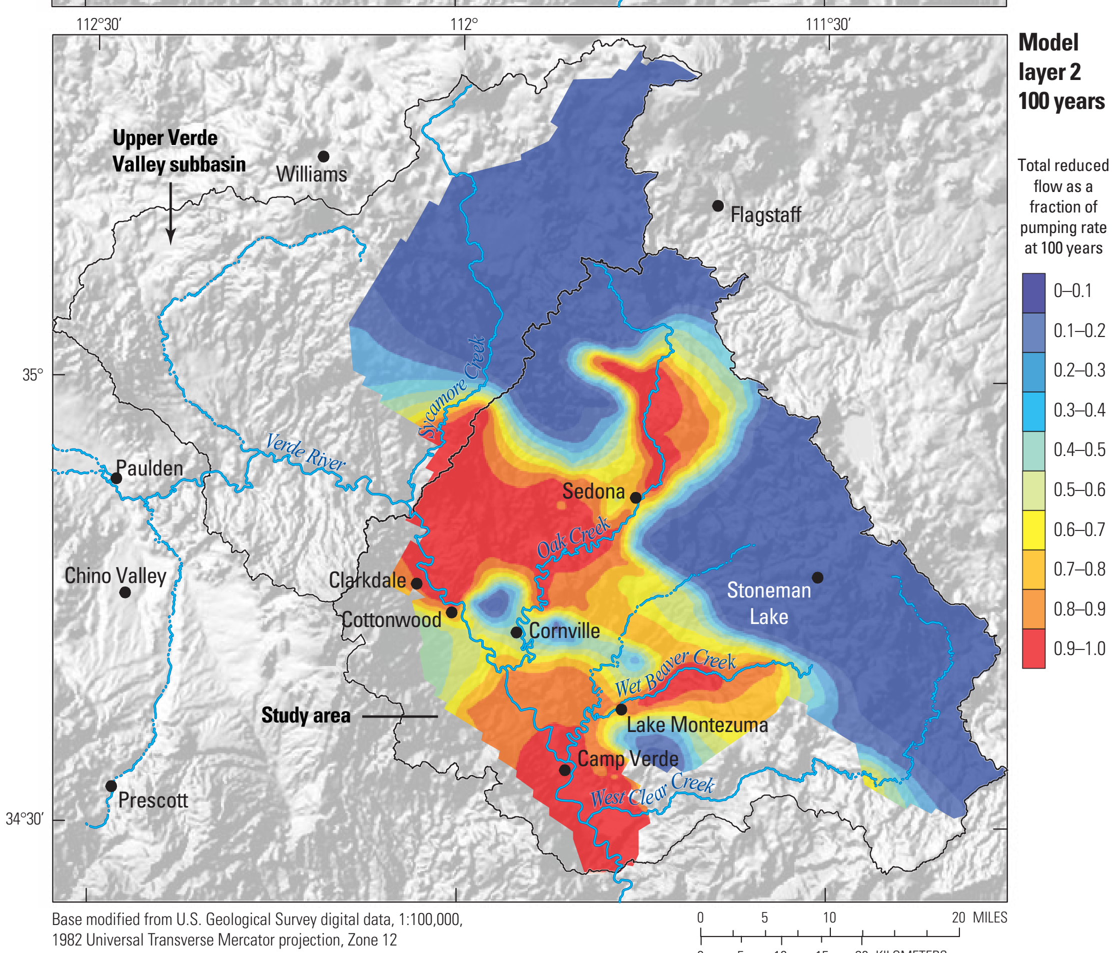
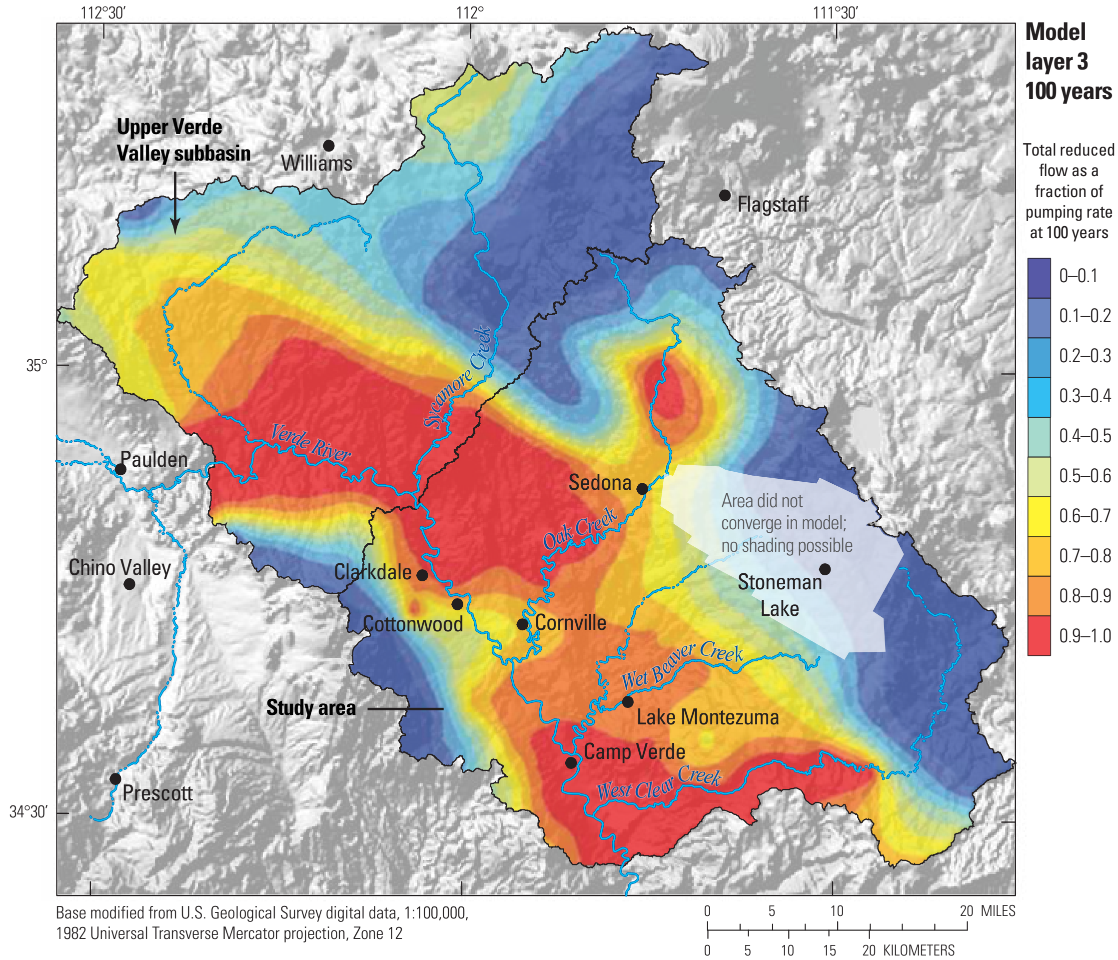


Figure 4.2 Map showing computed reduction in flow of streams and springs and reduction in riparian evapotranspiration as a fraction of pumping rate that would result from pumping groundwater from NARGFM layer 2 at a constant rate for 100 years. The color at any location represents the fraction of the pumping rate by a well at that location that can be attributed to changes in outflow from or inflow to the aquifer.

Figure 4.3. Map showing computed reduction in flow of streams and springs and reduction in riparian evapotranspiration as a fraction of pumping rate that would result from pumping groundwater from NARGFM layer 3 at a constant rate for 100 years. The color at any location represents the fraction of the pumping rate by a well at that location that can be attributed to changes in outflow from or inflow to the aquifer.



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