# SIMULATED GROUNDWATER AND SURFACE WATER CONDITIONS IN THE UPPER SAN PEDRO BASIN 1902-2105

## Preliminary Baseline Results


Task 1 Report for December 2010 Contract

Prepared for

Friends of the San Pedro River

and

The Walton Family Foundation

by

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# EXECUTIVE SUMMARY

This study updated and used the published U.S. Geological Survey (USGS) model by Pool and Dickinson (2007)[1] of the Upper San Pedro Basin (USPB) to simulate groundwater and baseflow conditions in the basin from 1902 to 2105 with no adjustments for climate change, but including the best available pumping and recharge data to date. As part of the model updating process, errors in historic pumping and recharge rates in the USGS model were corrected and the impacts of these changes on the transient model's calibration were evaluated and determined to be negligible. Arizona Department of Commerce (AzDC) population projections for the Sierra Vista sub-basin portion of the model area form the basis for projected pumping rates in the model. Simulated non-mining and non-agricultural pumping rates for 2002-2003 (end of USGS model period) were increased throughout the 21st Century simulation period according to published population growth rate projections. These growth rates were applied to simulated pumping across census county division areas to reflect the spatial distribution of growth anticipated by the AzDC. Projected population growth rates were applied to the latest pumping values within county census block groups to reflect the spatial distribution of growth anticipated by the AzDC. Projected pumping and artificial recharge on Fort Huachuca were based on the most recent Biological Assessment (ENRD, 2006) and input from the Fort's Environment and Natural Resources Division (ENRD) and Public Works staff. In the new simulation period from 2003 to 2105, net pumping (pumping minus incidental recharge) increases by over 10,000 acre-feet per year (AF/yr), recharge remains constant[2] at roughly 22,000 AF/yr, and evapotranspiration (ET) falls from approximately 9,000 to 6,100 AF/yr as a result of declining groundwater levels. By 2105, simulated cumulative storage loss in the model area, including the Mexican portion, exceeds 4.5 million acre-feet (AF).

Results from this projected development model were compared to a corresponding "natural conditions" model (no pumping, incidental recharge, or artificial recharge) in order to quantify simulated development-related hydrologic changes in the basin over the 203-year simulation period. During the 21st Century simulation period, the existing two major simulated cones of depression - one in the Sierra Vista/Fort Huachuca area and another near Cananea, Mexico - intensify and expand, and eventually merge at the 15- to 30-foot (ft.) drawdown contour level. As of October 2000, simulations show pumping-induced hydraulic head declines (drawdowns) across the entire central basin area, with a few localized exceptions. Minor cones of depression in the Tombstone, Bisbee, and Whetstone areas evolve over the 21st Century simulation period,

[1] The USGS model simulated groundwater conditions in the basin from 1902 to 2003.

[2] Artificial recharge at all wastewater treatment facilities is held constant after 2010 in spite of population growth due to uncertainty in future planned alternative uses for treated effluent.

with the Whetstone and Sierra Vista/Fort Huachuca area cones of depression substantially merging by 2050. By October 2100, simulated drawdowns across virtually the entire west side of the San Pedro River in the Sierra Vista sub-basin exceed 60 ft. Simulated drawdowns under the Babocomari River and the central portion of the mainstem of the San Pedro River exceed 40 ft. and 20 ft., respectively, and simulated drawdowns in the Mexican portion of the regional aquifer in the model area exceed 60 ft. by October 2100.

The USGS model simulates baseflow but not total streamflow, which includes storm runoff and bank-storage components. Simulated stream baseflows decline throughout the 203-year simulation period, but most significantly prior to 2000 as a result of increased simulated evapotranspiration (ET) rates starting in the 1940's (Pool and Dickinson, 2007) which were intended to reflect observed changes in riparian vegetation density. Simulated baseflows in the Palominas area drop to zero by October 2000. Simulated baseflow near the Charleston gaging station location falls by 77% in the 20$^{th}$ Century, and by another 10% in the 21$^{st}$ Century, while that near the Tombstone gaging station site declines by 80% and 100% over the 20$^{th}$ and 21$^{st}$ centuries, respectively.

Comparing these results with those of the natural conditions model permits quantification of the portion of baseflow changes attributable solely to the effects of human development, namely pumping, incidental recharge, and artificial recharge. These development-induced changes represent hydrologic "capture." Simulated baseflow capture from 2003 to 2100 occurs primarily in two areas: 1) in the north end of the model on the lower half of the Babocomari River and on the San Pedro River north of Sierra Vista, and 2) on the San Pedro River in Mexico. Pumping accounts for 18 to 36% of total baseflow declines between 1902 and 2100 near the Charleston and Tombstone gaging stations, respectively. Simulated ET accounts for the remaining impacts on baseflow during the 20$^{th}$ Century simulation period, but pumping alone is responsible for all simulated baseflow declines between 2000 and 2100. In general, the simulations predict that much of the San Pedro and Babocomari rivers will cease to have perennial baseflow over the next century as a result of increased groundwater pumping. Of the three long-term USGS stream-gaging station sites on the Upper San Pedro River within the model area (near Palominas, Charleston, and Tombstone), only the Charleston site is predicted to maintain any summer baseflow by the end of the 21$^{st}$ Century.

Ongoing modeling efforts under this contract are anticipated to include modifications to the model structure in the vicinity of the City of Sierra Vista's wastewater treatment facility to reflect observed flow conditions there, as well as simulation of various potential recharge scenarios. Additional refinements to the model will be made on a continuing basis as new data become available.

ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ADWR | Arizona Department of Water Resources |
| AF | acre-feet |
| AF/yr | acre-feet per year |
| AzDC | Arizona Department of Commerce |
| AZWSC | Arizona Water Science Center (part of the USGS) |
| BA | Biological Assessment |
| cu-ft/s | cubic-feet per second |
| ENRD | Environment and Natural Resources Division (Fort Huachuca) |
| EOP | Environmental Operations Facility (City of Sierra Vista) |
| ET | evapotranspiration |
| ft. | feet |
| GWSI | Groundwater Site Inventory |
| U.S. | United States |
| USGS | United States Geological Survey |
| USPB | Upper San Pedro River Basin |
| USPP | Upper San Pedro Partnership |

FORMAT PAGE

# TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

# SIMULATED GROUNDWATER AND SURFACE WATER CONDITIONS IN THE UPPER SAN PEDRO BASIN 1902-2105

## INTRODUCTION

The Upper San Pedro River flows north from the hills near the mining town of Cananea, Mexico into Arizona and is widely recognized as "one of the most important riparian areas in the United States" (BLM, 2011). In 1988, Congress designated a 40-mile reach of the San Pedro River between Mexico and St. David, Arizona as the San Pedro Riparian National Conservation Area[3] in recognition of this vital ecological resource (Figure 1). Population growth in the Upper San Pedro River Basin (USPB) in Arizona has been fueled by abundant groundwater in the regional basin-fill aquifer. For several decades, however, observed declines in stream flows within the USPB measured at the Charleston stream-gaging station (Figure 2) and elsewhere have raised widespread concern over the connection between groundwater pumping and flow rates in the San Pedro River and its tributaries, particularly the Babocomari River. Researchers and regulators have developed several generations of groundwater models to better understand the hydrological systems in the basin, and in particular, the impact of pumping on the river.

The USGS published the most recent calibrated groundwater flow model for the USPB in early 2007 (Pool and Dickinson, 2007). The model area extends from Cananea, Mexico in the south to just below the confluence of the San Pedro and Babocomari rivers in the north (Figure 1). The USGS model incorporated features from several earlier models (Freethey, 1982; Vionnet and Maddock, 1992; Corell, Putman, Lovvik, and Corkhill, 1996; Goode and Maddock, 2000), while adding significant complexity in model structure and extending the boundaries of the model area to include mountain ranges on the east and west of the USPB and the full extent of the USPB watershed in Mexico. The downstream boundary of the model is the USGS stream-gaging station near Tombstone, which marks the northern extent of the Sierra Vista sub-basin. The USGS model also implemented a two-season stress-period pattern to distinguish between summer and winter water use, stream baseflows, and evaporation patterns in the basin. The USGS model incorporates a steady-state calibration to simulate pre-development conditions prior to 1902 and a transient calibration that includes pumping, incidental recharge, and artificial recharge throughout the USPB from 1902 to 2003 (Pool and Dickinson, 2007).

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[3] United States Code TITLE 16 – CONSERVATION; CHAPTER 1 - NATIONAL PARKS, MILITARY PARKS, MONUMENTS, AND SEASHORES; SUBCHAPTER CIX - SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA.

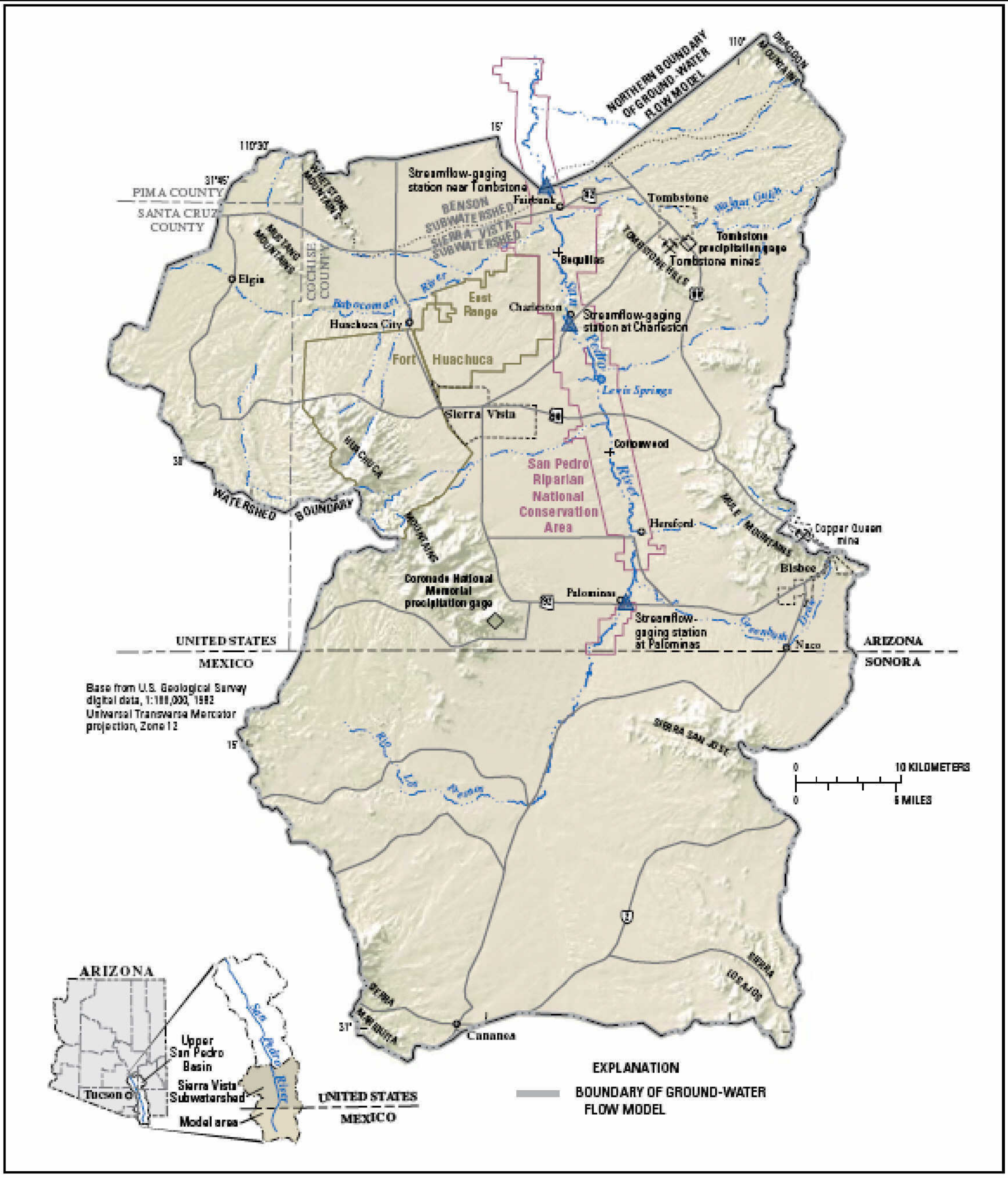


**FIGURE 1. MAP SHOWING THE SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA (SPRNCA) (IN RED) IN RELATIONSHIP TO THE UPPER SAN PEDRO RIVER BASIN GROUNDWATER MODEL AREA (ADAPTED FROM FIGURE 1 IN POOL AND DICKINSON (2007)). THE SPRNCA EXTENDS BEYOND THE NORTHERN BOUNDARY OF THE MODEL AREA.**

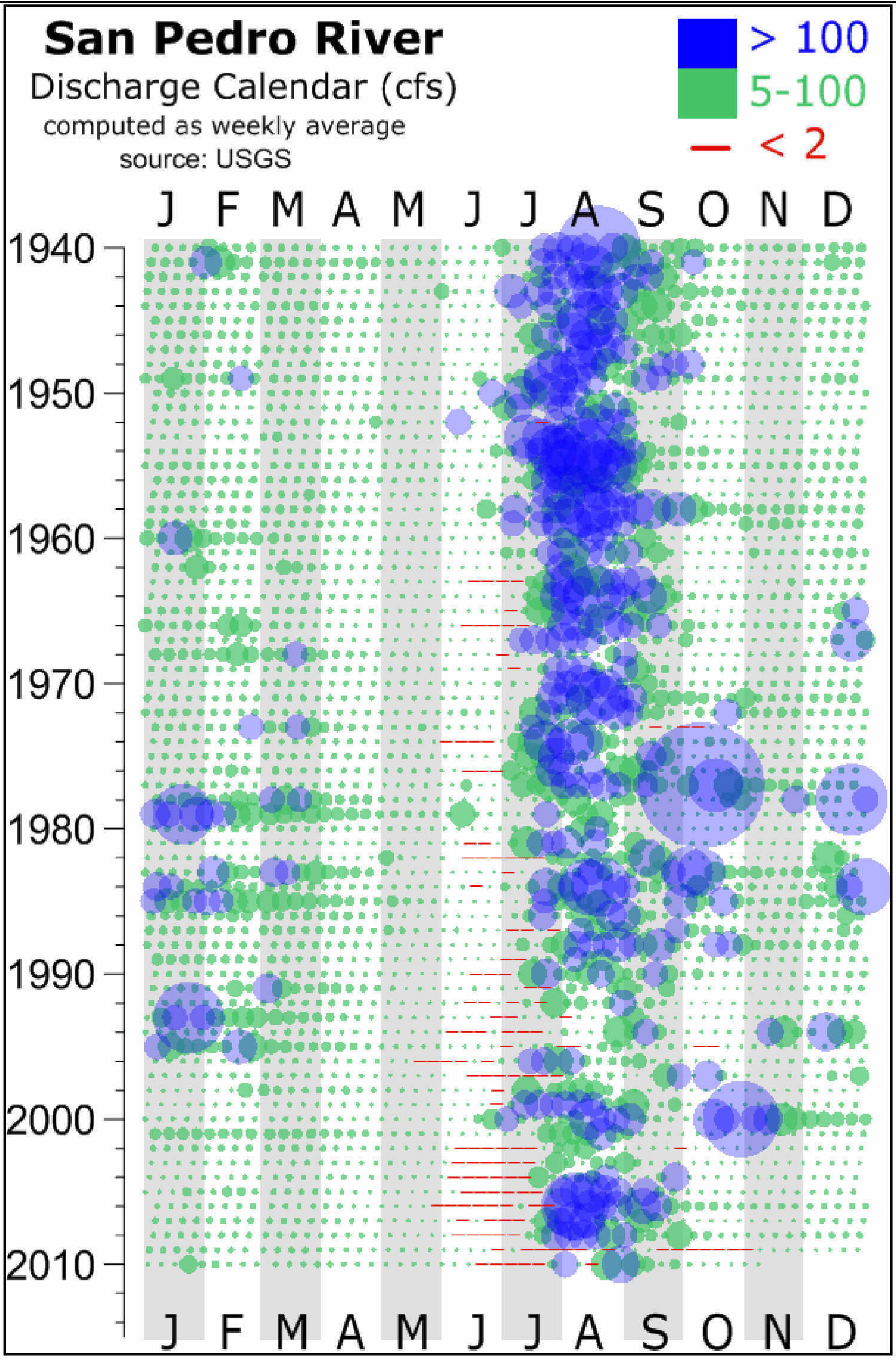


FIGURE 2. MAP OF AVERAGE WEEKLY FLOWS AT THE CHARLESTON STREAM-GAGING STATION FROM 1940-2010. MONTHS ARE ON THE HORIZONTAL AXIS AND YEARS ARE ON THE VERTICAL AXIS. A FLOW RATE FROM EVERY WEEK OF EVERY YEAR IS REPRESENTED BY ONE CIRCLE. CIRCLE SIZES CORRESPOND TO FLOW MAGNITUDES, WITH BLUE CIRCLES REPRESENTING ALL FLOWS EXCEEDING 100 CUBIC-FEET PER SECOND (CFS OR CU-FT/S), GREEN CIRCLES REPRESENTING FLOWS BETWEEN 5 AND 100 CFS, AND RED LINES CORRESPONDING TO FLOWS OF LESS THAN 2 CFS. IMAGE COURTESY OF ROBERT V. SOBCZAK AT [HTTP://WWW.GOHYDROLOGY.ORG/SEARCH?Q=SAN+PEDRO](HTTP://WWW.GOHYDROLOGY.ORG/SEARCH?Q=SAN+PEDRO).

## DESCRIPTION OF MODEL

The USPB groundwater model by Pool and Dickinson (2007) employs the USGS finite-difference numerical model known as MODFLOW-2000 (Harbaugh, Banta, Hill, and McDonald, 2000). Pool and Dickinson (2007) discretized the model area into 440 rows and 320 columns of hydrologic accounting "cells," each of which may gain or lose water during the course of a simulation. In this case, each model cell has a top area of 672,729 square ft. (62,500 square meters). Model cells vary in thickness according to the conceptual model of the geologic layers comprising the aquifer units. When the model simulates a pumping stress, that stress may propagate laterally from the pumping cell to neighboring model cells within the same layer, or vertically to cells in an adjacent layer. The maximum amount of water the model cell can yield in response to a specific pumping stress is controlled by the hydrologic properties assigned to the pumping cell and other cells in hydraulic communication with that cell. Storativity defines how much groundwater can be released from storage per unit volume of aquifer material per unit decline in hydraulic head. Hydraulic conductivity determines the relative rate at which water may be transmitted through a given aquifer material. Both of these parameters, combined with aquifer thickness, determine the model's response to a pumping stress. For example, if a well produces water from a very productive aquifer, groundwater may be easily conducted from distant model cells to the pumping cell, producing a shallow, but broad cone of depression. In contrast, if a well pumps from a very "tight" aquifer unit, aquifer storage in the vicinity of the well may be depleted first to meet the well's demand before the pumping stress propagates through low-conductivity material to adjacent model cells. In that case, a steep, but relatively localized cone of depression will form. In either case, a pumping stress may eventually propagate to a stream (or other boundary source), thereby either inducing leakage from the stream into the aquifer, or decreasing groundwater discharge from the aquifer to the stream. This water is said to have been "captured" from the stream by the pumping well. Likewise, recharge into the aquifer can raise heads and propagate stresses through the aquifer in the opposite sense, thereby either increasing flow to streams or decreasing flow from streams to the aquifer.

The structure of the numerical groundwater model represents the authors' (i.e., Pool and Dickinson, 2007) conceptualization of the hydrogeologic features that make up the USPB. In this case, the model has 5 layers, with layer 5 forming a kind of "bowl" comprising the edges and bottom of the basin, and the other four layers stacked sequentially in the center of the basin from lowest (layer 4) to highest (layer 1) (Figure 3). Layer 5 represents pre-Tertiary bedrock and Tertiary Pantano formation and basin fill "along the margin of the alluvial basin where subsurface data are insufficient to define the base of the alluvium" (Pool and Dickinson, p.19). Layer 4 overlies layer 5 and represents the primary regional aquifer. This layer includes the sand and gravel of the lower basin fill unit in the U.S. portion of the basin and also includes

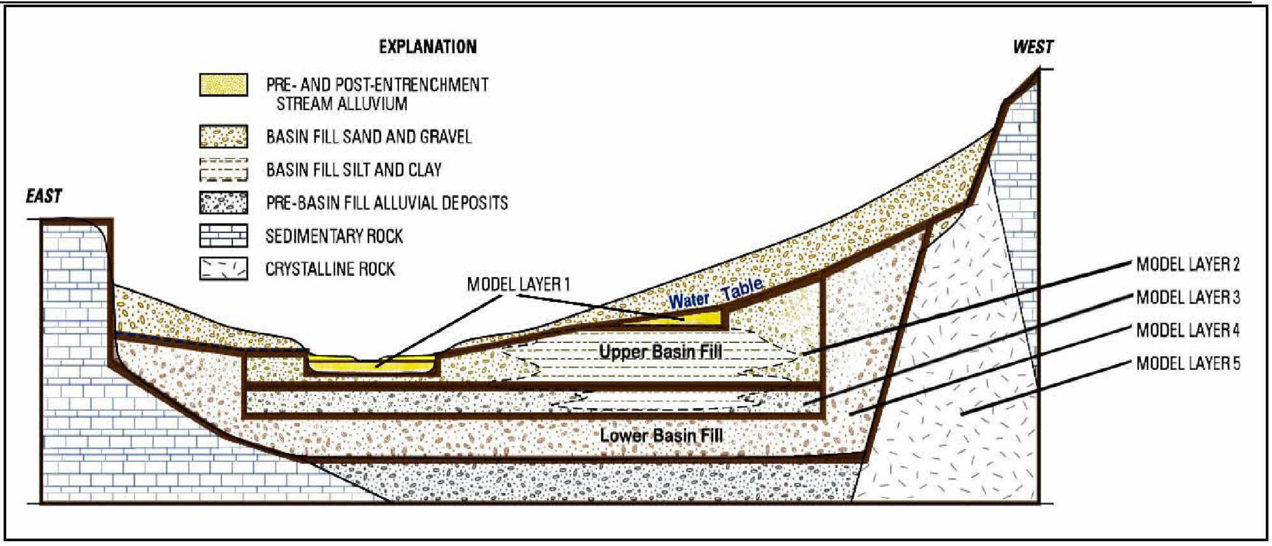


**FIGURE 3. CONCEPTUALIZED CROSS SECTION OF USPB SHOWING MODEL LAYERS (FROM FIGURE 3 IN POOL AND DICKINSON (2007)).**

stream alluvium and silt and clay facies in Mexico. Layers 2 and 3 lie above layer 4 and contain the silt and clay facies of the upper basin fill as well as adjacent interbedded facies and sand and gravel in the U.S. portion of the basin only. Layer 1 overlies layer 2 and includes "stream alluvium and shallow unconfined groundwater in the sand and gravel overlying the silt and clay" in layers 2 and 3 in the Sierra Vista sub-basin (Pool and Dickinson, p.19).[4] Figure 4 illustrates the surface coverage of each of the five model layers.

Pool and Dickinson (2007) calibrated the model to "steady-state"[5] (pre-development) conditions by applying natural basin inputs and outflows (e.g., natural recharge, subsurface flow, baseflow, and evapotranspiration), and adjusting hydraulic conductivity to match the estimated pre-development head condition across the basin. Streamflow in 1940 and groundwater level data from 1940-1960 were used for steady-state calibration purposes based on the assumption that the basin was still in a near-steady-state condition in the early years of pumping (Pool and Dickinson, p. 31).

For the development simulation period of 1902-2003, Pool and Dickinson (2007) applied historic pumping and estimated evapotranspiration to the steady-state model and adjusted aquifer storativity to match historic water level and streamflow records in what is known as transient model calibration. Once a model is well calibrated, simulations may be extended to

[4] Pool and Dickinson (2007, p.19) report that "layers 1, 2, and 3 are not defined in Mexico because of a lack of subsurface information."

[5] Pool and Dickinson (2007) indicate that true steady-state conditions have not existed in the basin and that storage changes have occurred in response to "several types of changes in recharge or discharge since about 1900" (Pool and Dickinson, p.31). Nonetheless, they chose 1902 as the start of the development period.

future time periods, allowing users to predict hydrologic conditions based on a set of pumping and recharge inputs.

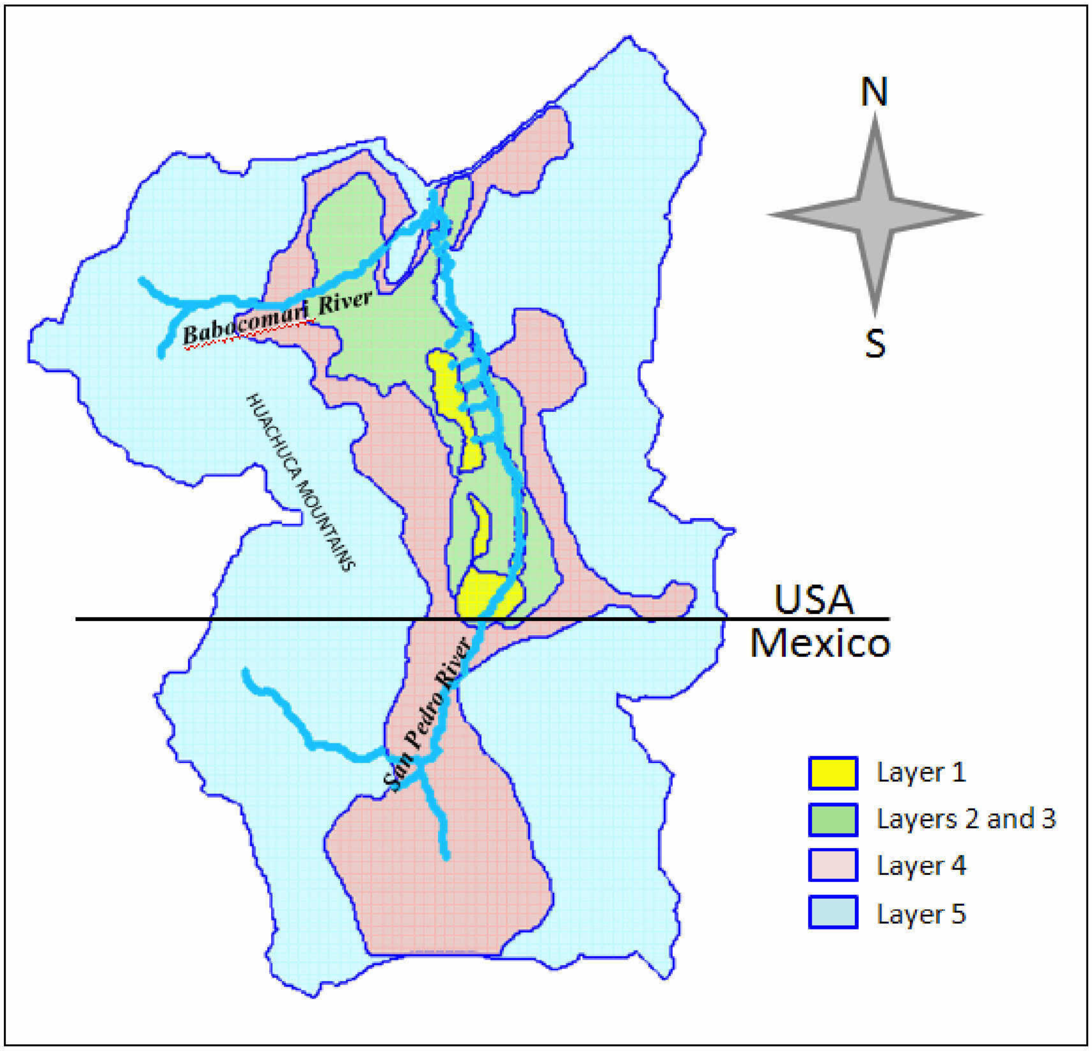


FIGURE 4. USPB MODEL LAYERS IN PLAN VIEW WITH SAN PEDRO RIVER INTERSECTING VARIOUS LAYERS. BLUE LINE REPRESENTS RIVER LOCATION BUT DOES NOT NECESSARILY SIGNIFY PERENNIAL FLOW CONDITION.

## Purpose Of Study

The purpose of this study is to update the USGS model (Pool and Dickinson, 2007) with the most current pumping and recharge data available and to run a "forward" simulation out to the year 2105 using projected pumping, incidental recharge, and artificial rates, but including no adjustments for potential effects of climate change. Pool and Dickinson (2007) ran the transient model up to March 2003. This study updates pumping and recharge values for public water supply companies and some golf courses through 2009. Artificial recharge rates at Fort Huachuca and the City of Sierra Vista were also updated through 2010 and 2009, respectively. Pumping rates for on-post wells at Fort Huachuca were updated through 2010. In addition, some significant errors in the published model – primarily omitted or erroneous pumping and recharge values – were also corrected. A significant modification to the model structure conducted as part of a detailed investigation into recharge at the Sierra Vista Environmental Operations Plant (EOP) for the City of Sierra Vista and the U.S. Bureau of Reclamation by Brown and Caldwell (2009) was not incorporated in this study but will be addressed in a subsequent report.

# METHODS

This study applied standard methods for model review and use as described below. The essential five-step process involved: 1) reviewing the published model report and verifying that the electronic files provided by the authors agreed with the report; 2) verifying that initial simulations (1902-2003) conducted for this study replicated those of the model authors; 3) correcting errors detected in the historic pumping and recharge values, 4) evaluating the effects of those changes on the model calibration, 5) proceeding with the forward simulation using updated and projected pumping and recharge values.

## Model Corrections (1902-2003)

Following a thorough review of the model, corrections to the model focused mainly on errors in recharge and pumping rates. Background natural recharge in the first decade of the simulation period was adjusted to match all subsequent simulation periods. Pumping wells that had inadvertently been omitted were included. Incidental recharge associated with major agricultural pumping wells in the Palominas/Hereford area that had already ceased pumping was removed.[6] Finally, recharge and pumping values at Fort Huachuca were changed to reflect recent data.

## Calibration Check

### Groundwater Levels

The impact of the aforementioned corrections to the USGS model (Pool and Dickinson, 2007) on the model's calibration was tested by comparing plots of computed vs. observed head for the original model and the corrected model. The authors supplied a set of 28 calibration hydrographs (wells with historic water level data) for use in calibrating the transient model. These data were collected primarily from the Arizona Department of Water Resources (ADWR) Groundwater Site Inventory (GWSI) database, with additional data provided from the USGS's GWSI records. Figures 5 and 6 plot computed vs. observed heads for these 28 calibration points

[6] Cessation of recharge applied at the surface does not impact previously recharged water that may continue to infiltrate through the subsurface in future time periods.

in both the original USGS model (Pool and Dickinson, 2007) and after the corrections described above. Figure 5 shows computed vs. observed heads for the simulation period ending on October 15, 1986, while Figure 6 shows the corresponding graph for October 15, 2002. These times were selected as representative of recent periods where pumping and observation data were reasonably abundant. In both cases, the new (corrected) model calibration was essentially unchanged from the original model, so the corrections were considered acceptable without further calibration of the model.

**BASEFLOWS**

Although the corrections to pumping and artificial recharge in the 2007 USGS model were not anticipated to strongly affect simulated baseflows over the 1902-2003 calibration period, Figure 7 illustrates the spatial distribution and quantity of the resulting changes in baseflow for a sample period (October 2000[7]). Changes in baseflow were calculated by:

$$\textit{Corrected Model Baseflow}_{(Oct\ 2000)} - \textit{Original Model Baseflow}_{(Oct\ 2000)}$$

$$= \textit{Change in Baseflow}_{(Oct\ 2000)}$$

Using this equation, baseflows that increased with the model corrections are represented by positive values in Figure 7 and baseflows that decreased with the model corrections are computed as negative values. The largest increase in simulated baseflow change for this simulation period 1902-2003 was 0.17 cubic-feet per second (cu-ft/s), which occurred as an increase in baseflow near the Tombstone gaging station (Figure 7). The largest decrease in simulated baseflow resulting from the model corrections (-0.13 cu-ft/s) occurred near the Palominas gaging station (Figure 7).

While the magnitudes of the changes in baseflow computed by the corrected model are small, their significance must be evaluated in comparison with measured stream flows. Figure 8 graphs mean monthly streamflow for October at the Palominas gaging station on the San Pedro River over the period of record, 1920-2010. Since the 1950's, these flows have hovered near zero. Thus, a -0.13-cu-ft/s change in simulated baseflow may constitute a significant proportion of observed flow at this location. However, simulation results indicate numerical "noise" in the model results occurs over a range of about 0.1 to -0.1 cu-ft/s, which is why these values are attributed a neutral grey color in Figure 7 and other similar figures. Thus, the -0.13 cu-ft/s value is scarcely outside this "noise" range, and is likely insignificant in terms of model calibration.

[7] The model contains two seasons: 1) March 12 to October 15 (spring/summer), and 2) October 15 to March 12 (fall/winter). Thus, October marks the end of the agricultural pumping and high ET season.

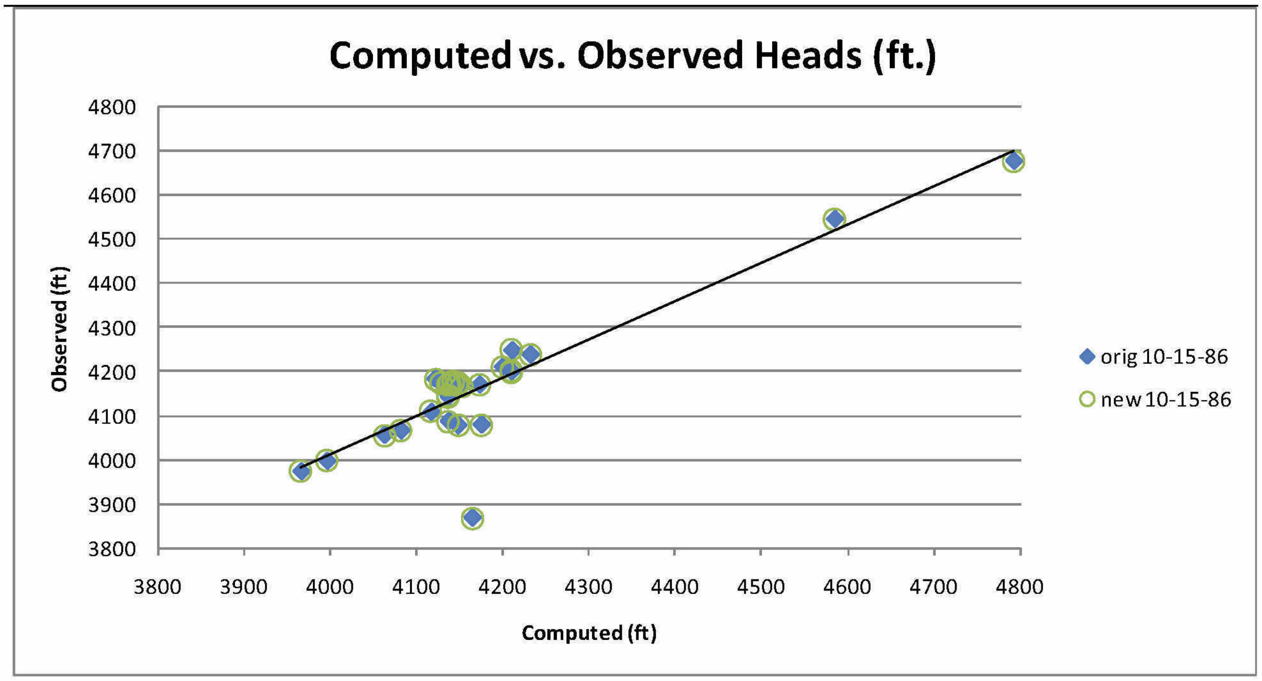


FIGURE 5. COMPUTED VS. OBSERVED HEADS (FT.) FOR OCTOBER 15, 1986 FOR THE ORIGINAL USGS MODEL (POOL AND DICKINSON, 2007) AND AFTER CORRECTIONS TO MODEL.

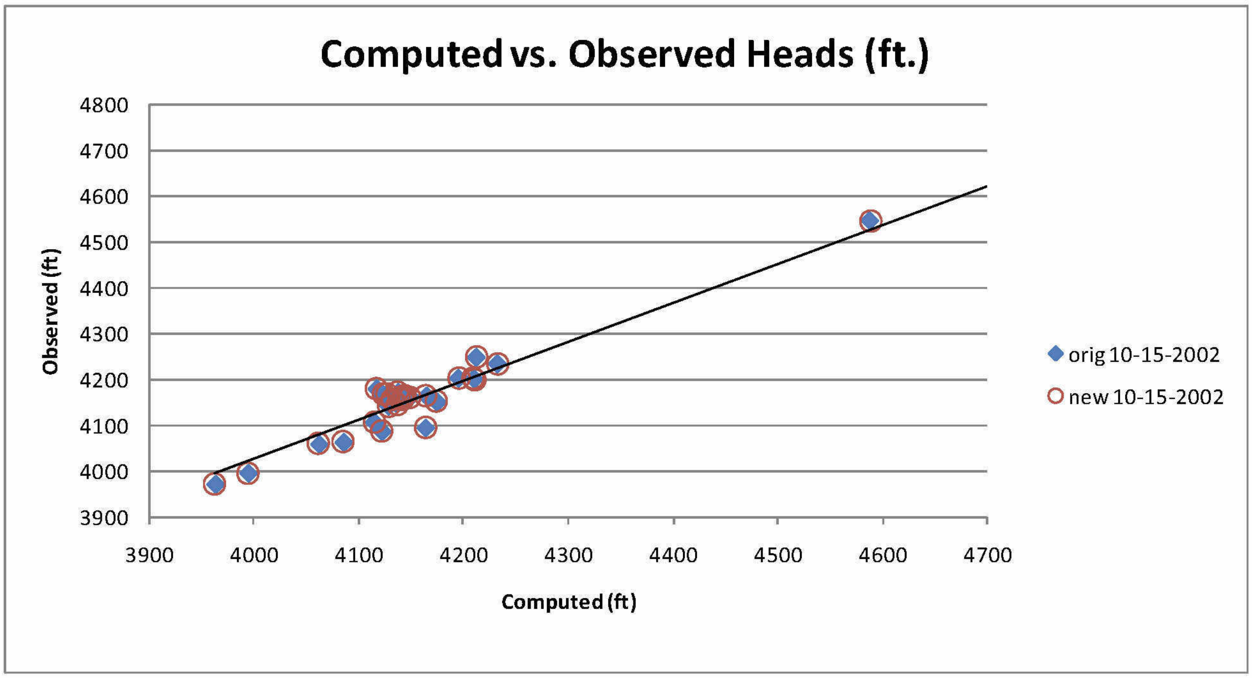


FIGURE 6. COMPUTED VS. OBSERVED HEADS (FT.) FOR OCTOBER 15, 2002 FOR THE ORIGINAL USGS MODEL (POOL AND DICKINSON, 2007) AND AFTER CORRECTIONS TO MODEL.

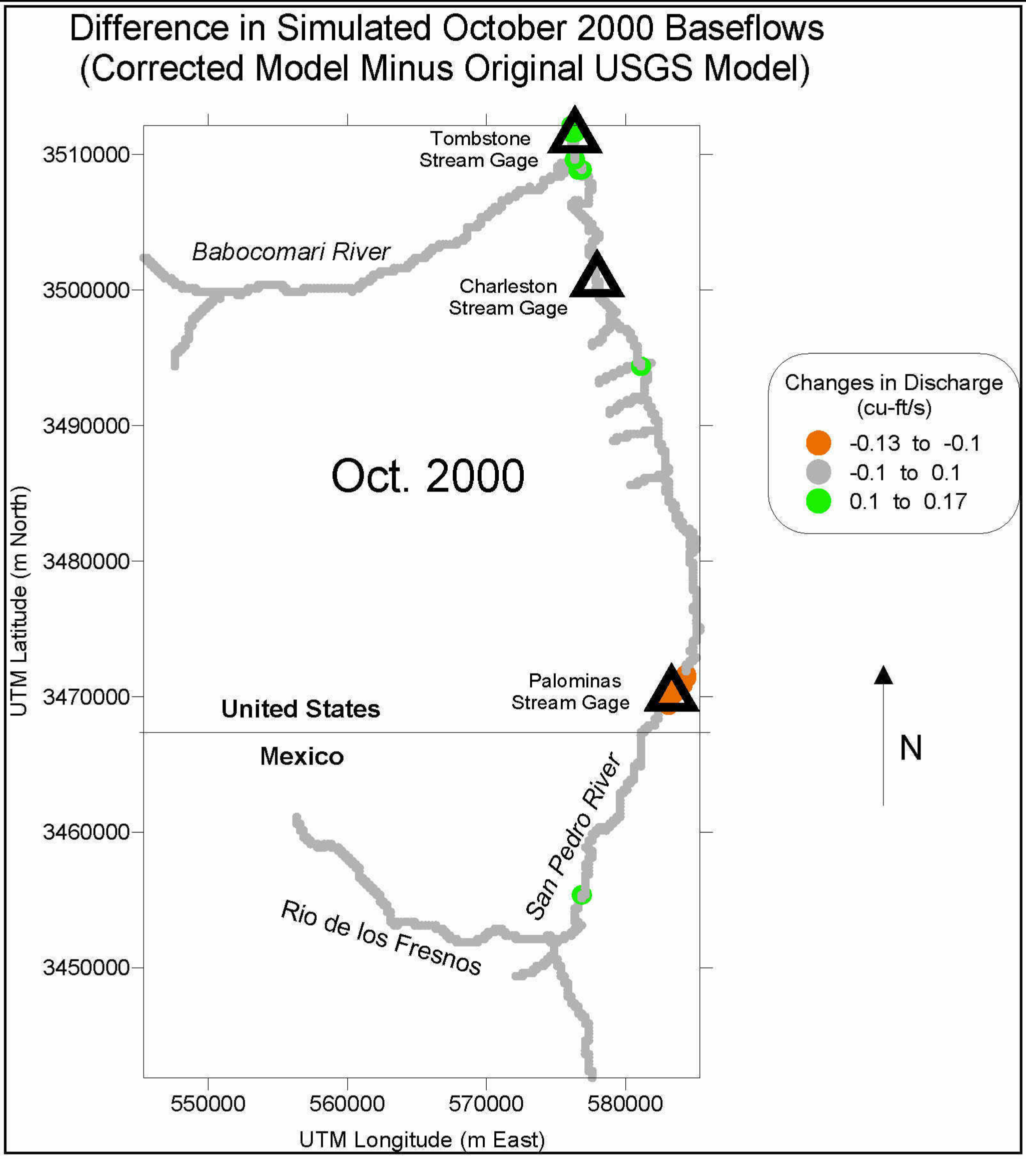


FIGURE 7. DIFFERENCE IN SIMULATED OCTOBER 2000 BASEFLOWS (CU-FT/S) AS COMPUTED BY SUBTRACTING ORIGINAL MODEL VALUES (POOL AND DICKINSON, 2007) FROM CORRECTED USGS MODEL VALUES. NEGATIVE CHANGE IN DISCHARGE VALUES INDICATES LOWER FLOWS AFTER MODEL CORRECTIONS; POSITIVE CHANGE IN DISCHARGE VALUES REPRESENTS HIGHER FLOWS AFTER CORRECTION.

Figure 9 plots mean October streamflow on the San Pedro River measured at the Tombstone gaging station from 1967 to 2008. Here, "low flows" (a subjective classification) appear to fluctuate between 0 and 12 cu-ft/s. Considering the large variability in natural low flows[8], the 0.17-cu-ft/s change in baseflow simulated by the corrected model is negligible. This analysis suggests that the corrected model replicates the 2007 model's baseflows within reason and does not merit recalibration to match the original model.

[8] True baseflow, defined as the portion of streamflow derived from groundwater, generally cannot be directly observed from streamflow data because of the unknown contributions of bank storage.

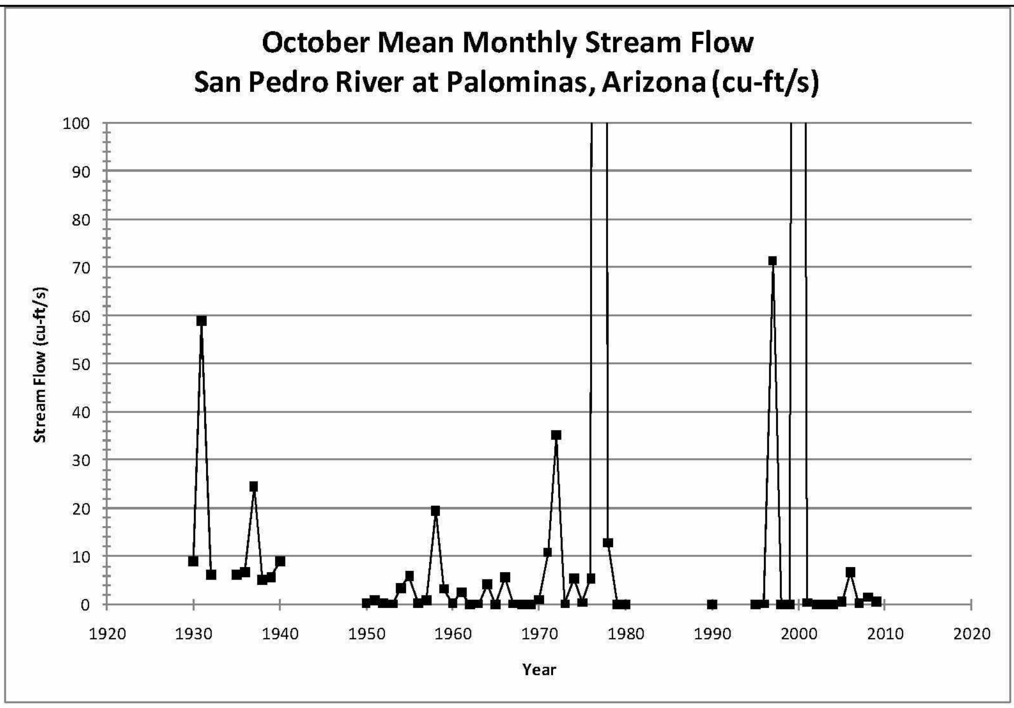


FIGURE 8. MEAN OCTOBER STREAM FLOW (CU-FT/S) MEASURED ON THE SAN PEDRO RIVER AT THE PALOMINAS GAGING STATION FOR THE PERIOD OF RECORD, 1920-2010 (USGS, 2011). VERTICAL AXIS IS TRUNCATED AT 100 CU-FT/S TO HIGHLIGHT LOW FLOWS.[9]

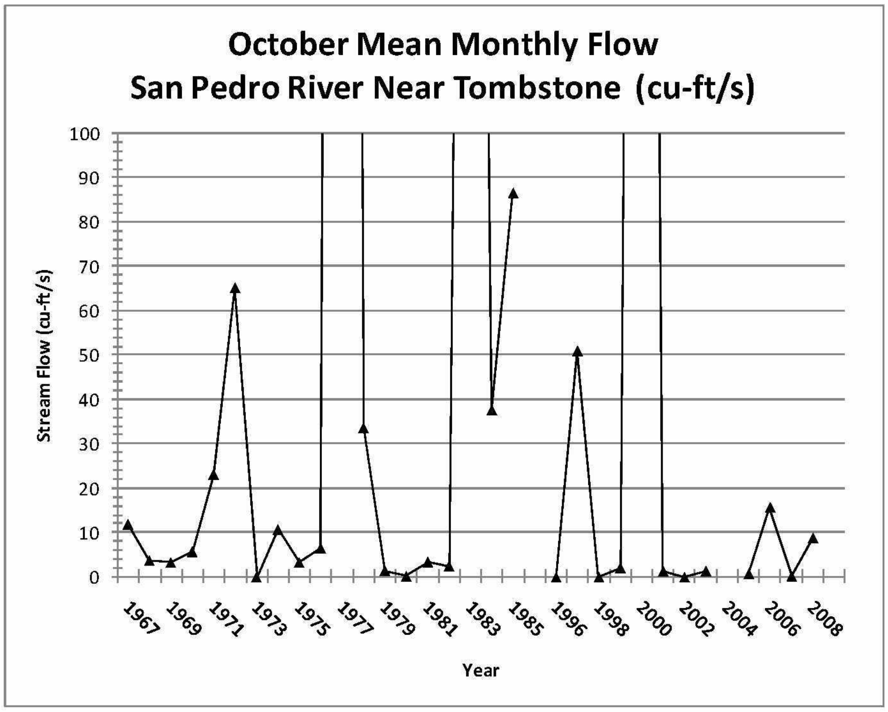


FIGURE 9. MEAN OCTOBER STREAM FLOW (CU-FT/S) ON THE SAN PEDRO RIVER MEASURED AT THE TOMBSTONE GAGING STATION FOR THE PERIOD OF RECORD, 1967-2008 (USGS, 2011). VERTICAL AXIS IS TRUNCATED AT 100 CU-FT/S TO HIGHLIGHT LOW FLOWS.[7]

[9] Missing data in Figures 8 and 9 reflect inoperable gaging stations at those times.

## UPDATES TO MODEL

### PUMPING (2003-2010)

For the purpose of projecting pumping rates into the future, simulated pumping from 2003-2105 is partitioned into seven water use sectors based on those in the original USGS model (Pool & Dickinson, 2007):

1) Public Supply – (U.S. only) municipal and other water company wells; includes municipal irrigation such as parks and golf courses;
2) Unincorporated – (U.S. only) non-public-supply wells; includes domestic, light industrial (e.g., sand & gravel), and commercial uses (e.g., wineries and ranches);
3) U.S. Agriculture – includes agricultural irrigation and incidental recharge in the U.S. portion of the model area;
4) U.S. Mining – includes mining-related pumping near Bisbee, AZ;[10]
5) Mexico Agriculture – agricultural irrigation and incidental recharge in the Mexican portion of the model area;
6) Mexico Mining - includes agricultural irrigation and incidental recharge in the Mexican portion of the model area;
7) Fort Huachuca – on-post pumping and incidental recharge.

Note that simulated pumping in Mexico includes no municipal or domestic pumping categories, in keeping with the USGS model by Pool and Dickinson (2007). Figure 10 presents simulated pumping rates by sector for the entire model area from 2002 to 2105.

The USGS Arizona Water Science Center (AZWSC) in Tucson provided pumping data for the period 2003 through 2009 for public water supply systems in the Sierra Vista sub-basin (B. Gungle – USGS AZWSC, email comm., 2011). These data were originally developed for the Upper San Pedro Partnership's (USPP) annual report to Congress on the basin's progress toward sustainable yield, as mandated by Public Law 108-136, Section 321. The data represent the USGS's best estimate of actual pumping, rather than quantities delivered, as is often reported by water companies. The USGS derived these data directly from the water producers or from the Arizona Corporation Commission files, where water companies must report their annual production, and made corrections for transmission losses, where applicable (S. Tadayon-USGS AZWSC, personal comm., Feb. 2011). Where possible, the data provided by USGS were compared with those available from ADWR's water resources database and with data provided from the Sierra Vista Public Works Department (Brown and Caldwell, 2009) and Fort

[10] Mining-related recharge is simulated as recharge applied at the ground surface rather than as "incidental recharge" which percolates from excess irrigation or septic tank seepage and is simulated via injection wells.

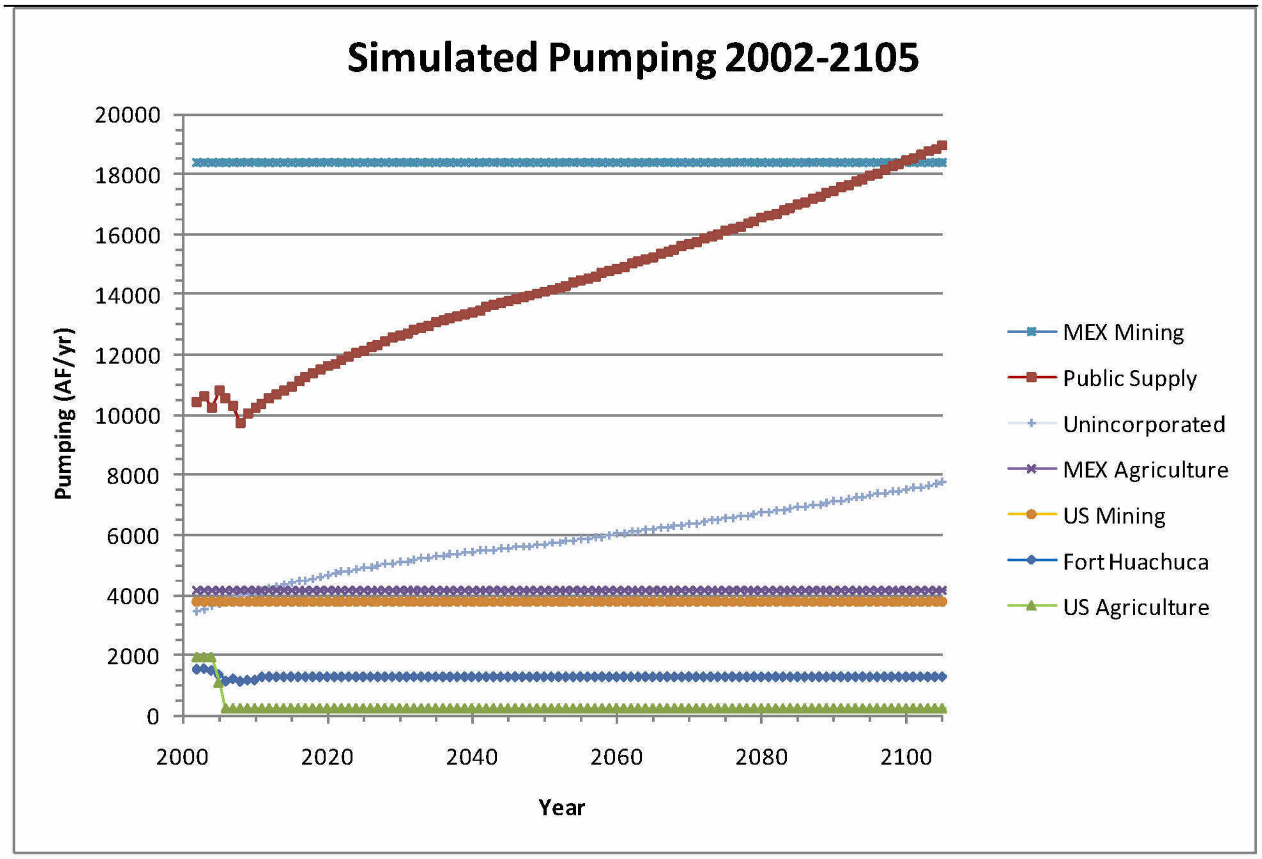


FIGURE 10. SIMULATED PUMPING RATES (AF/YR) FOR 2002-2105 PARTITIONED BY TYPE OF USE AND COUNTRY.

Huachuca's ENRD. Discrepancies among the various sources usually resulted from reporting of quantities of water sold as opposed to quantities pumped (S. Tadayon, personal comm., Feb. 2011). Pumping data from the Fort's ENRD were provided through December 2010 (T. Runyon-ENRD, personal comm., 2011).

Projected pumping rates in the Arizona portion of the model area (Sierra Vista sub-basin) for 2011-2105 were developed by applying projected growth rates to the most recent pumping rates for public water supply and private domestic wells outside of Fort Huachuca. Appendix A provides a detailed explanation of the method used for developing projected pumping rates for areas outside Fort Huachuca. Projected pumping on Fort Huachuca was held constant at 1300 AF/yr from 2011-2105, consistent with projections in the most recent BA for the Fort (ENRD, 2006). Appendix B provides details on the method used for distributing projected seasonal pumping among the active wells on post.

No updated pumping data were available for the portion of the USPB in Mexico, so all projected pumping rates for that area were held constant at 2002-2003 rates in lieu of additional information. A separate simulation explores the impact of the cessation of mine pumping in both Mexico and the Arizona portion of the USPB after 2050 (see "Effects of Mine Pumping" on p.46). Pumping rates for the Pueblo del Sol and Turquoise Valley golf courses were updated through 2009 (B. Gungle, email comm., 2011), and projected rates for these sites were held constant at 2009 rates from 2010-2105. Pumping at U.S. mines and other industrial sites was held constant at 2002-2003 rates (or the most recent non-zero rates) for the period 2003-2105 in lieu of additional information. Simulated pumping from the three Miller irrigation wells in the Palominas area ceased after 2004 (USPP, 2009), and all other agricultural pumping was held constant at 2002-2003 levels throughout the 21$^{st}$ Century. Figure 11 and Figure 12 illustrate the distribution of simulated pumping in the USPB by type of water use as of 2003 and 2105, respectively. In keeping with the plots in Figure 10, the "Public Supply" and "Unincorporated" water use sectors increase significantly over the new simulation period 2003-2105, while simulated U.S. agricultural pumping drops from 4% to 1% of basin-wide pumping during the same period.

**Artificial Recharge**

The USGS AZWSC provided artificial recharge values as reported by the City of Sierra Vista's Public Works Department for the City's Environmental Operations Plant (EOP) for the period 2003-2009 (Table 1) (B. Gungle, email comm., 2011) as part of the Section 321 reporting requirement described above. Fort Huachuca's ENRD provided data for their recharge basins through 2010 (see Table B.5 in Appendix B) (T. Runyon, email comm., 2011).

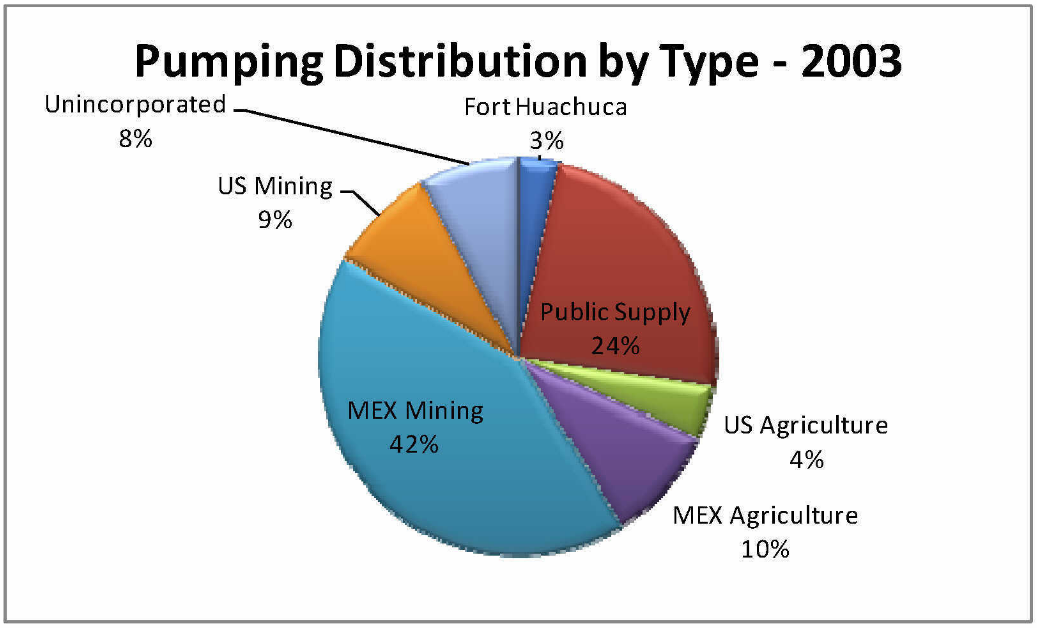


FIGURE 11. DISTRIBUTION OF SIMULATED PUMPING IN THE USPB BY TYPE AS OF MARCH 2003.

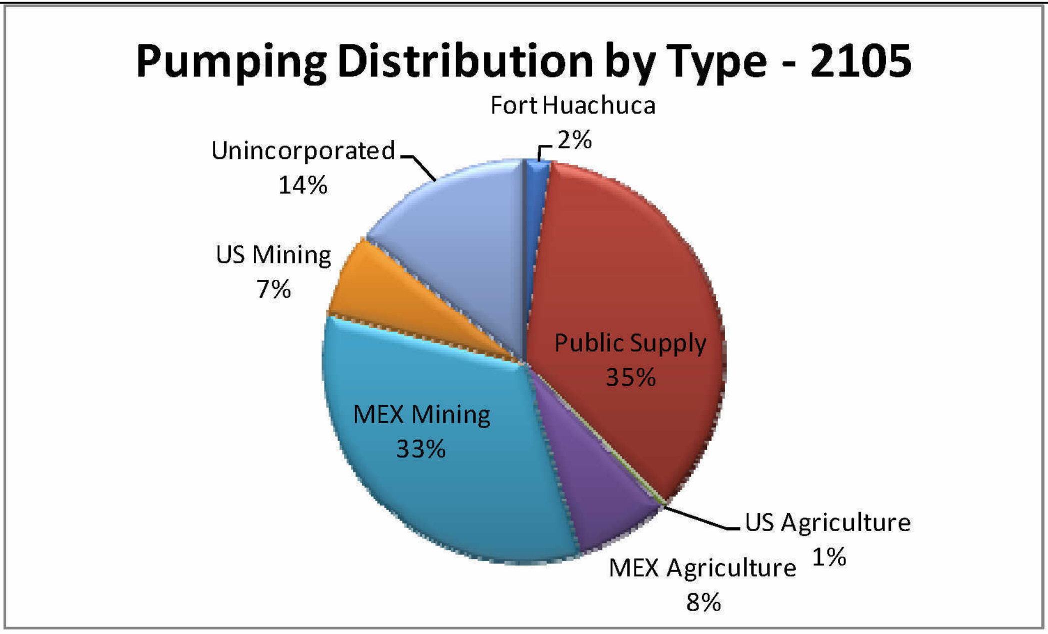


FIGURE 12. DISTRIBUTION OF SIMULATED PUMPING IN THE USPB BY TYPE AS OF MARCH 2105.

TABLE 1. ANNUAL SIMULATED RECHARGE (AF) FOR THE CITY OF SIERRA VISTA'S ENVIRONMENTAL OPERATIONS PLANT (2002-2009).

| Year | Recharge Through Rapid Infiltration Basins (AF) | Incidental Recharge Through Wetland Cells (AF) | Total Recharge (AF) | Total Recharge (MGD) |
|---|---|---|---|---|
| 2003 | 1750 | 700 | 2450 | 2.2 |
| 2004 | 1870 | 700 | 2570 | 2.3 |
| 2005 | 1945 | 700 | 2645 | 2.4 |
| 2006 | 2230 | 700 | 2930 | 2.6 |
| 2007 | 1976 | 700 | 2676 | 2.4 |
| 2008 | 1881 | 800 | 2681 | 2.4 |
| 2009 | 2237 | 350 | 2587 | 2.3 |
| AF = acre-feet (325,821 gallons) | | | | |
| MGD = million gallons per day | | | | |

Projected artificial recharge at the EOP was held constant at 2009 rates on the assumption that even though total water use will be increasing over time, effluent recharge may not increase at the same rate as pumping if the City of Sierra Vista makes greater use of treated effluent for irrigation. Under its agreement with the U.S. Bureau of Reclamation, the City of Sierra Vista agrees to maintain recharge at its present wastewater treatment facility (the EOP) at an annual rate of up to 4,000 AF (3.6 MGD) through 2022 (BOR, 2000), after which time the City has indicated that it plans to divert up to 4.7 MGD from the current plant to other new treatment plants to produce high-quality treated effluent for irrigation (PACE, 2008).[11] Projected recharge at the Fort Huachuca recharge basins was maintained at a constant percentage of pumping based on the observed relationship between pumping and artificial recharge during the period 2003-2010 (see Appendix B). However, since the Fort is planning to divert and treat effluent from Huachuca City starting in 2013 (T. Runyon, personal comm., 2010), 200 AF/yr of simulated recharge was transferred from the Huachuca City area to the Fort's basins starting in that simulation year. Appendix B provides a detailed description of the development of estimated recharge rates for Fort Huachuca's recharge basins from 2011-2105. All other artificial recharge rates (e.g., Bisbee, Tombstone) were held constant in lieu of additional data. Simulated recharge from septic tank seepage (referred to as incidental recharge) increased proportionately (at 14% of pumping (Pool and Dickinson (2007)) with projected unincorporated well pumping.

## RESULTS

Transient model simulations of the USPB from 1902-2105 (incorporating effects of human development) include inputs in the form of historic and projected pumping, estimated maximum evapotranspiration rate (ET), and estimated recharge (natural, incidental, and artificial). Model outputs include simulated groundwater levels (heads) within the basin, simulated stream baseflows[12], simulated ET, and water budgets that describe the flow of groundwater from one hydrologic model component to another (e.g., baseflow to/from aquifer; pumping into/out of aquifer, etc.). Figure 13 illustrates the major components of the simulated water budget for the period 1902-2105: annual net pumping[13], stream baseflow[14], ET, and total (natural plus incidental and artificial) recharge. Simulated baseflow declines from a basin-wide total of over 9,000 AF/yr prior to 1940 to roughly 1,400 AF/yr in 2105, with the sharpest drop in flows occurring between 1940 and 1980. The first simulated pumping in the basin occurs in the mines at Tombstone and Bisbee in the first decade of the 20$^{th}$ Century. Agricultural pumping in the Palominas/Hereford area began as early as 1930, but pumping increased significantly after 1940 when centrifugal electric pumps became more widely available. Pumping reached an historic peak around 2004 before dropping off slightly as some

[11] Future model simulations will likely incorporate the City's planned redistribution of pumping and recharge as described in their 2008 amended discharge application to ADWR (PACE, 2008).

[12] While most estimates of baseflow based on streamflow measurements include some component of bank storage, simulated baseflow is the portion of streamflow that derives solely from groundwater and does not include any storm runoff or bank storage.

[13] Net pumping is pumping (extraction) minus incidental recharge.

[14] In this case, the simulated baseflow values include flows in five small tributaries on the west side of the San Pedro River between Charleston and Hereford (Figure 7), as well as the Rio de los Fresnos in Mexico, but are dominated by flows in the main-stem portions of the Babocomari and San Pedro rivers.

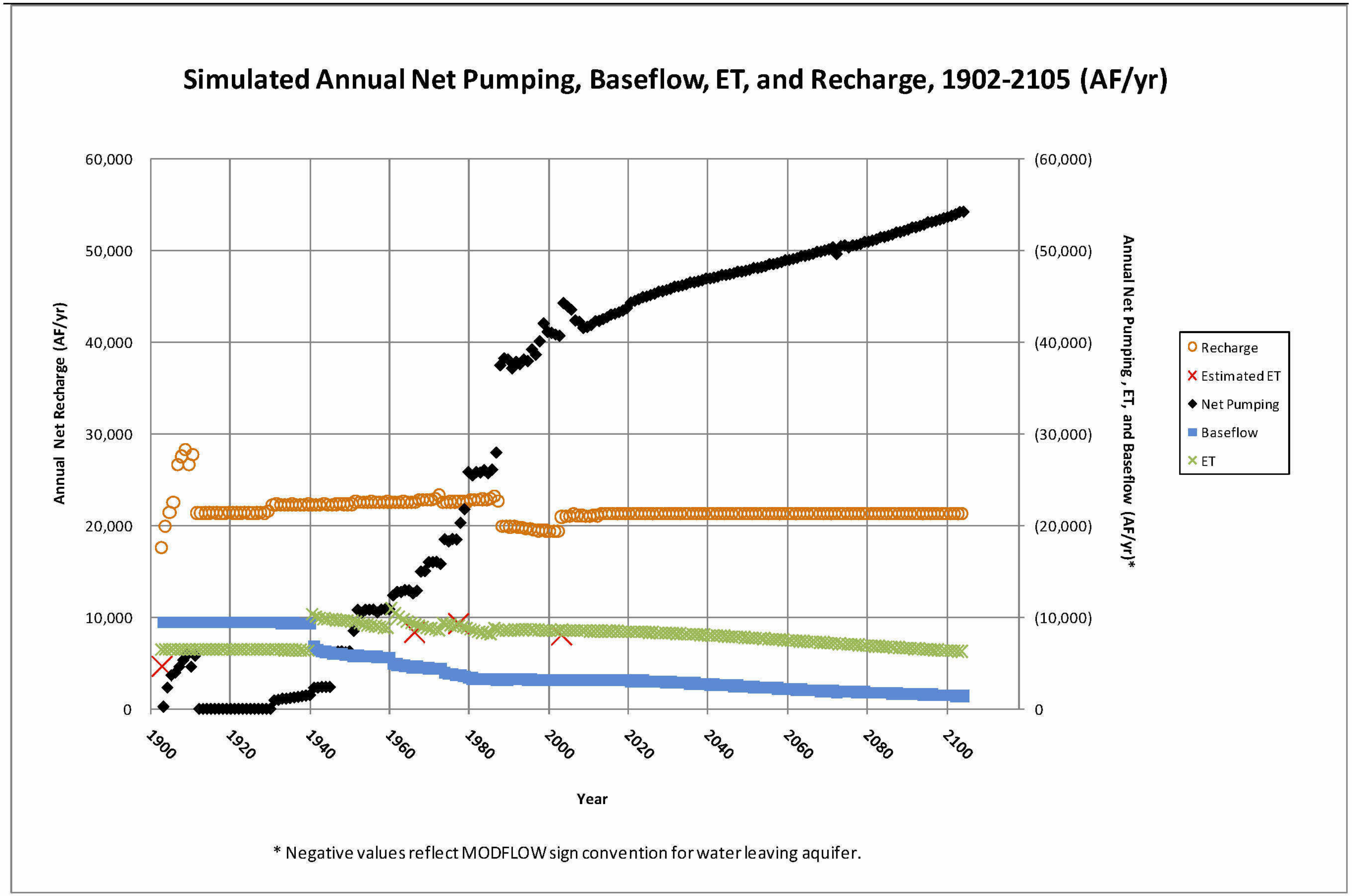


FIGURE 13. MAJOR COMPONENTS OF SIMULATED WATER BUDGET FOR 1902-2105: NET PUMPING, BASEFLOW, ET, AND RECHARGE (AF/YR).

agricultural wells were retired. Simulated projected non-mining and non-agricultural pumping increased from 2010 to 2105 according to population growth projections (see Appendix A).

Pool and Dickinson (2007) adjusted maximum ET rates upward through a series of "steps" to reflect a pronounced increase in observed riparian vegetation density associated with changes in stream morphology starting around 1940.[15] While maximum ET rates were held constant from 2003 to 2105, simulated ET rates start to drop off significantly starting in about 2020 as a result of declining groundwater levels in riparian areas. Such a dropoff could signify an important phase-shift in riparian ecology as shallow groundwater becomes less available to riparian vegetation. On the other hand, this effect does not account for the anticipated natural senescence of mature riparian forest anticipated by Stromberg, Tlucek, Hazelton, and Ajami (2010), which may reduce future ET demand and lessen the rate of water level decline in the vicinity of the San Pedro River and its tributaries.

Simulated recharge reached a peak prior to 1912 reflecting early dewatering of the Copper Queen Mine near Bisbee (Pool and Dickinson, 2007, p.14). Incidental recharge[16] decreased in the mid-1980's as a result of the discontinuation of some agricultural pumping in the Palominas/Hereford area, but then increased starting in 2001 when Sierra Vista began discharging its treated effluent to a recharge facility (Pool and Dickinson, p.14). Artificial (excluding incidental) and natural recharge were held constant throughout the simulation period of 2010-2105.

### CAPTURE

In order to gain insight into the impacts of human development, as defined by pumping, incidental recharge, and artificial recharge, on various components of the basin-wide water budget, results from the transient simulations described in this study were compared with a "natural conditions" simulation for the same time period. "Natural conditions" means that the model is identical to the projected development model described above except that it contains no pumping, incidental recharge, or artificial recharge inputs. The natural conditions model does include time-varying changes in ET between 1902 and 2003, as specified in the original USGS model (Pool and Dickinson, 2007). This natural conditions model provides a baseline from which to evaluate simulated hydrological effects associated with human development in the basin.

Figure 14 shows simulated cumulative baseflow (i.e., all streams' annual flow added up over time) for the simulation period 1902-2105. The black (top) curve represents simulation results

[15] Reichardt, Schladweiler, and Stelling (1978) report a 100% increase in total dense riparian land along the San Pedro River in the United States from 1935 to 1978.
[16] Incidental recharge refers to seepage from septic systems and excess irrigation.

for natural conditions in the absence of human development, and the red (bottom) curve shows a diminished baseflow value resulting from pumping associated with human

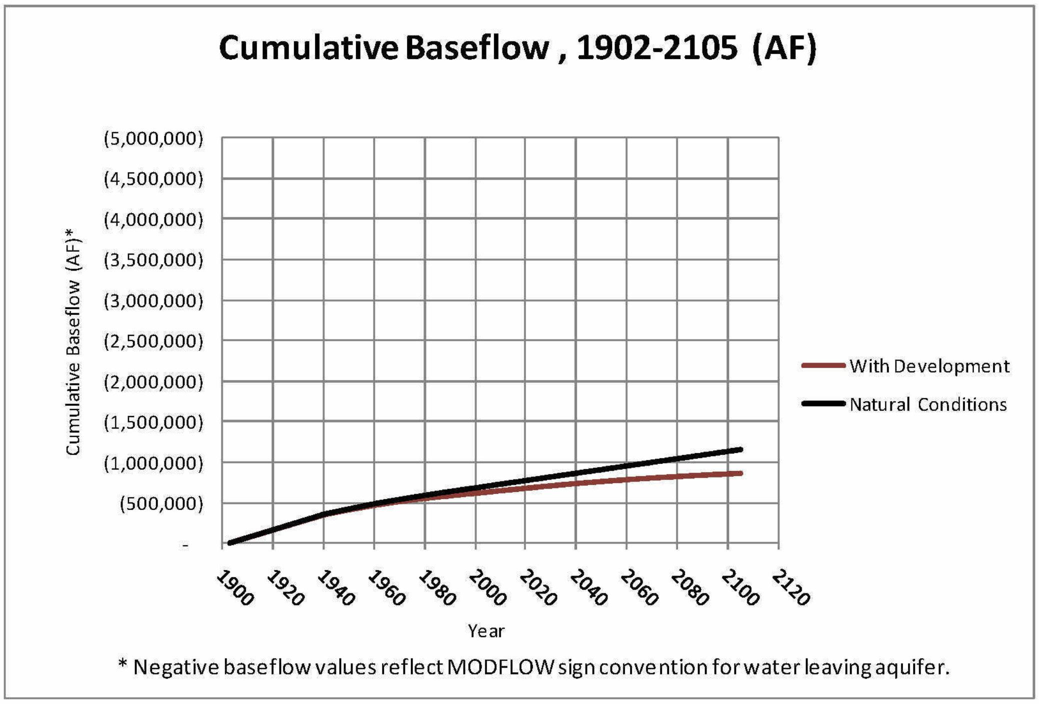


**FIGURE 14. SIMULATED CUMULATIVE BASIN-WIDE BASEFLOW (AF) FOR THE PERIOD 1902-2105. THE RED CURVE INCLUDES PUMPING, ARTIFICIAL, AND INCIDENTAL RECHARGE WHILE THE BLACK CURVE REPRESENTS NATURAL CONDITIONS IN THE ABSENCE OF HUMAN DEVELOPMENT.**

development. Both curves show a decrease in slope (inflection) around 1940 as a result of an abrupt change in simulated ET, as described above and illustrated in Figure 13. The curves begin to diverge significantly in the 1970's, indicating that significant pumping-induced impacts to the streams had already occurred by that time. By 2105, the gap between simulated cumulative baseflow with and without human development is roughly 277,000 AF. This value represents the total baseflow captured by pumping from all streams in the basin for the 203-year simulation period.

Figure 15 compares simulated cumulative aquifer storage loss with and without human development for the period 1902-2105. The "With Development" curve departs sharply from the "Natural Conditions" (zero storage loss) curve starting around 1980, indicating a significant shift toward more storage depletion and less stream and ET capture, which supplied more of the groundwater demand in the earlier decades.[17] By the end of the simulation period in March 2105, approximately 4.5 million AF of storage had been extracted from the aquifer in the

[17] The earliest pumping in the model occurs at the Tombstone and Bisbee Mines as well as along the San Pedro River in the Palominas-Hereford area.

"With Development" scenario. For reference, the March 2011 value for simulated storage depletion is 0.92 MAF.

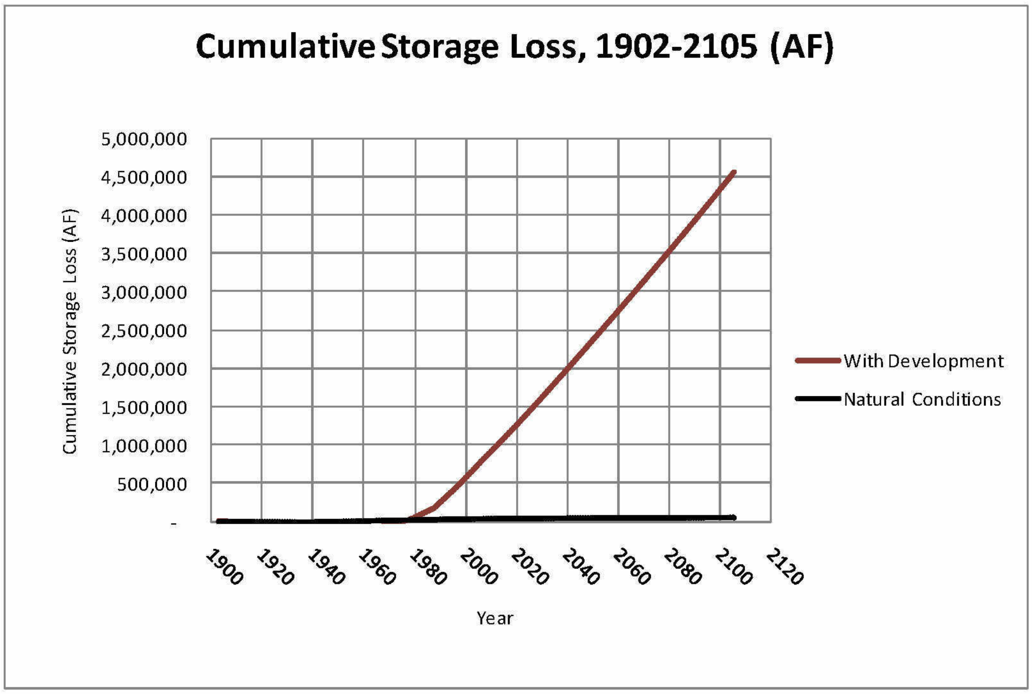


FIGURE 15. SIMULATED CUMULATIVE AQUIFER STORAGE (AF) LOSS WITH AND WITHOUT HUMAN DEVELOPMENT FOR THE SIMULATION PERIOD 1902-2105.

Figure 16 plots simulated ET with (red line) and without (black line) human development over the simulation period 1902-2105. Significant simulated ET capture (difference between development and natural conditions simulations) due to pumping begins in about 1970 and increasing steadily throughout the remainder of the simulation period, to a maximum of roughly 559,000 AF by 2105.

Simulated recharge to the basin's groundwater system increases with human development as a result of the application of mine dewatering water to the surface for irrigation, excess agricultural and turf irrigation, and artificial recharge through basins. Figure 17 shows simulated cumulative recharge with and without human development for the period 1902-2105. These two curves diverge immediately as a result of the large amount of simulated artificial recharge in the first decade of the simulation period associated with the Copper Queen Mine dewatering water which was applied to surface irrigation (Pool and Dickinson, 2007). Incidental recharge from agricultural and turf irrigation became significant in mid-century, while artificial basin recharge only began after the year 2000. The total simulated recharge associated with human development is roughly 896,000 AF over the 203-year simulation period.

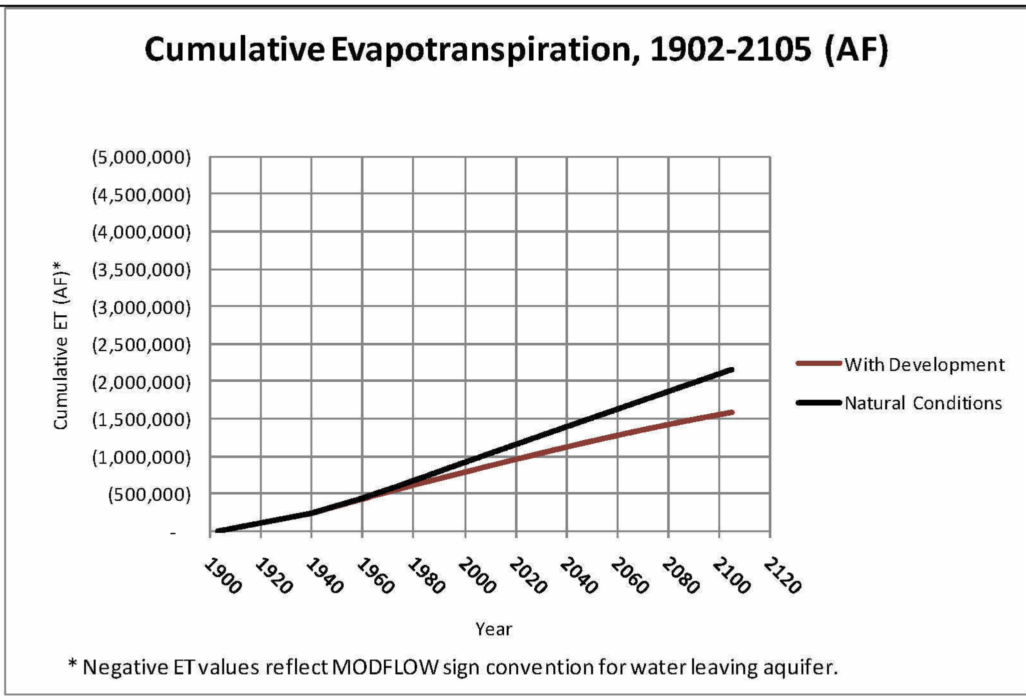


**FIGURE 16. SIMULATED CUMULATIVE EVAPOTRANSPIRATION (AF) WITH AND WITHOUT HUMAN DEVELOPMENT FOR THE PERIOD 1902-2105.**

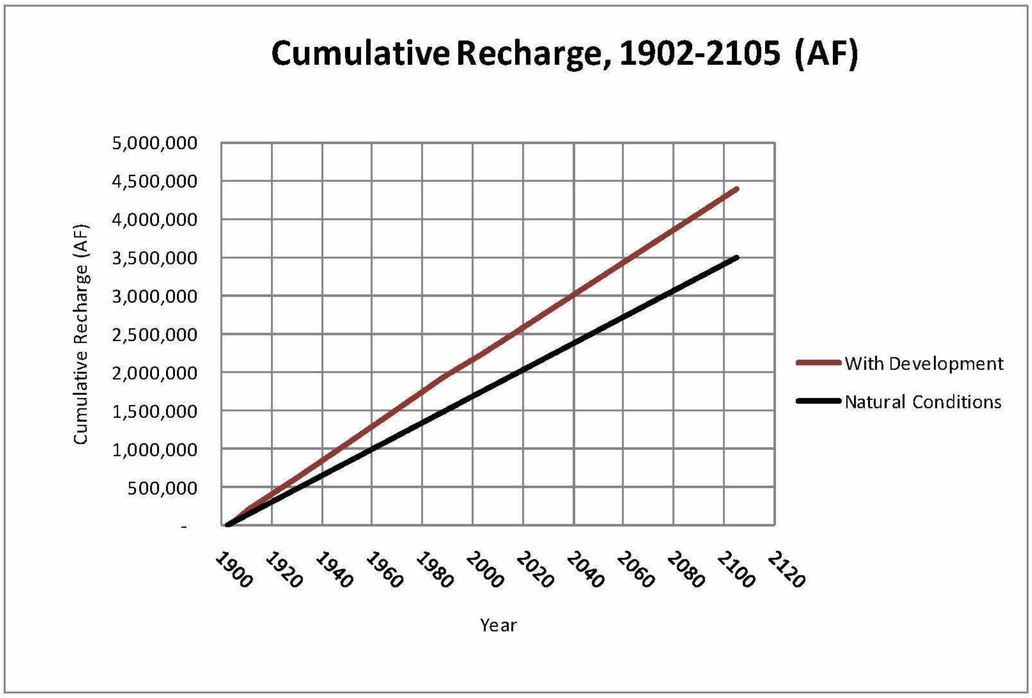


**FIGURE 17. SIMULATED CUMULATIVE TOTAL RECHARGE (AF) WITH AND WITHOUT HUMAN DEVELOPMENT, 1902-2105.**

## DRAWDOWN

"Drawdown" is a term used to describe the lowering of the water table or pressure head ("heads") in an aquifer as a result of pumping. We compute drawdown by subtracting simulated heads in the aquifer for two different time periods. The graphics in Figure 18 and Figure 19 show simulated drawdown (change in head) for the full development model described above from October 15, 1902 to three later dates: a) October 15, 2000, b) October 15, 2050, and c) October 15, 2100. Figure 18 presents drawdowns for these simulation periods in model layer 4, which represents the primary (basin-fill) unit of the regional aquifer. Drawdown in model layer 5, which contains the lower-most portion and the perimeter of the regional aquifer, is shown in Figure 19. The San Pedro and Babocomari river locations are mapped in each of the drawdown figures as a point of reference, even though only a portion of each river is in physical contact with the aquifers modeled in layers 4 and 5. The graphics do not indicate the flow condition (i.e., perennial, intermittent, or ephemeral) of the rivers. In some areas, layer 4 lies several hundred feet below the bed of the conceptualized San Pedro River, and is separated from the river by a thick sequence of "basin-fill silt and clay" (see model layers 2 and 3 in Figure 3). In other areas, like near Charleston (between Sierra Vista and Tombstone along the river), the San Pedro River is simulated within model layer 5 because it directly overlies bedrock at that location (see Pool and Dickinson, 2007, Figure 2, p.6).

### 1902 TO 2000

Figure 18(a) illustrates simulated drawdown conditions in the primary basin-fill aquifer (model layer 4) in October 2000, 98 years after the start of the simulation period. Drawdown contours are shown in 15-ft. intervals. Most of the basin shown in Figure 18(a) exhibits some drawdown by the year 2000. Two black arrows show the zero-drawdown contour lines in the extreme eastern edges of layer 4, indicating that the green area across the bulk of the basin within model layer 4 is in the 0 to 15-ft. drawdown zone. The blue-filled area in the "finger" just north of the Mexican border reflects groundwater levels recovering from mine dewatering at the Copper Queen Mine near Bisbee early in the 20th Century. As Figure 18(a) indicates, the area of model layer 4 underlying the San Pedro River exhibits drawdowns in the 0 to 15-ft. range, except in the localized cone of depression just north of the Mexican border between Palominas and Hereford. By October 2000, the simulated Palominas/Hereford cone of depression is more than 60 ft. deep in a small area beneath and west of the San Pedro River. Simulated drawdowns in layer 4 under the San Pedro River north of Hereford average about 6 ft. The 15-ft. drawdown contour in the Sierra Vista/Fort Huachuca area (refer to map in Figure 1) cone of depression extends north almost to the Babocomari River and east about half way between the City of Sierra Vista and the San Pedro River, with a relatively localized area of simulated drawdown exceeding 60 ft. in the west portion of Sierra Vista. A third cone of depression in Figure 18(a) occurs near the mining town of Cananea, Mexico (just southwest of

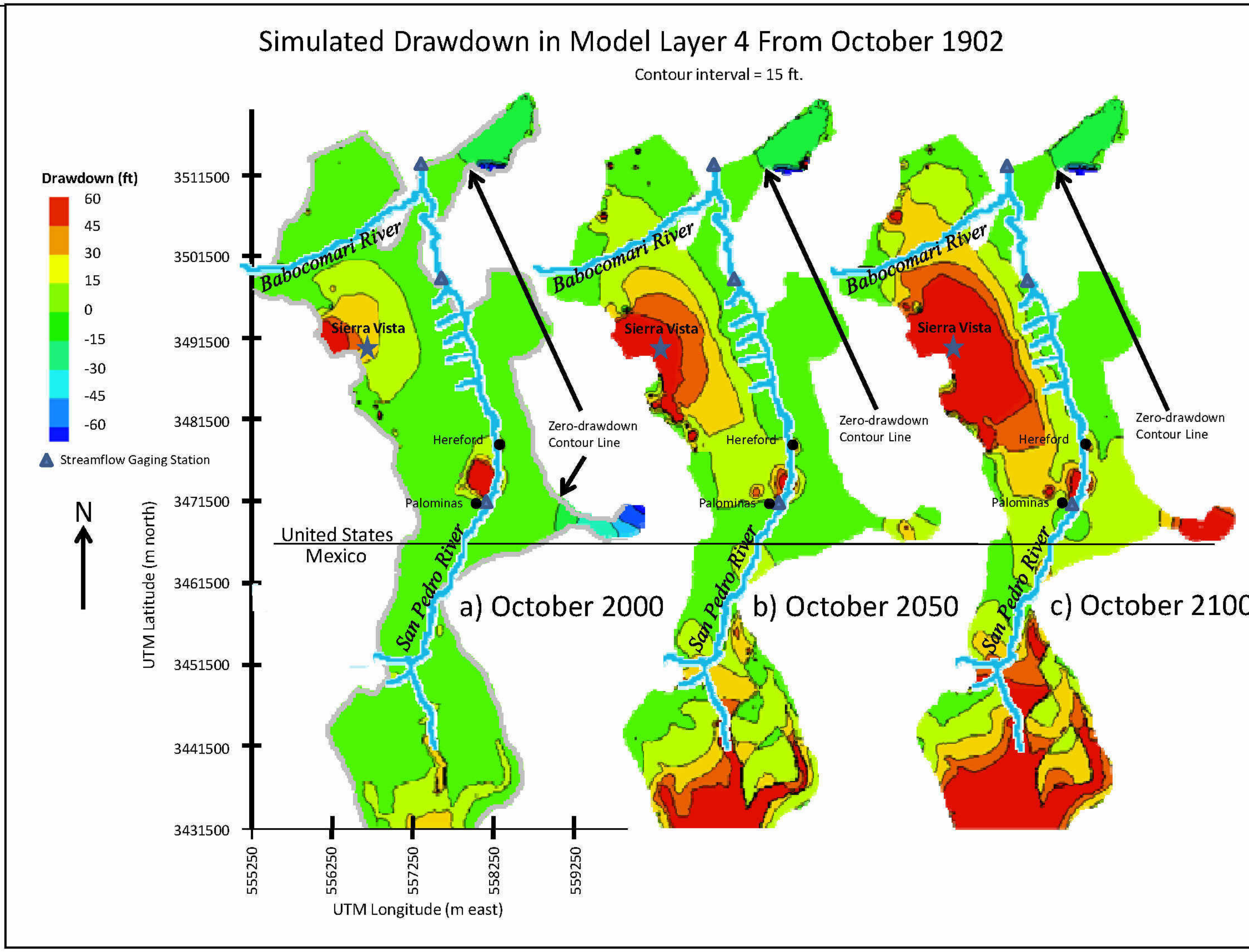


FIGURE 18. SIMULATED CHANGE IN HEAD (DRAWDOWN) (FT.) IN MODEL LAYER 4 (REGIONAL BASIN-FILL AQUIFER) FROM OCTOBER 1902 TO OCTOBER 2000, OCTOBER 2050, AND OCTOBER 2100. AREAS IN DARK RED REPRESENT DRAWDOWN OF 60 FT. OR MORE. BLUE LINE REPRESENTS LOCATION OF RIVERS BUT DOES NOT SIGNIFY THE CONDITION OF PERENNIAL FLOW.

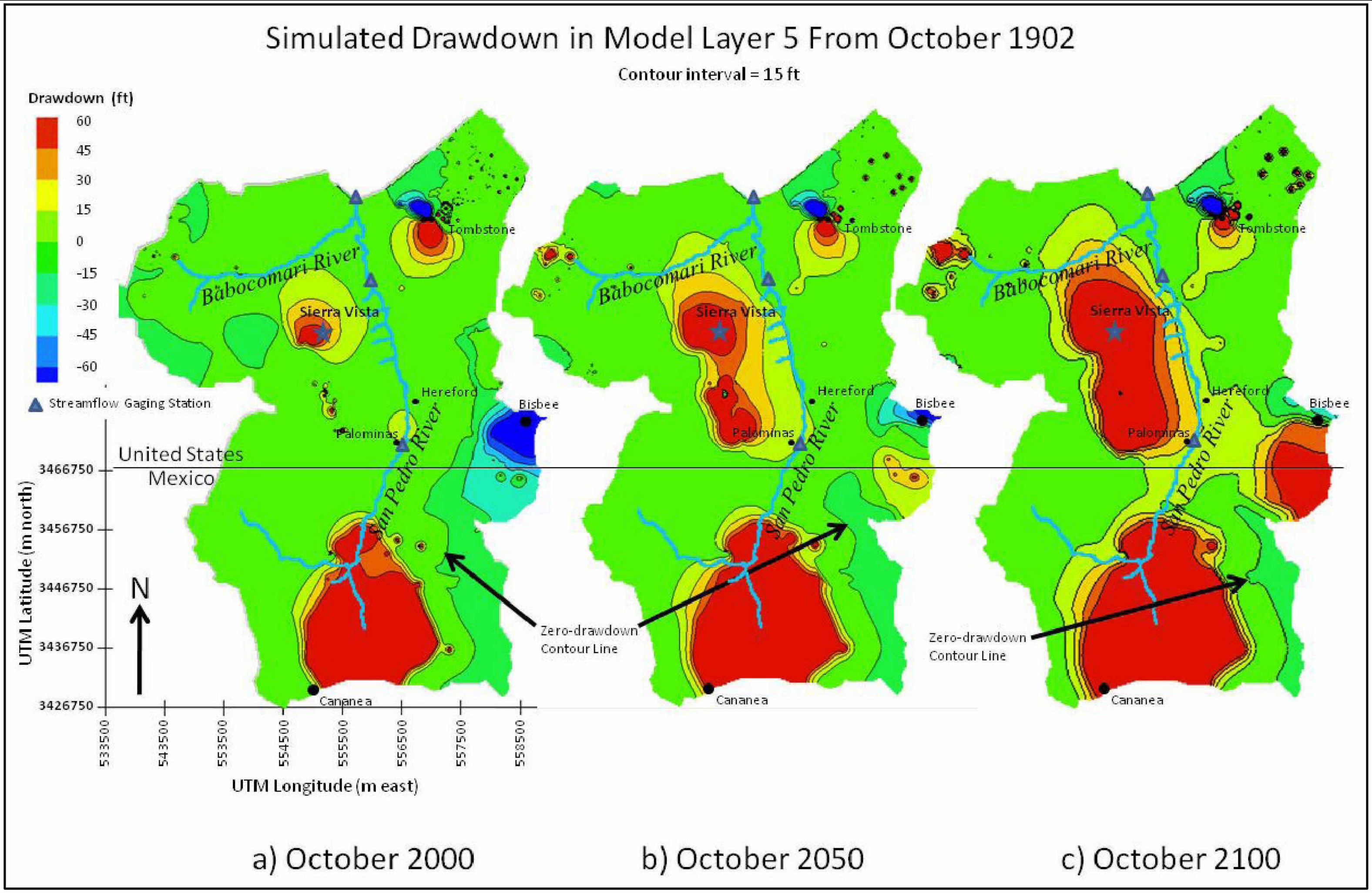


FIGURE 19. SIMULATED CHANGE IN HEAD (DRAWDOWN) (FT.) IN MODEL LAYER 5 (BASE OF REGIONAL AQUIFER) FROM OCTOBER 1902 TO OCTOBER 2000, OCTOBER 2050, AND OCTOBER 2100. AREAS IN DARK RED REPRESENT DRAWDOWN OF 60 FT. OR MORE. BLUE LINE REPRESENTS LOCATION OF RIVERS BUT DOES NOT SIGNIFY THE CONDITION OF PERENNIAL FLOW.

Layer 4) and has a maximum depth of 45 ft. A northward-reaching finger of this cone of depression aligns with the headwater area of the San Pedro River. In this area of the model, streambed occurs in layer 4, allowing simulated groundwater extraction in that layer direct hydrologic access to simulated baseflows.

Figure 19(a) shows simulated drawdown conditions as of October 15, 2000 in model layer 5, which underlies and surrounds layer 4 in a "stacked-bowl" configuration (see Figure 3 and 4). In layer 5, the Palominas/Hereford cone of depression is small and shallow (less than 15 ft. deep), but a larger cone of depression occurs in the Tombstone area. The simulated Sierra Vista/Fort Huachuca cone of depression extends farther east than in layer 4, but otherwise covers roughly the same area. The negative drawdowns south of Bisbee, Arizona in the eastern portion of layer 5 reflect recovery from mine dewatering. The simulated Cananea, Mexico cone of depression is significantly larger and deeper (mostly in excess of 60 ft. deep) in layer 5 than in layer 4, as all groundwater extraction in this area is simulated in layer 5 (Pool and Dickinson, 2007).

The simulated zero-drawdown contour line in Figure 19(a) lies east of the San Pedro River and extends from the southern boundary of the model area to north of Bisbee, Arizona. Simulated drawdowns in layer 5 under the location of the San Pedro River generally exceed 8 ft. north of the Mexican border. Simulated drawdowns in layer 5 under the Babocomari River in the vicinity of the Sierra Vista/Fort Huachuca cone of depression average about 10 ft.

**2000 TO 2050**

Comparison of Figure 18(a) and (b) reveals simulated changes in head between October 2000 and October 2050 in model layer 4. The most significant change is the vast expansion of the simulated Sierra Vista/Fort Huachuca cone of depression southward and northward on the west side of the San Pedro River. Arizona Department of Commerce population forecasts indicate that the region southeast of Sierra Vista and west of the San Pedro River will experience the most significant growth in the unincorporated portion of the basin over the next 50 years (AzDC, 2006; see Appendix A). Likewise, heavy growth is projected for the Whetstone area, north of the Babocomari River (AzDC, 2006; see Figure A.1). This anticipated growth is reflected in large changes in simulated groundwater levels in both of these areas in the first half of the 21st Century. Notably, the confining (clay-silt) units in model layers 2 and 3 appear to have a buffering effect on simulated drawdowns under the San Pedro River east of Sierra Vista, causing the simulated 2050 cone of depression to run mostly parallel to, and west of, the river in layer 4. In spite of this fact, simulated drawdowns under the San Pedro River east of Sierra Vista increase from about 6 ft. to about 10 ft. in layer 4 between 2000 and 2050, and drawdowns under the Babocomari River exceed 20 ft. over most of the reach shown in Figure 18(b). The simulated Cananea, Mexico cone of depression also expands significantly between 2000 and 2050. Simulated drawdowns in the Bisbee area reverse their trend as simulated pumping at the Copper Queen mine is resumed in the expectation of continued mining activity in the foreseeable future.

Simulated drawdown changes in layer 5 between October 2000 and October 2050 (Figure 19(a) and (b)) mirror those described above for layer 4. The simulated Sierra Vista/Fort Huachuca cone of depression expands along a north-south trend, with a second "lobe" of nearly equal magnitude as the original cone of depression forming just south of Sierra Vista. Simulated drawdowns under the San Pedro and Babocomari rivers increase from about 10 ft. in the north to 15 to 20 ft. in the central portion of the basin north of Mexico. The simulated Cananea, Mexico cone of depression continues to intensify and widen. The zero-drawdown contour line near Bisbee retreats, as the simulated mining-related cone of depression there expands. As artificial recharge into Walnut Gulch from the City of Tombstone's waste-water treatment plant continues to support a significant groundwater mound north of town, the simulated cone of depression near Tombstone decreases somewhat in intensity (area deeper than 60 ft. shrinks), but begins to extend southwestward toward the San Pedro River.

**2050 TO 2100**

Comparison of Figure 18(b) and (c) shows simulated changes in drawdown in layer 4 between October 2050 and October 2100. During this 50-year period, most of model layer 4 is affected by a single large cone of depression (outlined by the 15 ft.-contour) which extends under the San Pedro River and across the international boundary into Mexico. The most intense portion of the simulated cone of depression (60 ft. deep or greater) extends south from the Babocomari River to the Hereford area. The entire west side of the San Pedro River exhibits simulated drawdowns approaching or exceeding 15 ft. in layer 4. Simulated drawdowns in most of the layer 4 area under the Babocomari River shown in Figure 18(c) increase dramatically from less than 15 ft. in 2050 to near 45 ft. in 2100. The simulated groundwater divide (high point) between the Sierra Vista/Fort Huachuca area cone of depression and the expansive cone of depression in Mexico consists of a small "bridge" between adjacent 15-ft. drawdown contours south of the international boundary. Simulated drawdowns in the Bisbee area exceed 60 ft. and the cone of depression moves westward toward the San Pedro River.

Figure 19(c) shows simulated layer 5 drawdowns as of October 15, 2100. Comparison with Figure 19(b) shows that all four major cones of depression (Sierra Vista/Fort Huachuca, Tombstone, Bisbee, and Cananea) have expanded and intensified between 2050 and 2100. With the exception of the Tombstone cone of depression, the other three simulated cones of depression have substantially merged by 2100. The simulated Sierra Vista/Fort Huachuca area cone of depression still trends north-south west of the San Pedro River, but by 2100, the 30-ft. drawdown contour extends well north of the Babocomari River and underlies much of the San Pedro River in Arizona.

## BASEFLOW

Baseflow is that portion of streamflow which is supported entirely by groundwater. By definition, baseflow contains no storm runoff or bank storage components. Under natural (pre-development) conditions in the Upper San Pedro Basin, the aquifers were fully saturated below the elevation of the San Pedro and Babocomari river beds and natural recharge in the form of precipitation equaled that of natural discharge in the form of baseflow, ET, and subsurface outflow from the basin. The baseflow level in the stream reflected the gradient of the regional water table from the mountains in the east and west toward the center of the basin. In the absence of major shifts in climate or vegetation patterns, baseflow would remain constant indefinitely under natural conditions. Figure 20 maps simulated baseflow as of October 1902. These flows range from 0 to 10.5 cu-ft/s and generally increase in a downstream direction along the mainstem of the San Pedro River.

A significant increase (79%) in riparian vegetation density between 1935 and 1966 described by Pool and Dickinson (2007, p.15) is reflected in increasing simulated ET over the 20$^{th}$ Century. Increased riparian ET generally depletes summer baseflows and changes the balance of the basin's water budget. The extraction of significant volumes of groundwater by humans also disrupts the natural balance between inflow and outflow in the basin. After depleting aquifer storage in the immediate vicinity of groundwater pumps, the ensuing cones of depression modify the course of groundwater flow between the mountains and the center of the basin, intercepting natural recharge that would otherwise have discharged as baseflow in a river. As the cones of depression increase in area and depth, they may capture an increasing proportion of baseflow. In areas where drawdown from pumping lowers the water table below the bottom of the streambed, the river ceases to receive any baseflow and becomes either intermittent (replenished by seasonally recovered groundwater levels) or ephemeral (flowing only in response to storm events). The simulated combined impacts of ET and human development on baseflow over time are illustrated in Figure 21. Figure 21(a) shows simulated total change in baseflow between October 1902 and October 2000. While most of the stream reaches in the model area experience decreases in baseflow over this 98-year simulation period, the most significant declines include: 1) 2 to 3.3 cu-ft/s on the mainstem of the San Pedro River from the Rio de los Fresnos tributary in Mexico to just north of the Palominas gaging station in Arizona (100% of simulated historic baseflow); 2) 8 cu-ft/s on the San Pedro River below the Babocomari confluence (76-80% of simulated historic baseflow), and

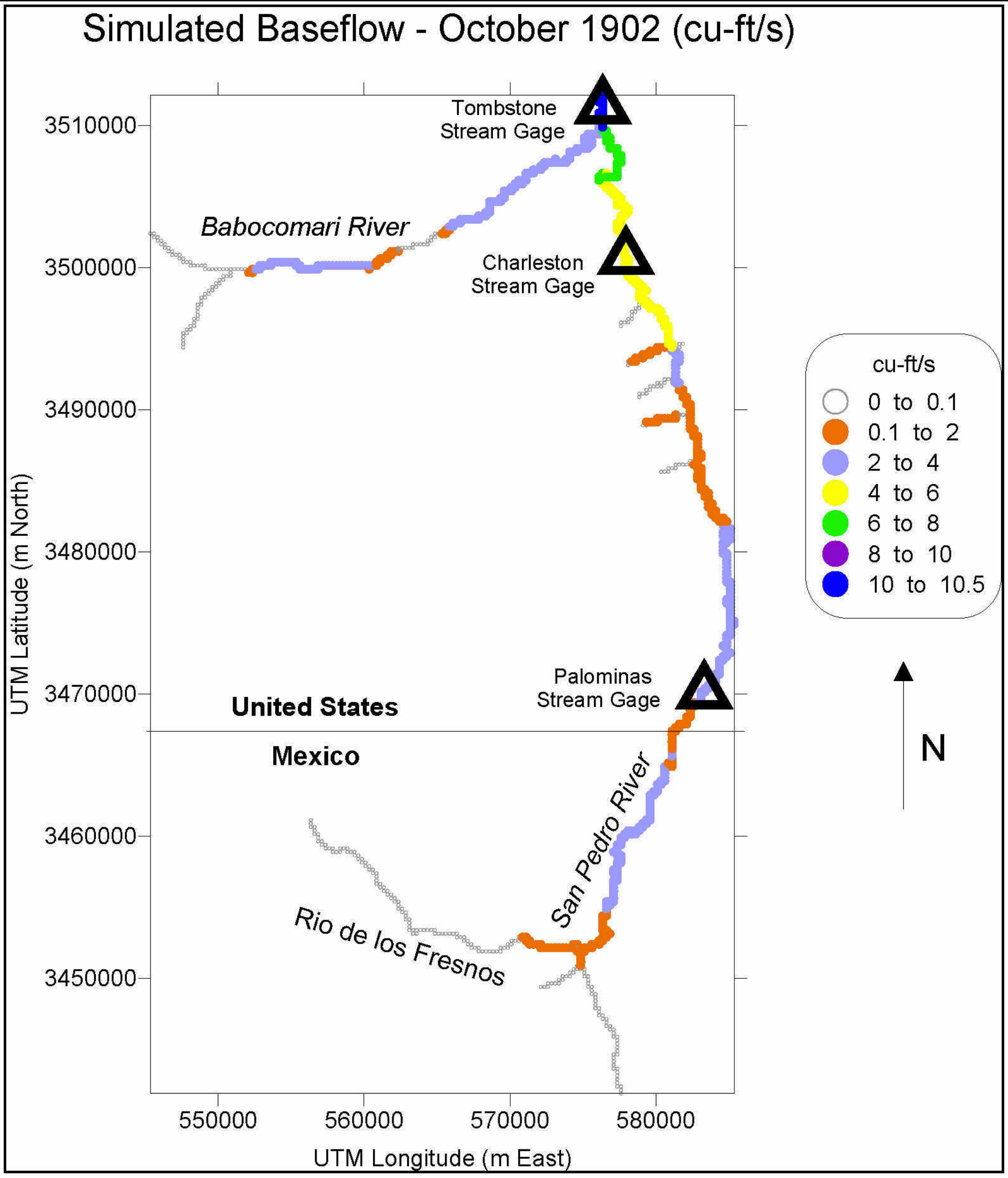


FIGURE 20. SIMULATED BASEFLOW FOR OCTOBER 1902 (CU-FT/S).

3) 1.5 cu-ft/s on the lower half of the Babocomari River (60% of simulated historic baseflow). By 2050, the simulated declines in these reaches continue to increase, with the most significant depletion (an additional 0.9 cu-ft/s; about 9% of historic simulated historic baseflow) occurring on the mainstem of the San Pedro River below the Babocomari confluence (Figure 21(b)). Additional baseflow depletions of 0.7 cu-ft/s (28% of simulated historic baseflow) for the lower Babocomari River and 0.3 cu-ft/s (12% of simulated historic baseflows) for the Palominas reach of the San Pedro River are predicted between 2000 and 2050. The largest simulated changes in

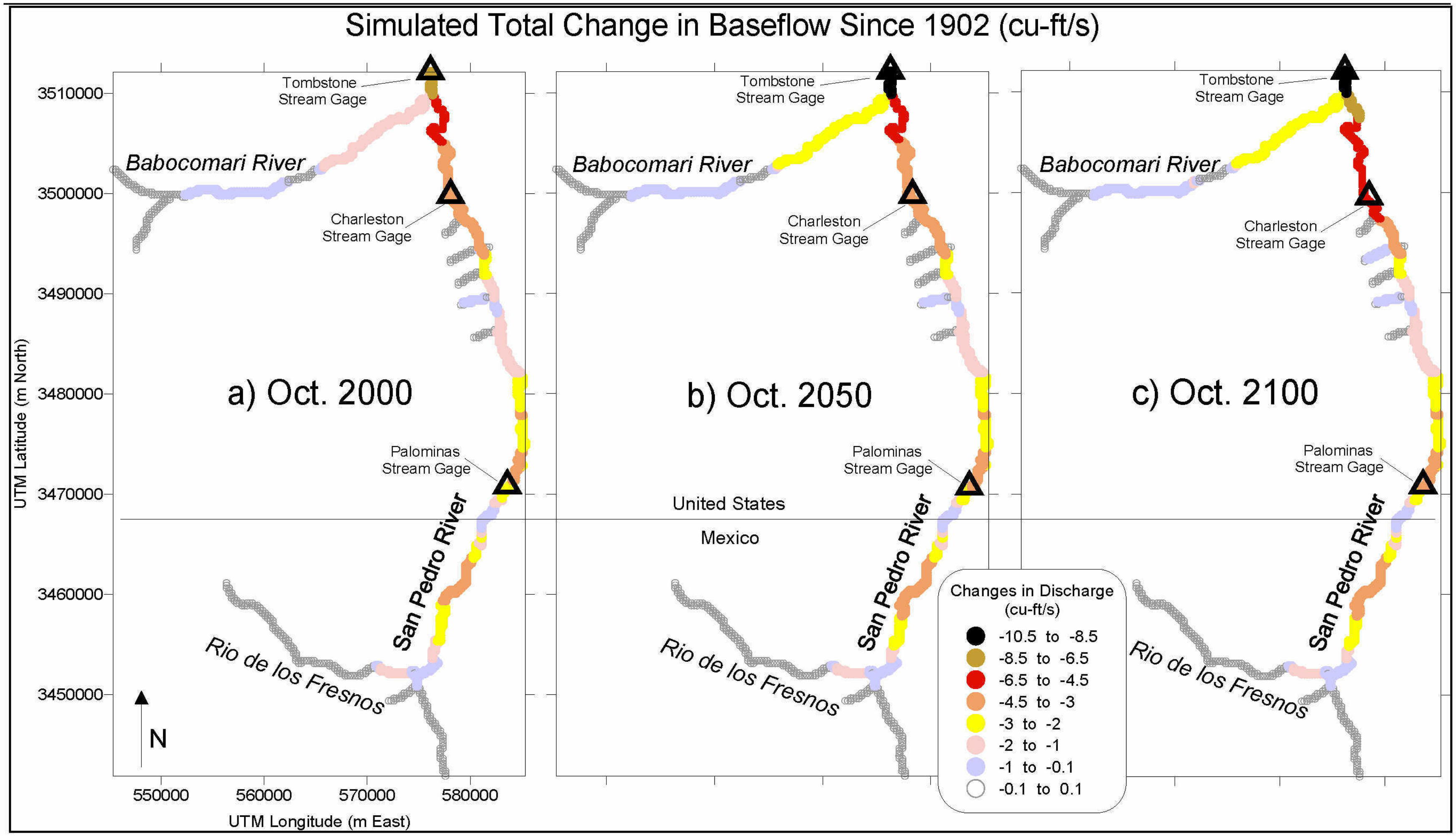


FIGURE 21. SIMULATED TOTAL CHANGE IN BASEFLOW FROM OCTOBER 1902 TO: A) OCTOBER 2000, B) OCTOBER 2050, AND C) OCTOBER 2100 (CU-FT/S). TOTAL CHANGE IN BASEFLOW INCLUDES CHANGES DUE TO ALL HUMAN AND NATURAL CAUSES, INCLUDING PUMPING, EVAPOTRANSPIRATION, AND RECHARGE.

baseflow between 2050 and 2100 occur in the reach of the San Pedro River downstream of Sierra Vista (Figure 21(c)). Simulated baseflows near the Charleston gaging station location drop another 0.6 cu-ft/s (10% of historic flows) and those near the Tombstone gaging station site fall by 1.1 cu-ft/s (11% of simulated historic baseflow) during the second half of the 21st Century.

Figure 22 illustrates simulated changes in baseflow over time by plotting simulated October baseflow for the three USGS stream gaging station locations on the Upper San Pedro River in the years 1902, 2000, 2050, and 2100. The graphs illustrate that most of the simulated baseflow decline occurs prior to 2000. In simulation year 1902, baseflows increase downstream from Palominas to Charleston to Tombstone. In simulation year 2000, this relative order persists, but the magnitude of simulated baseflow drops precipitously at all three gaging station locations, with Palominas having zero simulated October (end of summer) baseflow. Simulated baseflow holds steady at the Charleston location through 2050, but then declines from 1.3 to 0.7 cu-ft/s by 2100 (see Table 2). Simulated baseflow at Tombstone falls steadily from 2000 to 2100, dropping to zero flow by October 2100.

The results of these simulations can be summarized as follows: a) simulated baseflows on the extreme downstream (north) end of the model area (near the Tombstone gaging station) experience the greatest absolute declines (8.1 cu-ft/s; 80% of historic flows) in the model area from 1902 to 2000, and are predicted to drop to zero (10.1 cu-ft/s decline) by October 2100; b) simulated baseflows in the Charleston gaging station reach decline by 77% (4.4 cu-ft/s) over the 20th Century, but this reach is predicted to maintain a small amount of perennial flow (0.7 cu-f/s; 13% of historic baseflow) by October 2100; c) simulated baseflow on the San Pedro River from the Rio de los Fresnos tributary in Mexico to north of the Palominas gaging station is completely depleted by the year 2000 and is predicted to remain at or near zero flow over the next 100 years.

In order to quantify development-induced[18] changes in baseflow resulting from pumping, incidental recharge, and artificial recharge, calculated baseflows from the projected development model described in this study were subtracted from baseflows calculated in a "natural conditions" simulation. Figure 23 shows the result of this calculation. Because the depletions mapped in Figure 24 represent only development-induced changes in baseflow, not total change in baseflow (which includes the effects of ET), the magnitudes of the changes

[18] Land cover changes associated with cattle ranching near the end of the 19th Century may have played a role in significant flooding and stream entrenchment. Any changes in ET related to these effects are incorporated in the "natural conditions" simulations and are separate from the impacts of groundwater pumping, incidental recharge, and artificial recharge discussed here.

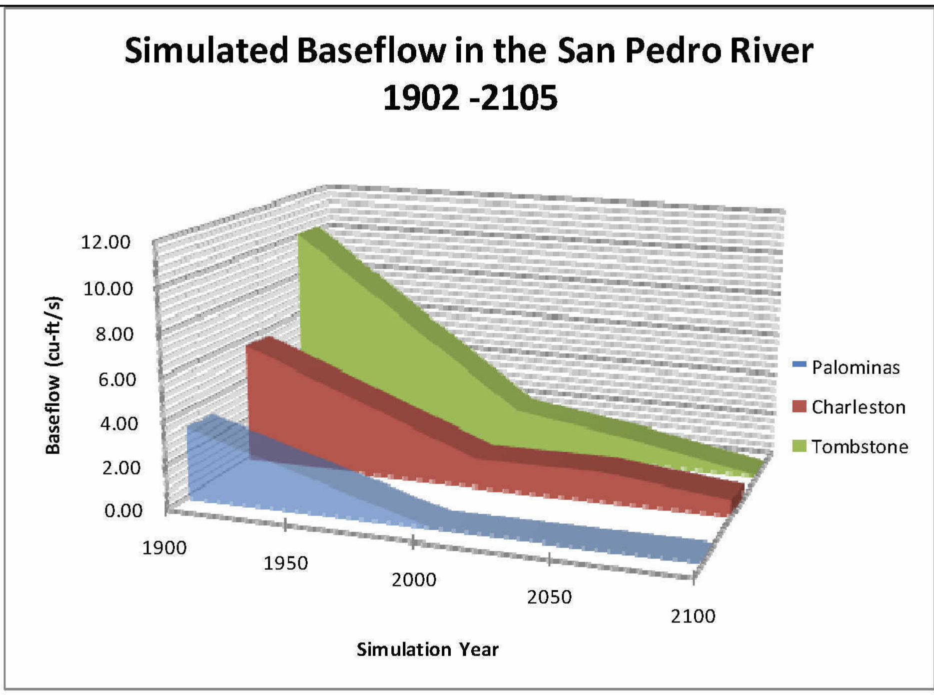


FIGURE 22. SIMULATED OCTOBER BASEFLOWS (CU-FT/S) IN THE SAN PEDRO RIVER AT THE PALOMINAS, CHARLESTON, AND TOMBSTONE GAGING STATIONS IN 1902, 2000, 2050, AND 2100.

TABLE 2. SIMULATED OCTOBER BASEFLOW (CU-FT/S) ON THE SAN PEDRO RIVER AT THE THREE USGS GAGING STATIONS FOR 1902, 2000, 2050, AND 2100.

| Gaging Station | Simulated October Baseflow (cu-ft/s) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1902 | 2000 | | 2050 | | | 2100 | | |
| | Baseflow | Baseflow | % Change Since 1902 | Baseflow | % Change Since 1902 | Difference in Baseflow from 2000 | Baseflow | % Change Since 1902 | Difference in Baseflow from 2050 |
| Palominas | 3.3 | 0.0 | 100% | 0.0 | 100% | 0.0 | 0.0 | 100% | 0.0 |
| Charleston | 5.7 | 1.3 | 77% | 1.3 | 77% | 0.0 | 0.7 | 87% | -0.6 |
| Tombstone | 10.1 | 2.0 | 80% | 1.1 | 89% | -0.9 | 0.0 | 100% | -1.1 |

plotted here are different from those in Figure 21. Figure 23(a) shows that most of the simulated development-induced baseflow depletions up to the year 2000 occur on the San Pedro River in Mexico and on the lower Babocomari River in Arizona. The mainstem of the San Pedro River from the Rio de los Fresnos tributary in Mexico to just south of the international boundary experiences simulated development-induced declines in baseflow of about 1.5 cu-ft/s (83% of simulated historic baseflow; 94% of total baseflow decline) by October 2000, and is predicted to have zero baseflow over the 21st Century. Simulated baseflow capture on the Babocomari River increases from 1.3 to 2.3 cu-ft/s between 2000 and 2100, whereas total simulated baseflow decline increases from 1.45 to 2.47 cu-ft/s (59% to 100% of simulated historic baseflow) for this reach during the same period. After 2050, the simulations predict

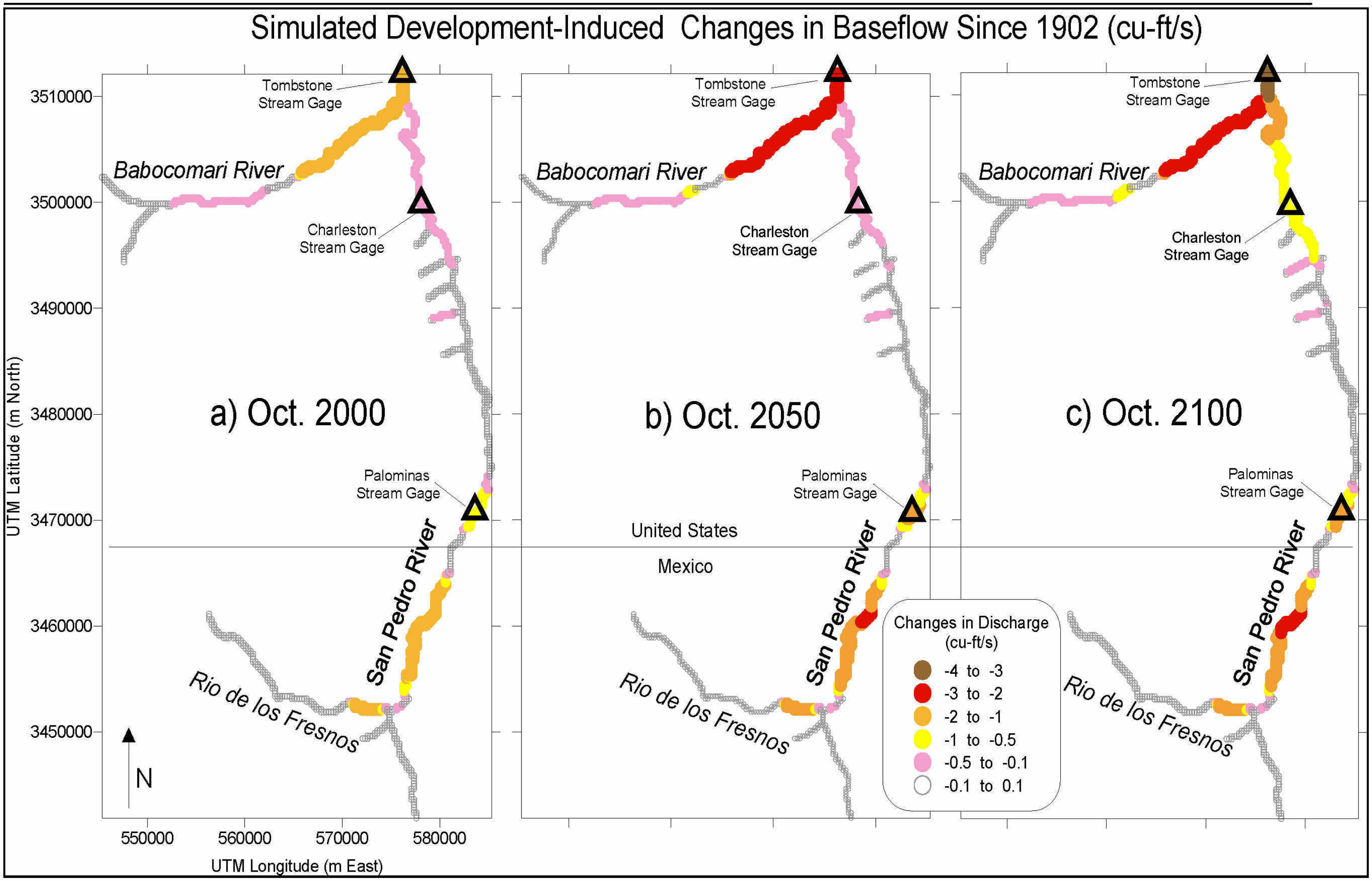


FIGURE 23. SIMULATED CHANGES IN STREAM BASEFLOW (CU-FT/S) ATTRIBUTABLE TO HUMAN DEVELOPMENT FROM 1902 TO: A) OCTOBER 2000, B) OCTOBER 2050, AND C) OCTOBER 2100. NEGATIVE CHANGE IN DISCHARGE CORRESPONDS TO DECLINING FLOW.

that development-induced baseflow depletions (capture) will primarily affect the Charleston and Tombstone reaches of the San Pedro River (see Figure 23(b) and (c)).

Figure 24 illustrates the simulated baseflow capture at the Palominas, Charleston, and Tombstone gaging station locations in 2000, 2050, and 2100. Data used to produce the graphs are presented in Table 3. Table 3 also shows capture as a percentage of simulated *total* baseflow decline from 1902. Consistent with findings in Figure 23 and Table 2 for total baseflow decline, the simulation predicts that the bulk of future baseflow capture will occur on the lower Babocomari River and the San Pedro River north of Sierra Vista, both of which would diminish flows at the Tombstone gaging station location. At the Palominas gaging station site, simulated baseflow capture decreases from 0.93 to 0.83 cu-ft/s (about 28 to 26% of total baseflow decline) throughout the 21$^{st}$ Century because little or no baseflow is available for capture. Simulated baseflow capture from 2000 to 2050 decreases slightly (by less than 0.1 cu-ft/s) at Palominas[19], remains constant at Charleston, and increases by 0.9 cu-ft/s at Tombstone. In the period from 2050 to 2100, simulated baseflow capture is 0.0, 0.6, and 1.1 cu-ft/s for the Palominas, Charleston, and Tombstone gaging station locations, respectively (see column 9 in Table 3). By October 2100, simulated baseflow capture at the Tombstone gaging station is 3.6 cu-ft/s, or 36% of the total baseflow decline at that location (see column 8 in Table 3). Simulated capture at the Charleston gaging station location increases from 0.3 to 0.9 cu-ft/s over the 21$^{st}$ Century and constitutes 18% of the total decline in baseflow at that location by October 2100. Comparing these values with columns 6 and 9 of Table 2 confirms that **human development is responsible for all simulated baseflow declines between 2000 and 2100.** This finding incorporates the assumption that ET during this period peaks in 2000 (see Figure 13). Figure 25 maps the distribution of river reaches simulated as going dry as a result of pumping.

[19] Note that simulation "noise" in baseflow values is about ±0.1 cfs.

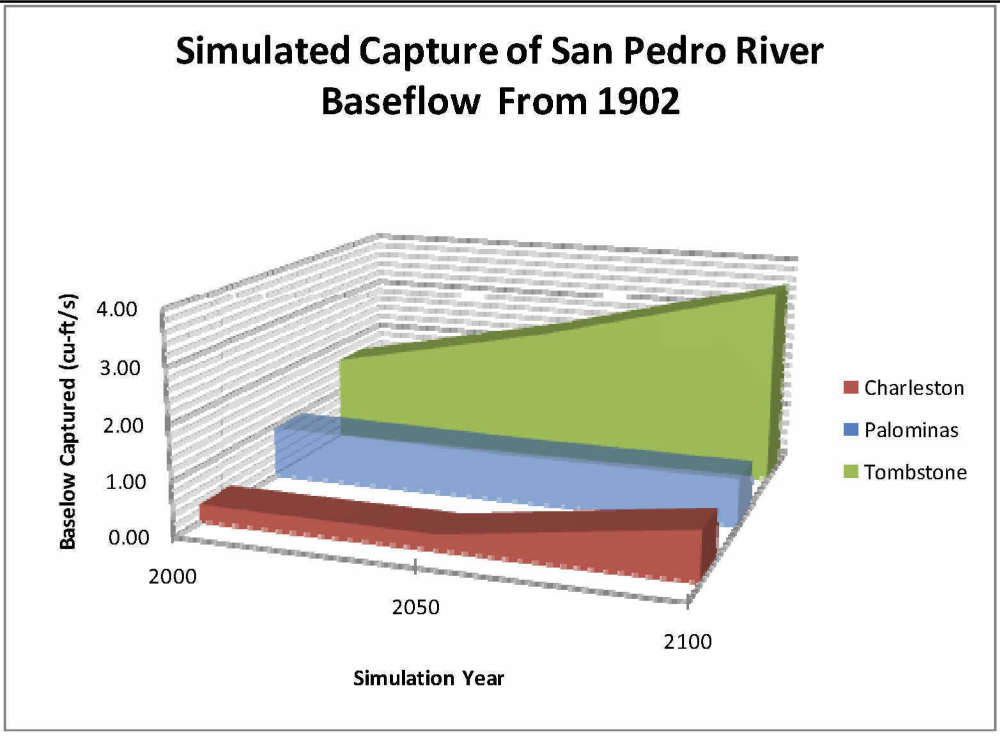


FIGURE 24. SIMULATED DEVELOPMENT-INDUCED CAPTURE OF OCTOBER BASEFLOW FROM THE SAN PEDRO RIVER AT THE THREE USGS GAGING STATION SITES FROM 1902 TO 2000, 2050, AND 2100 (CU-FT/S).

TABLE 3. SIMULATED OCTOBER BASEFLOW CAPTURE (DEVELOPMENT-INDUCED DECREASE IN FLOW) AT THREE GAGING STATIONS ON THE UPPER SAN PEDRO RIVER FROM 1902 TO 2000, 2050, AND 2100, AND BASEFLOW CAPTURE AS A PERCENTAGE OF TOTAL BASEFLOW DECLINE SINCE 1902 (CU-FT/S).

| Gaging Station | Baseflow Capture Since 1902 (cu-ft/s) and Capture as a Percentage of Total Baseflow Decline Since 1902 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | | 2050 | | | 2100 | | |
| | Capture | % total decline | Capture | % total decline | Difference in Capture From 2000 | Capture | % total decline | Difference in Capture From 2050 |
| Palominas | 0.9 | 28% | 0.9 | 26% | -0.1 | 0.8 | 26% | 0.0 |
| Charleston | 0.3 | 7% | 0.3 | 6% | 0.0 | 0.9 | 18% | 0.6 |
| Tombstone | 1.6 | 20% | 2.5 | 28% | 0.9 | 3.6 | 36% | 1.1 |

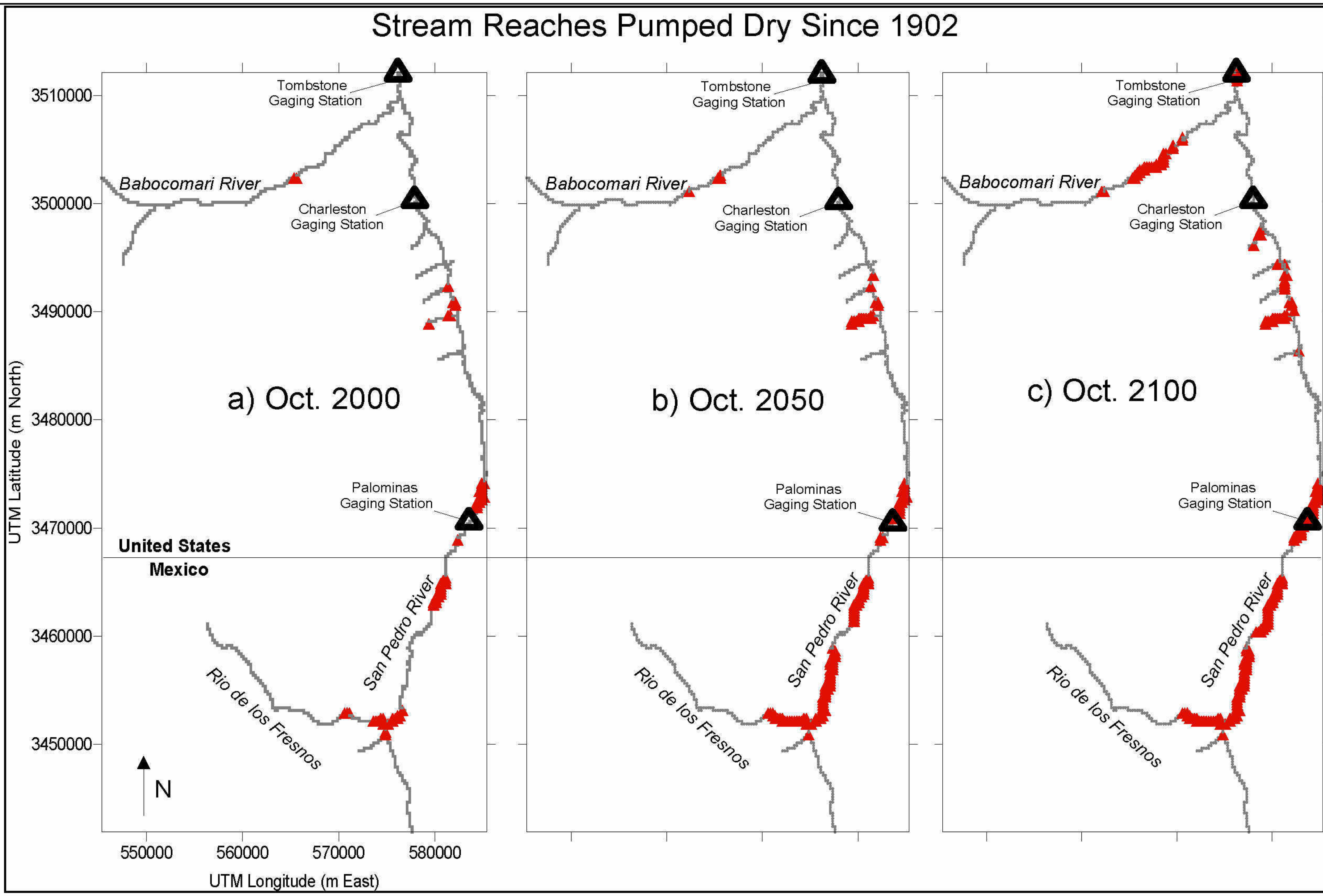


FIGURE 25. SIMULATED STREAM REACHES WITH NO FLOW AS A RESULT OF PUMPING IN: A) OCTOBER 2000, B) OCTOBER 2050, AND C) OCTOBER 2100. REACHES DRIED BY PUMPING ARE MARKED WITH RED TRIANGLES.

## EFFECTS OF MINE PUMPING

Future pumping at the porphyry copper deposit mines near Cananea, Mexico and Bisbee, Arizona is very difficult to predict because of uncertainties in both mine life (e.g., time until ore body exhaustion) and market prices for metals. A "Low Mine" simulation explores the significance of this mine-related pumping in the USPB by discontinuing all mine-related pumping after the year 2050. All other features of the simulation remain the same as described in the sections above.

Figure 26 shows drawdown in model layer 4 in October 2100 without mine pumping (a) and with mine pumping (b). Figure 26(b) is identical to the plot in Figure 18(c). A comparison of these two figures reveals that any significant effects of mine pumping on drawdown in layer 4 are limited to the model area in Mexico and in the southeast quadrant of the model area within the United States, specifically east of the San Pedro River and south of Hereford. Figure 27 provides the same comparison for model layer 5 with Figure 27(b) being identical to the plot in Figure 19(c). In this case, drawdown effects from mine pumping extend from Mexico along the both sides of the San Pedro River all the way to just north of Sierra Vista, near the Charleston gaging station location.

Figure 28 shows the changes in simulated baseflow in October 2100 resulting from the discontinuation of all mine pumping after 2050. The maximum effect of removing this significant amount of pumping (roughly 3,800 AF/yr from the Bisbee area and 18,400 AF/yr from the Cananea area)[20] is a 0.17 cu-ft/s increase in simulated baseflow near the Tombstone gaging station. The location of this minor change in baseflow – at the most distant point from the mine pumping – is significant because it demonstrates the influence of the simulated silt-clay layer (see model layers 2 and 3 in Figure 4) along the west side of the San Pedro River. This thick, low-conductivity unit effectively forces pumping stresses (drawdowns) to propagate north and south much more rapidly than in an east-west direction across the basin. Thus, simulated pumping in Bisbee may have a larger impact on the San Pedro River near Tombstone (where the silt-clay unit is very narrow or absent) than on much closer reaches of the river.

[20] Simulated total pumping (with mines) increased from 47,500 to 55,400 AF/yr from 2050 to 2100.

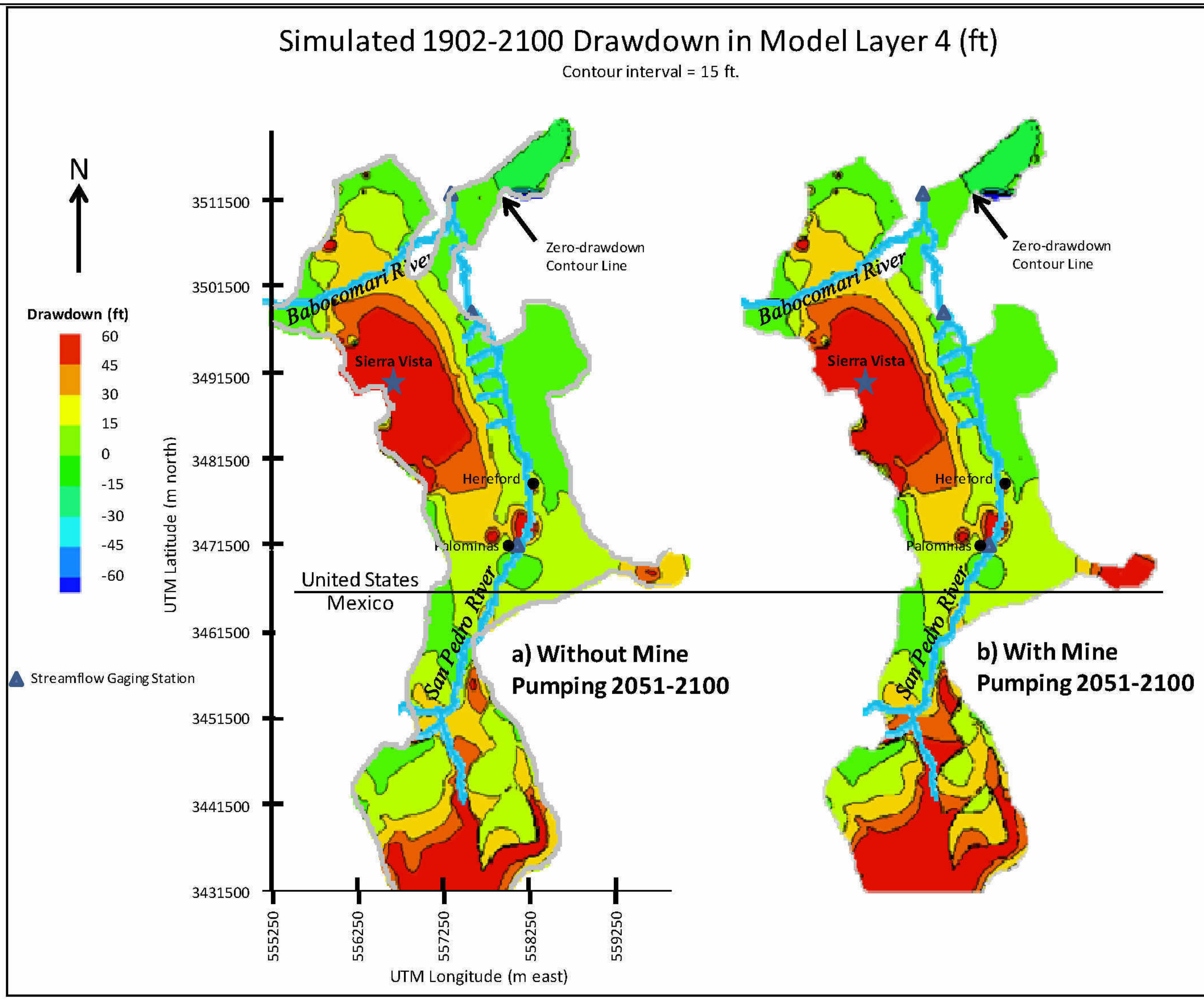


FIGURE 26. SIMULATED DRAWDOWN (FT.) FROM 1902 TO 2100 IN MODEL LAYER 4: A) WITHOUT MINE PUMPING FROM 2051-2100, AND B) WITH MINE PUMPING FROM 2051-2100. THE "WITH MINE PUMPING" SCENARIO IS THE SAME AS THE PROJECTED DEVELOPMENT MODEL DESCRIBED IN THIS STUDY AND PRESENTED IN FIGURE 18(C).

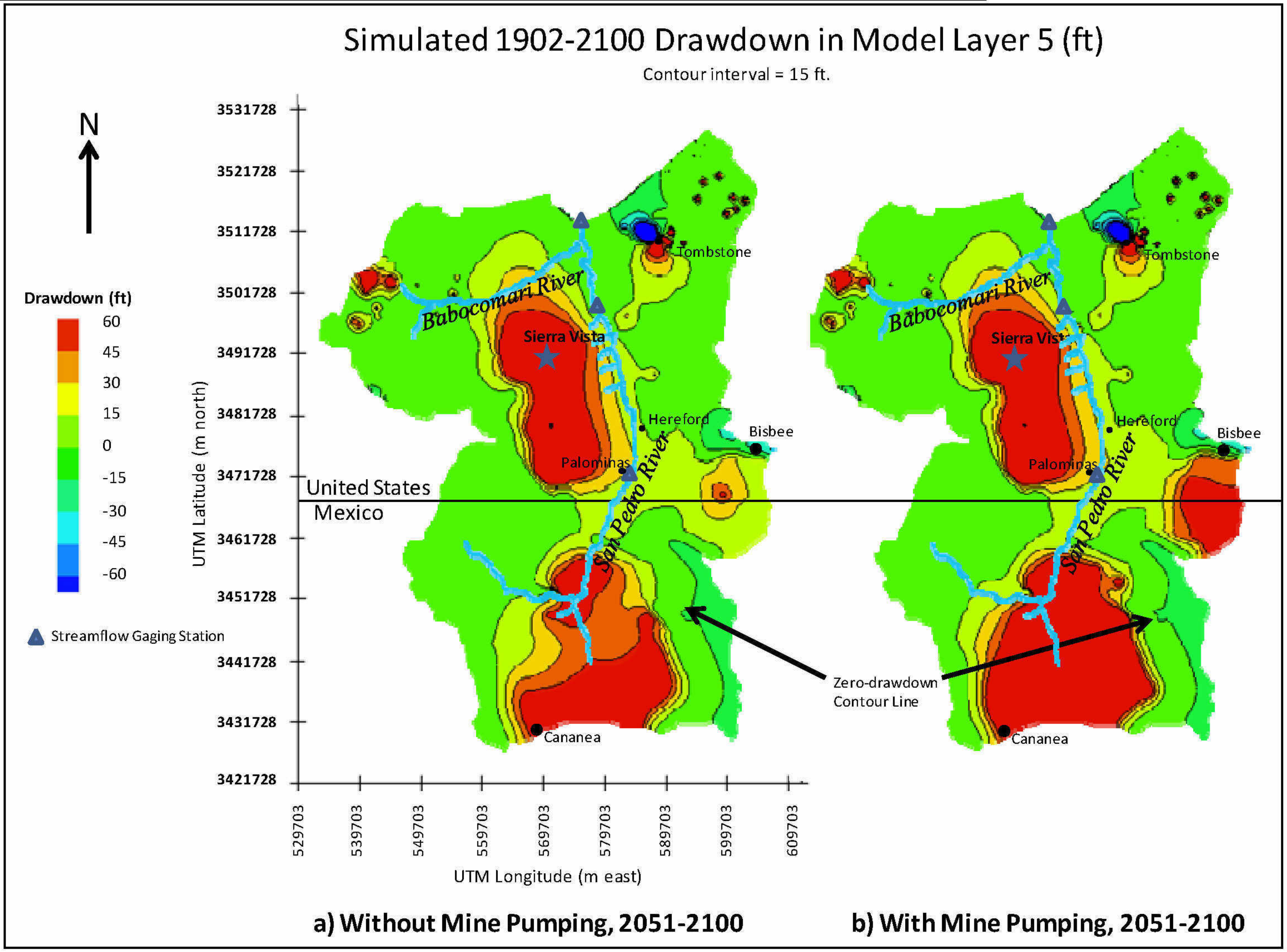


FIGURE 27. SIMULATED DRAWDOWN (FT.) FROM 1902 TO 2100 IN MODEL LAYER 5: A) WITHOUT MINE PUMPING FROM 2051-2100, AND B) WITH MINE PUMPING FROM 2051-2100. THE "WITH MINE PUMPING" SCENARIO IS THE SAME AS THE PROJECTED DEVELOPMENT MODEL DESCRIBED IN THIS STUDY AND PRESENTED IN FIGURE 19(C).



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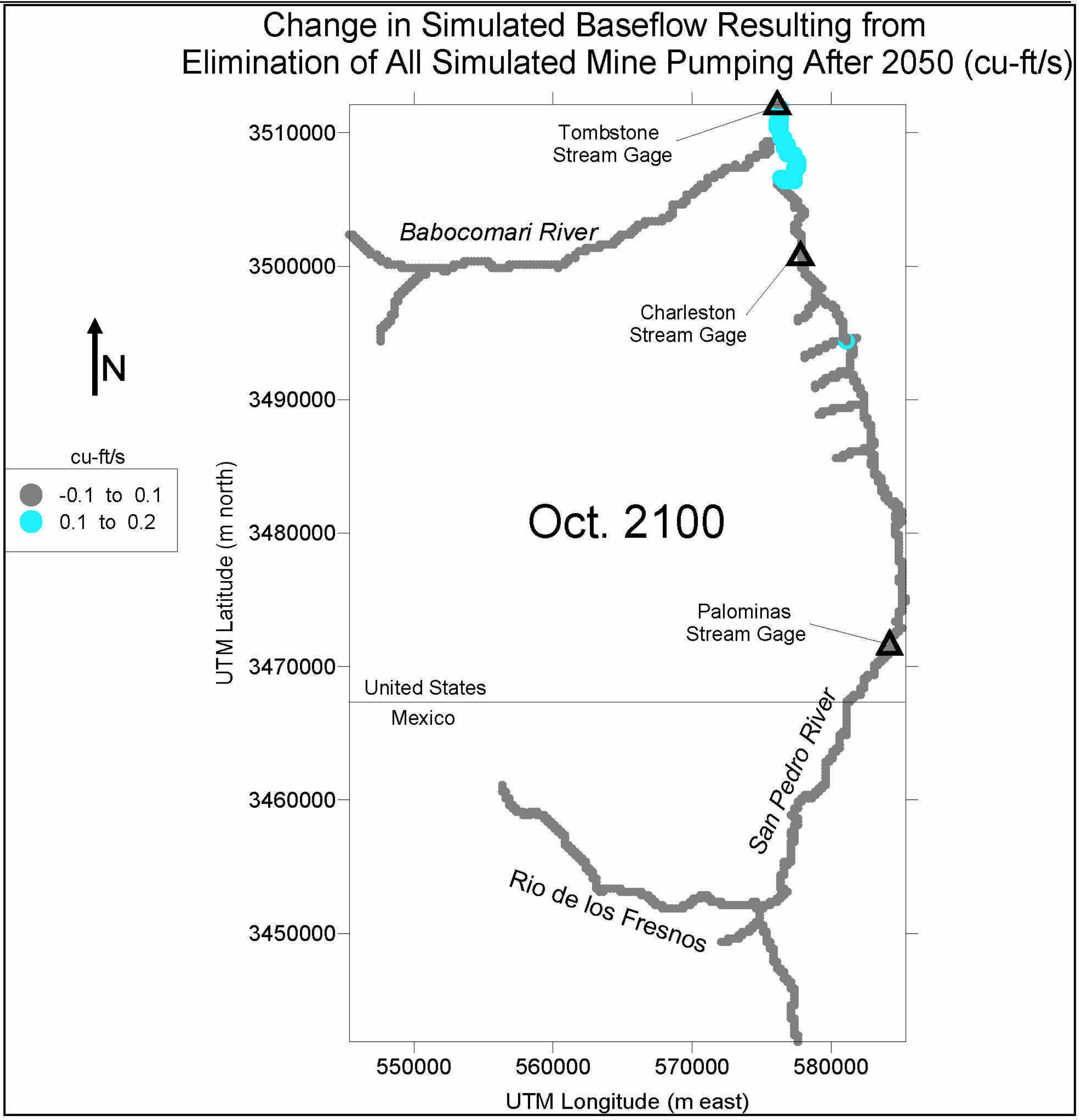


FIGURE 28. SIMULATED CHANGES IN BASEFLOW (CU-FT/S) AFTER DISCONTINUING MINE PUMPING NEAR CANANEA, MEXICO (SOUTH OF FIGURE BOUNDARY) AND NEAR BISBEE, ARIZONA (EAST OF FIGURE BOUNDARY JUST NORTH OF THE INTERNATIONAL BOUNDARY) AFTER 2050.

# SUMMARY AND CONCLUSIONS

This study updated and used the published USGS model of the USPB by Pool and Dickinson (2007) to simulate groundwater and baseflow conditions in the basin from 1902 to 2105 with no adjustments for climate change, but including the best available pumping and recharge data to date. As part of the updating process, errors detected in historic pumping and recharge rates were corrected and the impacts of these changes on the transient model's calibration were evaluated and determined to be negligible. AzDC population projections for the Sierra Vista sub-basin portion of the model area formed the basis for projected pumping rates in the simulation period 2003 to 2105. Simulated pumping rates for 2002-2003 (end of USGS model period) were increased throughout the 21$^{st}$ Century simulation period according to published population growth rate projections. These growth rates were applied to simulated pumping across census county division areas to reflect the spatial distribution of growth anticipated by the AzDC. Projected pumping and artificial recharge on Fort Huachuca were based on the most recent Biological Assessment (ENRD, 2006) and input from ENRD staff. For the simulation period 2003 to 2105, total net pumping (pumping minus incidental recharge) increased by over 10,000 AF/yr, recharge remained constant at roughly 22,000 AF/yr, and ET fell from approximately 9,000 to 6,100 AF/yr in response to groundwater declines. By 2105, simulated cumulative storage loss in the entire model domain (including Mexico) exceeded 4.5 million AF.

A corresponding natural conditions simulation predicted hydrologic conditions in the absence of any pumping, incidental recharge, or artificial recharge in the USPB for the period 1902 to 2105. Comparison of the projected development model (with all pumping and artificial and incidental recharge) to the natural conditions model permitted quantification of development-related hydrologic changes in the basin over the 203-year simulation period. Maps of simulated cones of depression in October 2000, October 2050, and October 2100 show the intensification and expansion of the two major cones of depression in the USPB: one in the Sierra Vista/Fort Huachuca area and another near Cananea, Mexico. As of October 2000 in the simulation period, only the far eastern extremities of the model area (near Bisbee and north of Tombstone) show no groundwater declines since 1902. Minor cones of depression in the Tombstone, Bisbee, and Whetstone areas evolve over the 21$^{st}$ Century simulation period, with the Whetstone and Sierra Vista/Fort Huachuca area cones of depression substantially merging by 2050. By October 2100 in the simulation period, virtually the entire west side of the San Pedro River shows simulated drawdowns of 60 ft. or more. Simulated drawdowns under the Babocomari River and the central portion of the mainstem of the San Pedro River exceed 40 ft. and 20 ft., respectively, by October 2100. Simulated drawdowns in the Mexican portion of the model area exceed 60 ft. across most of model layers 4 and 5 by October 2100.

Simulated increases in riparian vegetation density during the 20th Century and depletion of aquifer storage by pumping produce baseflow declines over the entire 203-year simulation period, but these declines are most pronounced during the 20th Century. Comparison with the natural conditions model permitted quantification of the portion of these depletions attributable solely to human development (capture) via pumping, incidental recharge, and artificial recharge. By October 2000, simulated baseflow capture on the mainstem of the San Pedro River from the Rio de los Fresnos tributary in Mexico to just south of the international boundary is about 1.5 cu-ft/s (83% of simulated historic baseflow; 94% of total baseflow decline), with this reach predicted to have zero baseflow over the 21st Century.[21] The other significant areas of simulated baseflow capture are on the lower half of the Babocomari River and the San Pedro River north of Sierra Vista. Simulated baseflow capture on the Babocomari River between 2000 and 2100 comprises 90 to 93% of total baseflow decline and equates to 53 to 93% of total historic baseflow over that century. For the simulation period 1902 to 2100, capture is predicted to account for 18 to 36% of total simulated baseflow declines (including those caused by ET) near the Charleston and Tombstone gaging station locations, respectively, with pumping alone accounting for all simulated baseflow declines in the model area from 2000 to 2100. This finding incorporates the assumption that ET peaks in or near the year 2000. Simulated baseflow capture of 0.9 cu-ft/s (28% of total simulated baseflow decline) occurs in a small section of the San Pedro River near Palominas by October 2000, with little change over the next 100-year simulation period. In general, the simulations predict that, in the absence of any major water use changes in the basin, much of the San Pedro and Babocomari rivers will cease to have perennial baseflow over the next century due to the widespread impacts of projected groundwater pumping.

## FUTURE WORK

This report presents findings from the first in an ongoing series of updates and forward simulations based on the USGS model published in 2007 (Pool and Dickinson, 2007). Future applications of the model under this and related contracts are anticipated to include:

- modifications to the model structure and hydraulic parameters in the vicinity of the City of Sierra Vista's EOP, as developed by Brown and Caldwell (2009).
- simulation of potential options for redistribution of municipal effluent.
- simulation of the effects of future near-stream recharge at various select locations along the San Pedro River and/or Babocomari River.

[21] Note that zero baseflow does not equate to zero flow; bank storage may yield prolonged periods of flow following wet season precipitation events.

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FORMAT PAGE

# APPENDIX A

## DEVELOPMENT OF PROJECTED PUMPING RATES IN THE SIERRA VISTA SUB-BASIN, EXCLUDING FORT HUACHUCA, FOR THE SIMULATION PERIOD 2003-2105

# METHOD FOR ESTIMATING PUMPING RATES IN THE SIERRA VISTA SUB-BASIN OUTSIDE OF FORT HUACHUCA, 2003-2105

The Upper San Pedro Basin (USPB) groundwater model published by the U.S. Geological Society (USGS) simulates pumping from 1902 to early 2003 (Pool and Dickinson, 2007). We developed estimates of future pumping in the Arizona portion (Sierra Vista subwatershed) of the USPB in order to run groundwater simulations out to 2105, thereby extending the total simulation period to 203 years.[22] Arizona Department of Commerce (AzDC) population estimates (2003-2009) and projections (2009-2055) were used to estimate future domestic, municipal, and industrial pumping demand in the Sierra Vista (SV) subwatershed portion of the USPB. AzDC projections are grouped by Census County Divisions (CCDs) for population centers and population growth outside of the CCDs is covered under an "unincorporated" area estimate (refer to Cochise County link at http://www.azcommerce.com/EconInfo/Demographics/Population+Projections.html). Figure A.1 shows U.S. Census Bureau CCDs in the SV subwatershed as slightly modified for this study.

Table A.1 lists AzDC population estimates for select communities in Cochise County from 2002 to 2009 and shows the percent change from one year to the next as well as the 7-year average rate of change for each Census County Division (CCD) listed and for the unincorporated area of the county outside of any CCD.

**TABLE A.1. ARIZONA DEPARTMENT OF COMMERCE POPULATION ESTIMATES FOR SELECT PORTIONS OF COCHISE COUNTY.**

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | |
|---|---|---|---|---|---|---|---|---|---|
| Census County Divis | **1-Jul-02** | **1-Jul-03** | **1-Jul-04** | **1-Jul-05** | **1-Jul-06** | **1-Jul-07** | **1-Jul-08** | **1-Jul-09** | 7-yr avg |
| **COCHISE COUNTY** | | | | | | | | | |
| Bisbee | 6,140 | 6,360 | 6,585 | 6,570 | 6,355 | 6,310 | 6,389 | 6,423 | |
| % change | | 3.6% | 3.5% | -0.2% | -3.3% | -0.7% | 1.3% | 0.5% | 0.7% |
| Huachuca City | 1,800 | 1,825 | 1,830 | 1,830 | 1,825 | 1,832 | 1,952 | 1,955 | |
| % change | | 1.4% | 0.3% | 0.0% | -0.3% | 0.4% | 6.6% | 0.2% | 1.2% |
| Sierra Vista | 40,415 | 40,410 | 42,725 | 43,690 | 44,870 | 44,736 | 45,908 | 46,597 | |
| % change | | 0.0% | 5.7% | 2.3% | 2.7% | -0.3% | 2.6% | 1.5% | 2.1% |
| Tombstone | 1,535 | 1,570 | 1,585 | 1,610 | 1,655 | 1,682 | 1,709 | 1,720 | |
| % change | | 2.3% | 1.0% | 1.6% | 2.8% | 1.6% | 1.6% | 0.6% | 1.6% |
| Unincorporated | 48,505 | 49,565 | 51,150 | 52,270 | 54,055 | 55,583 | 56,336 | 56,723 | |
| % change | | 2.2% | 3.2% | 2.2% | 3.4% | 2.8% | 1.4% | 0.7% | 2.3% |

Sources: http://www.azcommerce.com/econinfo/demographics/Population+Estimates.html (AzDC, 2009) and http://www.azcommerce.com/doclib/econinfo/FILES/2009Estimates.pdf (AzDC, 2010).

[22] Pumping for the Mexico portion of the USPB and for all mining and agricultural pumping in the SV subwatershed was maintained at 2002-2003 levels throughout the 2004-2105 simulation period in lieu of any appropriate population or water-use projections for those sectors.

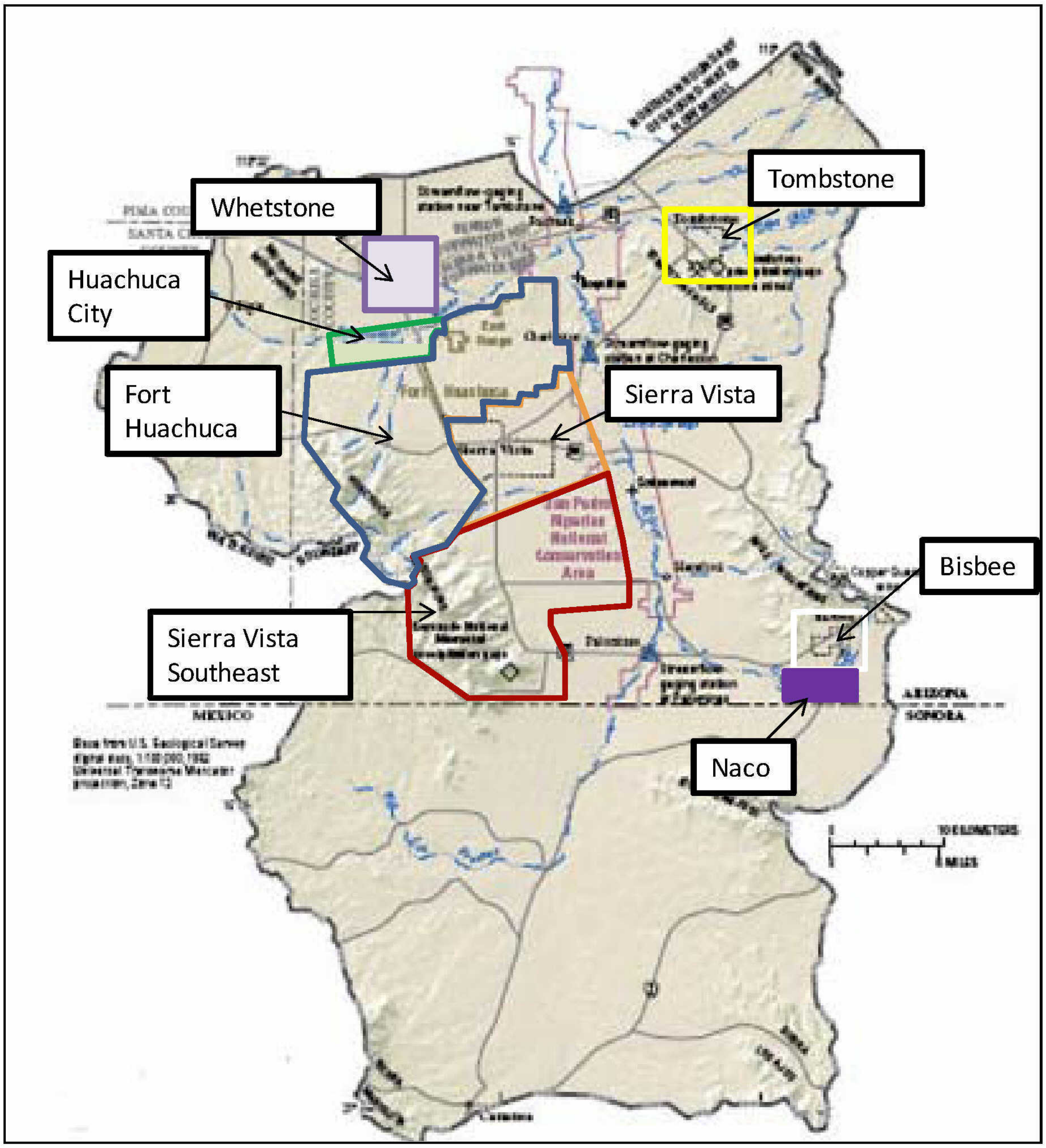


FIGURE A.1. MODIFIED CENSUS COUNTY DIVISIONS OVERLAID ON GROUNDWATER MODEL AREA IN UPPER SAN PEDRO BASIN.

Source: U.S. Census Bureau online Reference Maps
(http://factfinder.census.gov/jsp/saff/SAFFInfo.jsp?_pageId=referencemaps&_submenuId=maps_2)



USF200010829

TABLE A.2 provides AzDC population projections for Census County Divisions within the Sierra Vista subwatershed (AzDC, 2006). Table A. 3 shows projected population developed by TischlerBise (2009) for the City of Sierra Vista including Fort Huachuca. Projected populations for the City of Sierra Vista in 2006 through 2009 differ significantly from estimates in TABLE A.2 In order to adjust the projections to the estimates, we replaced the 2006 “projected” value for the City of Sierra Vista in Table A.2 with the 2006 estimate for the City in Table A. 3, and applied the projected annual growth rates from Table A.2 to that starting value to produce the set of adjusted projections out to 2055 in Table A.2.

**TABLE A.2. ARIZONA DEPARTMENT OF COMMERCE POPULATION PROJECTIONS FOR CENSUS COUNTY DIVISIONS WITHIN THE SIERRA VISTA SUBWATERSHED AREA OF COCHISE COUNTY.**

| Census County Division | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bisbee | 6,673 | 6,772 | 6,870 | 6,965 | 7,057 | 7,147 | 7,236 | 7,322 | 7,406 | 7,489 | 7,569 | 7,647 | 7,723 | 7,796 | 7,867 |
| **% change** | | 1.5% | 1.4% | 1.4% | 1.3% | 1.3% | 1.2% | 1.2% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 0.9% |
| Naco | 869 | 875 | 881 | 887 | 893 | 899 | 904 | 910 | 915 | 920 | 925 | 930 | 934 | 939 | 943 |
| **% change** | | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| Huachuca City | 1,847 | 1,863 | 1,879 | 1,895 | 1,910 | 1,925 | 1,940 | 1,954 | 1,968 | 1,981 | 1,994 | 2,007 | 2,020 | 2,032 | 2,043 |
| **% change** | | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% |
| Tombstone | 1,633 | 1,655 | 1,676 | 1,697 | 1,718 | 1,738 | 1,757 | 1,776 | 1,795 | 1,813 | 1,831 | 1,848 | 1,865 | 1,881 | 1,896 |
| **% change** | | 1.4% | 1.3% | 1.3% | 1.2% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 0.9% | 0.9% | 0.9% | 0.8% |
| Whetstone | 2,810 | 2,888 | 2,965 | 3,039 | 3,111 | 3,182 | 3,251 | 3,319 | 3,385 | 3,449 | 3,512 | 3,573 | 3,632 | 3,690 | 3,746 |
| **% change** | | 2.8% | 2.6% | 2.5% | 2.4% | 2.3% | 2.2% | 2.1% | 2.0% | 1.9% | 1.8% | 1.7% | 1.7% | 1.6% | 1.5% |
| | | | | | | | | | | | | | | | |
| All Sierra Vista City | 44,954 | 46,184 | 47,386 | 48,560 | 49,694 | 50,805 | 51,895 | 52,959 | 53,997 | 55,010 | 55,999 | 56,961 | 57,892 | 58,797 | 59,674 |
| **% change** | | 2.7% | 2.6% | 2.5% | 2.3% | 2.2% | 2.1% | 2.1% | 2.0% | 1.9% | 1.8% | 1.7% | 1.6% | 1.6% | 1.5% |
| **All Sierra Vista corrected to 2006 estimate in Table 1** | 44,870 | 44736 | 45908 | 46597 | 47685 | 48751 | 49797 | 50818 | 51814 | 52786 | 53735 | 54658 | 55552 | 56420 | 57262 |
| All Sierra Vista Southeast | 16,551 | 16,929 | 17,298 | 17,658 | 18,006 | 18,347 | 18,681 | 19,008 | 19,327 | 19,638 | 19,941 | 20,236 | 20,522 | 20,800 | 21,069 |
| **% change** | | 2.3% | 2.2% | 2.1% | 2.0% | 1.9% | 1.8% | 1.7% | 1.7% | 1.6% | 1.5% | 1.5% | 1.4% | 1.4% | 1.3% |
| All remainder SV and Bisbee | 6,063 | 6,154 | 6,243 | 6,330 | 6,414 | 6,496 | 6,577 | 6,656 | 6,732 | 6,807 | 6,880 | 6,952 | 7,021 | 7,088 | 7,152 |
| **% change** | | 1.5% | 1.4% | 1.4% | 1.3% | 1.3% | 1.2% | 1.2% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 0.9% |

TABLE A.2 (CONTINUED)

| Census County Division | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bisbee | 7,936 | 8,004 | 8,069 | 8,133 | 8,195 | 8,256 | 8,315 | 8,373 | 8,428 | 8,483 | 8,536 | 8,587 | 8,637 | 8,685 | 8,731 |
| **% change** | 0.9% | 0.8% | 0.8% | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.5% |
| Naco | 948 | 952 | 956 | 960 | 964 | 968 | 971 | 975 | 978 | 982 | 985 | 988 | 991 | 994 | 997 |
| **% change** | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% |
| Huachuca City | 2,055 | 2,066 | 2,077 | 2,087 | 2,098 | 2,107 | 2,117 | 2,127 | 2,136 | 2,145 | 2,154 | 2,162 | 2,170 | 2,178 | 2,186 |
| **% change** | 0.6% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% |
| Tombstone | 1,912 | 1,927 | 1,941 | 1,955 | 1,969 | 1,982 | 1,995 | 2,008 | 2,020 | 2,032 | 2,044 | 2,056 | 2,066 | 2,077 | 2,087 |
| **% change** | 0.8% | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.5% | 0.5% | 0.5% |
| Whetstone | 3,800 | 3,853 | 3,904 | 3,954 | 4,003 | 4,050 | 4,096 | 4,141 | 4,185 | 4,228 | 4,270 | 4,310 | 4,349 | 4,386 | 4,422 |
| **% change** | 1.4% | 1.4% | 1.3% | 1.3% | 1.2% | 1.2% | 1.1% | 1.1% | 1.1% | 1.0% | 1.0% | 0.9% | 0.9% | 0.9% | 0.8% |
| | | | | | | | | | | | | | | | |
| All Sierra Vista City | 60,527 | 61,357 | 62,167 | 62,953 | 63,720 | 64,466 | 65,196 | 65,903 | 66,590 | 67,264 | 67,921 | 68,550 | 69,163 | 69,754 | 70,326 |
| **% change** | 1.4% | 1.4% | 1.3% | 1.3% | 1.2% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 0.9% | 0.9% | 0.9% | 0.8% |
| **All Sierra Vista corrected to 2006 estimate in Table 1** | 58080 | 58877 | 59654 | 60408 | 61144 | 61860 | 62560 | 63239 | 63898 | 64544 | 65175 | 65779 | 66367 | 66934 | 67483 |
| All Sierra Vista Southeast | 21,331 | 21,586 | 21,834 | 22,075 | 22,311 | 22,540 | 22,764 | 22,981 | 23,192 | 23,398 | 23,600 | 23,793 | 23,981 | 24,163 | 24,338 |
| **% change** | 1.2% | 1.2% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 0.9% | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% | 0.7% |
| All remainder SV and Bisbee | 7,216 | 7,277 | 7,337 | 7,395 | 7,452 | 7,507 | 7,561 | 7,613 | 7,664 | 7,714 | 7,763 | 7,809 | 7,855 | 7,898 | 7,941 |
| **% change** | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% | 0.5% |

TABLE A.2 (CONTINUED)

| Census County Division | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 | 2046 | 2047 | 2048 | 2049 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bisbee | 8,776 | 8,819 | 8,861 | 8,902 | 8,943 | 8,983 | 9,023 | 9,062 | 9,101 | 9,140 | 9,180 | 9,219 | 9,259 | 9,300 | 9,341 |
| **% change** | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% |
| Naco | 1,000 | 1,003 | 1,005 | 1,008 | 1,010 | 1,013 | 1,015 | 1,018 | 1,020 | 1,023 | 1,025 | 1,028 | 1,030 | 1,033 | 1,035 |
| **% change** | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.3% |
| Huachuca City | 2,193 | 2,200 | 2,207 | 2,214 | 2,221 | 2,227 | 2,234 | 2,240 | 2,247 | 2,253 | 2,260 | 2,266 | 2,273 | 2,279 | 2,286 |
| **% change** | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% |
| Tombstone | 2,097 | 2,107 | 2,116 | 2,125 | 2,134 | 2,143 | 2,152 | 2,160 | 2,169 | 2,178 | 2,186 | 2,195 | 2,204 | 2,213 | 2,222 |
| **% change** | 0.5% | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% |
| Whetstone | 4,457 | 4,491 | 4,524 | 4,556 | 4,588 | 4,619 | 4,650 | 4,681 | 4,712 | 4,743 | 4,774 | 4,804 | 4,836 | 4,867 | 4,900 |
| **% change** | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.7% | 0.7% | 0.7% |
| | | | | | | | | | | | | | | | |
| All Sierra Vista City | 70,872 | 71,406 | 71,924 | 72,433 | 72,934 | 73,423 | 73,914 | 74,397 | 74,880 | 75,365 | 75,852 | 76,336 | 76,829 | 77,326 | 77,841 |
| **% change** | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.7% |
| **All Sierra Vista corrected to 2006 estimate in Table 1** | 68007 | 68519 | 69016 | 69505 | 69985 | 70454 | 70925 | 71389 | 71853 | 72319 | 72785 | 73250 | 73723 | 74200 | 74694 |
| All Sierra Vista Southeast | 24,506 | 24,670 | 24,829 | 24,985 | 25,139 | 25,289 | 25,439 | 25,588 | 25,736 | 25,885 | 26,034 | 26,183 | 26,334 | 26,487 | 26,645 |
| **% change** | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% |
| All remainder SV and Bisbee | 7,981 | 8,021 | 8,059 | 8,097 | 8,134 | 8,170 | 8,206 | 8,242 | 8,278 | 8,313 | 8,349 | 8,385 | 8,422 | 8,459 | 8,497 |
| **% change** | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.5% |

TABLE A.2 (CONTINUED)

| Census County Division | 2051 | 2052 | 2053 | 2054 | 2055 |
|---|---|---|---|---|---|
| Bisbee | 9,384 | 9,427 | 9,471 | 9,515 | 9,561 |
| % change | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| Naco | 1,038 | 1,040 | 1,043 | 1,046 | 1,049 |
| % change | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% |
| Huachuca City | 2,293 | 2,300 | 2,307 | 2,315 | 2,322 |
| % change | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% |
| Tombstone | 2,231 | 2,241 | 2,251 | 2,260 | 2,270 |
| % change | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% |
| Whetstone | 4,933 | 4,967 | 5,001 | 5,036 | 5,072 |
| % change | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% |
| | | | | | |
| All Sierra Vista City | 78,361 | 78,893 | 79,437 | 79,986 | 80,542 |
| % change | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% |
| **All Sierra Vista corrected to 2006 estimate in Table 1** | 75193 | 75703 | 76225 | 76752 | 77285 |
| All Sierra Vista Southeast | 26,804 | 26,968 | 27,134 | 27,303 | 27,474 |
| % change | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% |
| All remainder SV and Bisbee | 8,535 | 8,575 | 8,615 | 8,655 | 8,697 |
| % change | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |

Source: http://www.azcommerce.com/EconInfo/Demographics/Population+Projections.htm (AzDC, 2006).

Figure A. 2 plots estimated and projected growth rates for the City of Sierra Vista from AzDC (2006, 2009, 2010) and TischlerBise (2009). While the shapes of the projected growth rate curves for the two sources diverge in the early years (2010-2020), the projected growth rates remain fairly similar through mid-century.

TABLE A. 3. TISCHLERBISE (2009) POPULATION PROJECTIONS FOR THE CITY OF SIERRA VISTA INCLUDING FORT HUACHUCA.

| year | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| population | 46,380 | 46,834 | 47,313 | 47,841 | 48,406 | 49,002 | 52,312 | 55,999 | 59,945 | 64,087 | 67,380 | 71,253 |
| annual growth rate | | 1.0% | 1.0% | 1.1% | 1.2% | 1.2% | 1.4% | 1.4% | 1.4% | 1.4% | 1.0% | 1.1% |

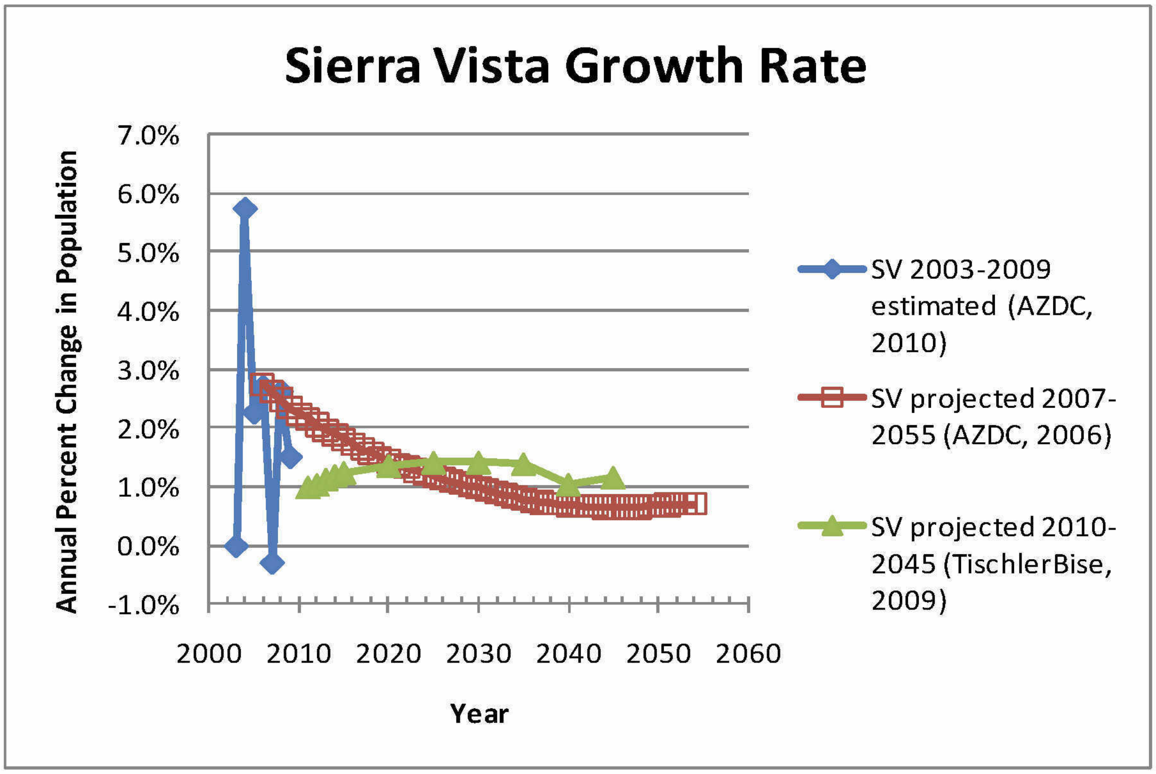


FIGURE A. 2. ESTIMATED AND PROJECTED POPULATION GROWTH RATES FOR THE CITY OF SIERRA VISTA (SV) FOR THE PERIOD 2002 TO 2055.

Figure A.3 plots estimated and projected population for the City of Sierra Vista from the AzDC (2006, 2009, 2010) and TischlerBise (2009). The purple curve in the plot shows the adjusted population growth curve used in this study (see discussion above). Figure A.4 plots estimated and projected population growth rates for various CCDs within the SV subwatershed.

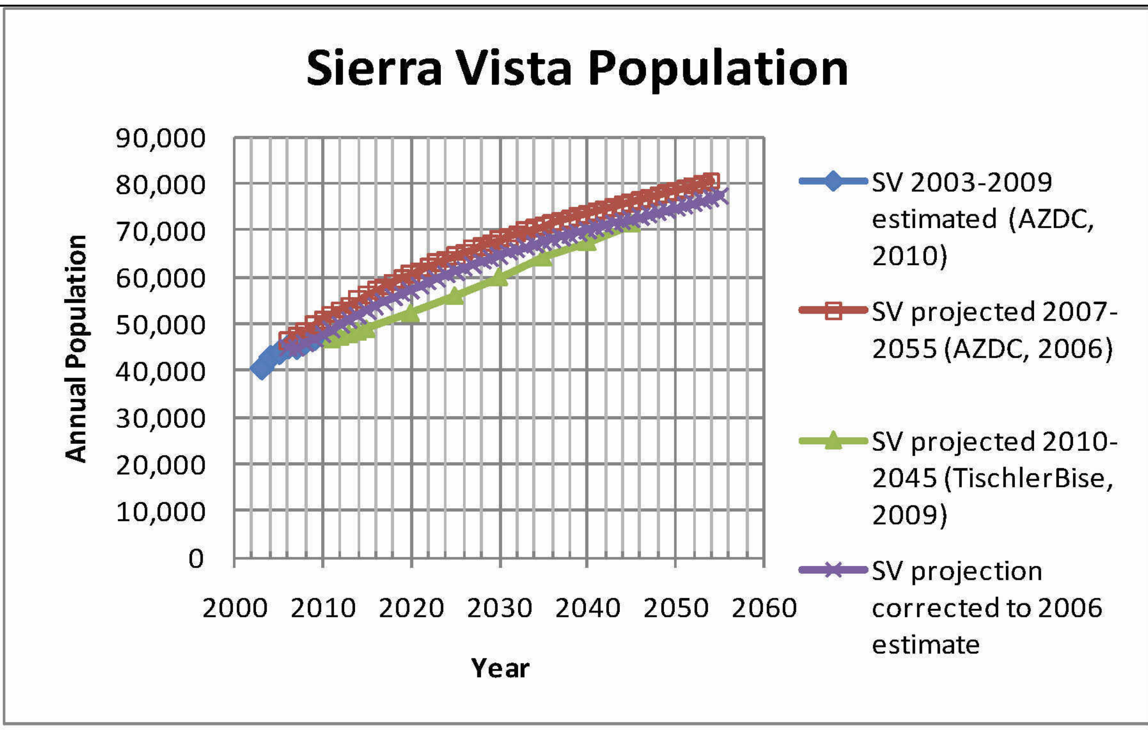


**FIGURE A.3 ESTIMATED AND PROJECTED POPULATION FOR THE CITY OF SIERRA VISTA (SV) FOR THE PERIOD 2002 TO 2055.**

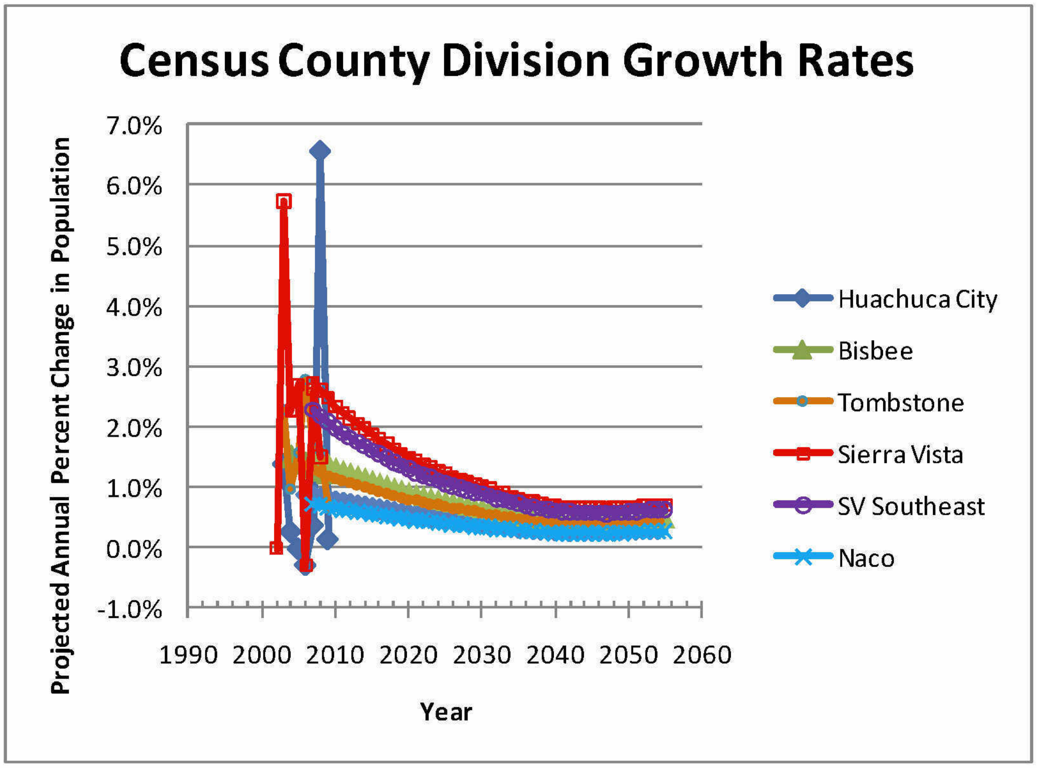


**FIGURE A.4. ESTIMATED (NOT AVAILABLE FOR SIERRA VISTA (SV) SOUTHEAST AND NACO) AND PROJECTED POPULATION GROWTH RATES FOR CENSUS COUNTY DIVISIONS WITHIN THE SIERRA VISTA SUBWATERSHED OF COCHISE COUNTY** (SOURCES: AZDC, 2006; AZDC, 2009; AZDC, 2010).



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FORMAT PAGE

# APPENDIX B

## SIMULATED PUMPING RATES AND ARTIFICIAL RECHARGE AT FORT HUACHUCA 2003-2105

# METHOD FOR DISTRIBUTING ESTIMATED FUTURE FORT HUACHUCA PUMPING IN ON-POST WELLS

Fort Huachuca's Public Works Department provided monthly pumping data from the eight active wells operating within the external boundaries of Fort Huachuca for the period 2003-2010 (T. Runyon, email comm., 2007 and 2011). Table B.1 shows the average seasonal contribution to total annual pumping for the eight wells for 2003-2009. SP1 and SP2 in Table B.1 represent model stress periods, with SP1 being the summer period (mid-March through mid-October), and SP2 being the winter period (mid-October through mid-March). Because Fort Huachuca's pumping data were provided on a monthly basis, pumping for the months of April through October was assigned to SP1, while November through March pumping fell into SP2.

**TABLE B.1. CONTRIBUTIONS OF INDIVIDUAL WELLS TO TOTAL FORT HUACHUCA ON-POST PUMPING, 2003-2009.**

| Ft Huachuca Pumping Distribution by Well and by Season | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | WELL #1 | WELL #2 | WELL #3 | WELL #4 | WELL #5 | WELL #6 | WELL #7 | WELL #8 | Annual |
| **2003** | | | | | | | | | |
| SP1% of total Q for all wells | 0% | 26% | 19% | 15% | 3% | 4% | 0% | 1% | 67% |
| SP2 % of total Q for all wells | 0% | 11% | 10% | 0% | 3% | 10% | 0% | 0% | 33% |
| **2004** | | | | | | | | | |
| SP1 % of total Q for all wells | 0% | 20% | 5% | 0% | 16% | 23% | 0% | 0% | 65% |
| SP2 % of total Q for all wells | 1% | 17% | 6% | 4% | 5% | 2% | 0% | 0% | 35% |
| **2005** | | | | | | | | | |
| SP1 % of total Q for all wells | 1% | 26% | 20% | 0% | 18% | 0% | 0% | 1% | 65% |
| SP2% of total Q for all wells | 0% | 13% | 6% | 0% | 15% | 0% | 0% | 0% | 35% |
| **2006** | | | | | | | | | |
| SP1 % of total Q for all wells | 0% | 24% | 2% | 17% | 17% | 1% | 0% | 0% | 62% |
| SP2 % of total Q for all wells | 0% | 3% | 3% | 11% | 7% | 15% | 0% | 0% | 38% |
| **2007** | | | | | | | | | |
| SP1 % of total Q for all wells | 0% | 0% | 15% | 21% | 21% | 7% | 0% | 2% | 66% |
| SP2 % of total Q for all wells | 1% | 5% | 9% | 6% | 1% | 11% | 0% | 0% | 34% |
| **2008** | | | | | | | | | |
| SP1 % of total Q for all wells | 1% | 15% | 16% | 12% | 0% | 18% | 1% | 0% | 62% |
| SP2 % of total Q for all wells | 0% | 13% | 9% | 0% | 0% | 15% | 0% | 0% | 38% |
| **2009** | | | | | | | | | |
| SP1 % of total Q for all wells | 0% | 9% | 24% | 2% | 6% | 25% | 0% | 0% | 66% |
| SP2 % of total Q for all wells | 0% | 0% | 4% | 1% | 9% | 19% | 0% | 0% | 34% |
| | | | | | | | | | |
| **Average - Summer** | **0%** | **17%** | **15%** | **10%** | **11%** | **11%** | **0%** | **1%** | **64.7%** |
| **Average - Winter** | **0%** | **9%** | **7%** | **3%** | **6%** | **10%** | **0%** | **0%** | **35.3%** |

**SP = model stress period (217 days March-October; 148 or 149 days October-March)**

Fort Huachuca's simulated on-post total pumping rate was held constant at 1300 AF/yr for the period 2011-2105, as directed by ENRD Hydrologist, Tom Runyon (pers. comm., 2010), and as supported by the 2006 Biological Assessment (BA) (ENRD, 2006). We estimated and assigned seasonal pumping rates to each of the eight active wells on post by applying the appropriate average percentage from the last 2 lines in Table B.1 to the total annual rate of 1300 AF/yr. Table B.2 shows the resulting estimated seasonal pumping rates for Fort Huachuca wells #1 through #8. Table B.3 lists all reported pumping data by season for 2003 through October 2010 and estimated winter-season pumping for the period November 2010 through March 2011). Simulated Fort Huachuca pumping was held constant at 2010-11 rates for the period 2012-2105 (see SP17 and SP18 values in Table B.3).

TABLE B.2. PROJECTED PUMPING RATES FOR ON-POST WELLS BASED ON DISTRIBUTION IN TABLE B.1, 2011-2105.

| Projected Pumping ON POST | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | WELL #1 | WELL #2 | WELL #3 | WELL #4 | WELL #5 | WELL #6 | WELL #7 | WELL #8 | Annual |
| | 2011-2105 | | | | | | | | |
| | AF | | | | | | | | |
| Spring-Summer (SP1) | 3.07 | 221.70 | 190.79 | 123.95 | 149.03 | 141.73 | 2.94 | 8.11 | 841.31 |
| Fall-Winter (SP2) | 3.37 | 114.82 | 89.37 | 42.67 | 73.39 | 133.89 | 0.57 | 0.61 | 458.69 |
| | | | | | | | | Total | 1300.00 |
| | cu-m/d | | | | | | | | |
| SP 17-33 | **17** | **1260** | **1084** | **705** | **847** | **806** | **17** | **46** | 4782 |
| SP 18-34 | **28** | **955** | **744** | **355** | **611** | **1114** | **5** | **5** | 3816 |
| | | | | | | | | Total | 8599 |

[1]Set 1300 AF/yr as long-term goal based on APP. H in 2006 BA (ENRD, 2006)

TABLE B.3. PROJECTED PUMPING RATES FOR ON-POST WELLS BASED ON DISTRIBUTION IN TABLE B.1, 2009-2105.

| | | Reported and Estimated Pumping Rates for Fort Huachuca Wells, 2003-2011 (cu-m/d) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | REPORTED | | | | | | | | | | | | | | ESTIMATED | | | |
| | | SP1 | SP2 | SP3 | SP4 | SP5 | SP6 | SP7 | SP8 | SP9 | SP10 | SP11 | SP12 | SP13 | SP14 | SP15 | SP16 | SP17 | SP18 |
| Well Name (GWSI/ADWR) | Fort ID | 2003 | 2003-2004 | 2004 | 2004-2005 | 2005 | 2005-2006 | 2006 | 2006-2007 | 2007 | 2007-2008 | 2008 | 2008-2009 | 2009 | 2009-2010 | 2010 | 2010-2011 | 2011 | 2011-2012 |
| 626105 | 8 | 73.62 | 7.34 | 12.69 | 0.00 | 56.79 | 12.49 | 10.57 | 0.00 | 138.25 | 0.00 | 13.62 | 5.03 | 12.09 | 0.00 | 0.00 | 5 | 44.08 | 4.85 |
| 626105 | 8 | 3.36 | 0.34 | 0.58 | 0.00 | 2.59 | 0.57 | 0.48 | 0.00 | 6.32 | 0.00 | 0.62 | 0.23 | 0.55 | 0.00 | 0.00 | 0.222 | 2.01 | 0.22 |
| 626106 | 7 | 18.52 | 1.57 | 8.84 | 0.00 | 17.02 | 13.01 | 10.19 | 0.00 | 13.04 | 0.00 | 36.72 | 4.66 | 11.87 | 12.18 | 24.59 | 5 | 16.72 | 4.70 |
| 626108 | 5 | 243.91 | 334.56 | 1333.14 | 668.84 | 1388.15 | 1636.33 | 1156.87 | 650.76 | 1495.80 | 50.98 | 2.65 | 0.00 | 414.40 | 902.62 | 565.42 | 611 | 847.12 | 610.59 |
| 626109 | 4 | 1302.73 | 4.23 | 0.00 | 514.57 | 0.00 | 41.16 | 1141.28 | 1061.42 | 1517.81 | 616.52 | 813.24 | 2.24 | 112.45 | 97.23 | 7.08 | 355 | 704.57 | 355.02 |
| 626110 | 3 | 1697.70 | 1206.35 | 452.57 | 775.53 | 1577.60 | 694.66 | 153.36 | 286.56 | 1090.98 | 932.66 | 1086.32 | 861.73 | 1686.95 | 429.97 | 1280.35 | 744 | 1084.48 | 743.61 |
| 626107 | 6 | 341.75 | 1287.46 | 1985.55 | 235.97 | 0.00 | 0.00 | 38.15 | 1379.59 | 466.30 | 1115.73 | 1169.73 | 1416.94 | 1705.58 | 1862.37 | 602.20 | 1114 | 805.64 | 1114.00 |
| 313313110182301 | 1 | 0 | 0.00 | 0 | 71.60 | 43.30 | 0.00 | 20.55 | 0 | 0.00 | 116.10 | 50.73 | 0.00 | 2.30 | 6.50 | 420.99 | 28 | 17.43 | 28.03 |
| 626111 | 2 | 2291.47 | 1322.25 | 1755.05 | 2050.26 | 2053.67 | 1447.58 | 1609.03 | 258.46 | 0.00 | 528.24 | 978.67 | 1267.57 | 585.80 | 0.00 | 1302.87 | 955 | 1260.19 | 955.35 |
| **TOTAL** | **cu-m/d** | **5973** | **4164** | **5548** | **4317** | **5139** | **3846** | **4140** | **3637** | **4728** | **3360** | **4152** | **3558** | **4532** | **3311** | **4204** | **3816** | **4782** | **3816** |
| | **AF/yr** | **1551** | | **1495** | | **1366** | | **1166** | | **1236** | | **1158** | | **1195** | | **1198** | | **1300** | |

NOTE: 2012-2105 simulated pumping replicates 2010-2011 rates.

# METHOD FOR ESTIMATING FUTURE EFFLUENT RECHARGE AT FORT HUACHUCA FOR THE SIMULATION PERIOD 2010-2105

The 2006 Programmatic Biological Assessment for Fort Huachuca (BA) (ENRD, 2006) projects artificial recharge in the effluent basins at Fort Huachuca, as shown in Table B.4. Values in the third row of Table B.4 ("Effluent to Basins") provided the basis for estimating future effluent recharge based on projected pumping rates.

**TABLE B.4. PROJECTED ON-POST PUMPING AND EFFLUENT RECHARGE AT FORT HUACHUCA, 2005-2015, PUBLISHED IN 2006 BIOLOGICAL ASSESSMENT.**

| | On-Post Pumping and Artificial Recharge - Projected (AF/yr) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2005 | 2006 | 2007 | 2009 | 2010 | 2011 | 2014 | 2015 |
| On-Post Pumping (AF/yr) | 1403 | 1391 | 1387.3 | 1316.4 | 1315.9 | 1315.4 | 1300.70 | 1287.00 |
| Effluent to Basins | 426 | 517 | 547 | 506 | 506 | 505 | 497.00 | 489.00 |
| Effluent as % of Pumping | 30.4% | 37.2% | 39.4% | 38.4% | 38.5% | 38.4% | 38.2% | 38.0% |
| Contribution from Huachuca City | 0 | 0 | 0 | 0 | 200 | 200 | 200 | 200 |
| Evaporative Losses (2.5%) | -10.65 | -12.925 | -13.675 | -12.65 | -17.65 | -17.625 | -17.425 | -17.225 |
| Total Recharge | 415.35 | 504.1 | 533.3 | 493.4 | 688.4 | 687.4 | 679.6 | 671.8 |
| Source: 2006 Programmatic Biological Assessment - Appendix H (ENRD, 2006). | | | | | | | | |

Table B.5 provides reported values for influent recharge[23] and pumping, as well as estimated recharge corrected for evapotranspiration (ET) loss. The 2.5% ET loss rate comes from the 2006 BA (ENRD, 2006), as shown in Table B.4.

The bottom two rows of Table B. 5 calculate seasonal recharge and pumping as percentages of total annual recharge and pumping, respectively. These seasonal values are utilized in Table B. 5 to parse annual recharge and pumping values into seasonal components for the purpose of simulation. Table B.6 lists projected artificial recharge at the Fort Huachuca recharge facility for the simulation period 2011-2015. From 2015 to 2105, simulated artificial recharge remains constant at 2015 values with the same seasonal distribution.

[23] Influent is the inflow to the recharge basins and is comprised of total effluent minus any effluent "re-use" for irrigation.

**TABLE B. 5. REPORTED BASIN INFLUENT (AFTER RE-USE), REPORTED PUMPING, AND ESTIMATED RECHARGE FOR FORT HUACHUCA, 2002-2010**

| INFLUENT TO FORT HUACHUCA RECHARGE BASINS (AFTER RE-USE) | | | | | | | | ESTIMATED EFFLUENT RECHARGE CORRECTED FOR ET LOSSES[3] | | | | REPORTED ON-POST PUMPING RATES | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Annual | | Seasonal | | |
| Influent to Basins (AFY) | Start Date | Seasonal Influent Value[1] (AF) | # Days in Season | Model Stress Period (2003-2020) | Seasonal % differ-ence | Seasonal Influent as % of Seasonal Pumping | Seasonal Influent as % of Annual Influent | Total Annual Recharge (AF) | Seasonal Recharge Value | | cu-m/d per 250m x 250m cell (2 cells) | Kgal | AF | Kgal[1] | AF | Seasonal Pumping as % of Annual Pumping |
| | | | | | | | | | AF | cu-m/d | | | | | | |
| | 4/1/2002 | 248.91 | 214 | na | | 25% | 50% | 493 | 246 | 1420.35 | 0.011363 | | | 322348 | 989.25 | 68% |
| 497.8 | 11/1/2002 | 248.89 | 152 | na | 0% | 53% | 50% | 493 | 246 | 1999.55 | 0.015996 | 475645 | 1459.70 | 153297 | 470.45 | 32% |
| | 4/1/2003[2] | 237.13 | 214 | 1 | | 23% | 51% | 461 | 235 | 1353.13 | 0.010825 | | | 337674 | 1036.28 | 67% |
| 465.9 | 11/1/2003 | 228.77 | 152 | 2 | 4% | 45% | 49% | 461 | 226 | 1837.91 | 0.014703 | 504880 | 1549.42 | 167206 | 513.14 | 33% |
| | 4/1/2004 | 223.19 | 214 | 3 | | 23% | 48% | 456 | 221 | 1273.59 | 0.010189 | | | 313668 | 962.61 | 65% |
| 460.84 | 11/1/2004 | 237.65 | 151 | 4 | -6% | 45% | 52% | 456 | 235 | 1921.89 | 0.015375 | 485864 | 1491.06 | 172196 | 528.45 | 35% |
| | 4/1/2005 | 203.43 | 214 | 5 | | 23% | 50% | 400 | 201 | 1160.83 | 0.009287 | | | 290529 | 891.60 | 65% |
| 404.25 | 11/1/2005 | 200.82 | 151 | 6 | 1% | 43% | 50% | 400 | 199 | 1624.04 | 0.012992 | 443938 | 1362.39 | 153409 | 470.79 | 35% |
| | 4/1/2006 | 214.33 | 214 | 7 | | 30% | 58% | 363 | 212 | 1223.03 | 0.009784 | | | 234074 | 718.35 | 62% |
| 366.6 | 11/1/2006 | 152.27 | 151 | 8 | 29% | 34% | 42% | 363 | 151 | 1231.42 | 0.009851 | 379146 | 1163.55 | 145072 | 445.21 | 38% |
| | 4/1/2007 | 182.17 | 214 | 9 | | 22% | 48% | 378 | 180 | 1039.52 | 0.008316 | | | 267315 | 820.36 | 66% |
| 382.031 | 11/1/2007 | 199.861 | 151 | 10 | -10% | 48% | 52% | 378 | 198 | 1616.29 | 0.01293 | 402242 | 1234.43 | 134927 | 414.08 | 34% |
| | 4/1/2008 | 247.7509 | 214 | 11 | | 34% | 58% | 419 | 245 | 1413.74 | 0.01131 | | | 234742 | 720.40 | 62% |
| 423.5151 | 11/1/2008 | 175.7642 | 151 | 12 | 29% | 40% | 42% | 419 | 174 | 1421.42 | 0.011371 | 377626 | 1158.89 | 142884 | 438.49 | 38% |
| | 4/1/2009 | 191.8942 | 214 | 13 | | 24% | 48% | 393 | 190 | 1095.00 | 0.00876 | | | 256206 | 786.27 | 66% |
| 396.9416 | 11/1/2009 | 205.0474 | 151 | 14 | -7% | 50% | 52% | 393 | 203 | 1658.23 | 0.013266 | 389518 | 1195.39 | 133312 | 409.12 | 34% |
| | 4/1/2010 | 221.3831 | 214 | 13 | | 30% | | 219 | 219 | 1263.28 | 0.010106 | | | 237636 | 729.28 | |
| | 11/1/2010 | | 151 | 14 | | | | | | | | | | | | |
| 414.30 | 7-yr avg (2003-2009) | | | | 6% | 34% | 50% | | | | | | | | | |
| | | | | Average summer influent as % of Annual Influent | | 52% | | | | | | | | Average Summer Pumping as a % of Annual Pumping | | 65% |
| | | | | Average Winter Influent as % of Annual Influent | | 48% | | | | | | | | Average Winter Pumping as a % of Annual Pumping | | 35% |

Source: Fort Huachuca Dept. of Public Works via T. Runyon, ENRD Hydrologist (pers. comm., 2007, 2010, 2011).

TABLE B.6 PROJECTED EFFLUENT RECHARGE RATES AND PUMPING RATES AT FORT HUACHUCA, 2010-2015.

| Projected Artificial Recharge Values at Fort Huachuca Recharge Basins | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual Influent (after re-use) | Start Date | Seasonal Influent | Notes | Annual Recharge (97.5% of Influent) | Seasonal Recharge (97.5% of Influent)* | | Recharge Rate per 250m x 250m Model Cell (2 cells) | SP | Annual Pumping | | Seasonal Pumping |
| AF | | AF | | AF | AF | cu-m/d | cu-m/d | | AF | cu-m/d | AF |
| 500 | 11/1/2010 | 241 | no Huachuca City Effluent Contri-bution | 452 | 241 | 1967.98 | 0.015744 | 16 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2011 | 259 | | | 246 | 1418.39 | 0.011347 | 17 | | | 844.1417 |
| 499 | 11/1/2011 | 241 | | 487 | 241 | 1951.91 | 0.015615 | 18 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2012 | 258 | | | 245 | 1414.47 | 0.011316 | 19 | | | 844.1417 |
| 498 | 11/1/2012 | 240 | | 485 | 240 | 1959.40 | 0.015675 | 20 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2013 | 361 | Huachuca City Effluent Added (200 af/yr) | | 344 | 1981.53 | 0.015852 | 21 | | | 844.1417 |
| 697 | 11/1/2013 | 336 | | 680 | 336 | 2744.93 | 0.021959 | 22 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2014 | 361 | | | 344 | 1980.09 | 0.015841 | 23 | | | 844.1417 |
| 697 | 11/1/2014 | 336 | | 679 | 336 | 2742.93 | 0.021943 | 24 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2015 | 360 | | | 342 | 1972.15 | 0.015777 | 25 | | | 844.1417 |
| 694 | 11/1/2015 | 334 | | 677 | 334 | 2713.96 | 0.021712 | 26 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2016 | 360 | | | 342 | 1972.15 | 0.015777 | 27 | | | 844.1417 |
| 694 | 11/1/2016 | 334 | | 677 | 334 | 2731.94 | 0.021855 | 28 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2017 | 360 | | | 342 | 1972.15 | 0.015777 | 29 | | | 844.1417 |
| 694 | 11/1/2017 | 334 | | 677 | 334 | 2731.94 | 0.021855 | 30 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2018 | 360 | | | 342 | 1972.15 | 0.015777 | 31 | | | 844.1417 |
| 694 | 11/1/2018 | 334 | | 677 | 334 | 2731.94 | 0.021855 | 32 | 1300 | 4393.22 | 453.7223 |
| | 4/1/2019 | 360 | | | 342 | 1972.15 | 0.015777 | 33 | | | 844.1417 |
| 694 | 11/1/2019 | 334 | | 677 | 334 | 2713.96 | 0.021712 | 34 | 1300 | 4393.22 | 453.7223 |

*All evaporative losses applied in summer. SP = Model Stress Period

Note: Seasonal values of simulated artificial recharge repeat from 2015-2105.