SIMULATED NEAR-STREAM RECHARGE AT THREE SITES IN THE SIERRA VISTA SUBBASIN, ARIZONA

Tasks 2-4 Report for December 2010 Contract

Prepared for

Friends of the San Pedro River

and

The Walton Family Foundation

by

Laurel J. Lacher, PhD, RG
Lacher Hydrological Consulting
Tucson, Arizona

REGISTERED GEOLOGIST
CERTIFICATE NO.
49074
LAUREL J.
LACHER
Date Signed 1-12-12
ARIZONA U.S.A.
Expires 3/31/12

January 2012

FORMAT PAGE

EXECUTIVE SUMMARY

This study explores near-stream recharge as a mechanism for sustaining stream baseflows and riparian habitat in the face of continued groundwater-based development in the Upper San Pedro Basin of southeast Arizona through a series of computer simulations. The source of the simulated recharge water is unspecified, but its use is assumed to have no negative impact on the existing basin-wide water budget during the 100-year simulation period.

Simulations of artificial recharge at three sites in the Sierra Vista subbasin of the Upper San Pedro Basin demonstrate how different antecedent hydrologic and ecological conditions at the sites govern the fate of water recharged through the surface. The Palominas site, near the south end of the Sierra Vista subbasin, exhibits model characteristics of low hydraulic conductivity, high potential for increased riparian evapotranspiration, and moderately deep groundwater under the San Pedro River. The Garden Canyon recharge site in the center of the basin has model characteristics that include moderate hydraulic conductivity, shallow groundwater, and limited potential for increased riparian plant growth. The Babocomari recharge site in the northeast portion of the model area lies along the Babocomari River, approximately 10.5 miles upstream of its confluence with the San Pedro River. This site's model characteristics include high hydraulic conductivity, moderately deep groundwater under the stream, and low potential for increased riparian evapotranspiration (ET).

Three sets of simulations apply to each of the three hypothetical near-stream recharge sites. In all cases, artificial recharge is added to the baseline model, which simulates pumping growth and artificial recharge at existing sites over the next 100 years. The first set of simulations, "constant-rate recharge", applies surface recharge at a constant rate of 500 acre-feet per year (AF/yr) to each site independently over the period 2012-2111. The second set of simulations, "variable-rate recharge", increases recharge incrementally at each site, as necessary, to sustain downstream baseflows (groundwater-driven stream flow) at 2003 levels[1] over the next 100 years. The third set of simulations, "concurrent variable-rate recharge," applies the same variable-rate recharge at all three sites concurrently, then optimizes that recharge to determine the water savings afforded by concurrent operation of the sites.

The constant-rate recharge simulation at the Palominas site reveals limited recharge capacity and high riparian ET demand. While a small (1.25-mile) reach of the San Pedro River downstream of this site exhibits a positive response to near-stream recharge of 500 AF/yr at the Palominas site, most of the recharged water is consumed by simulated riparian ET demand,

[1]2003 marks the end of the transient model's calibration period, and was therefore considered a good representation of recent flow conditions.

FMC000959

and increasing demand for aquifer storage replenishment after 2030. The same rate of recharge applied at the Garden Canyon site produces steadily-increasing simulated baseflows in the entire 16.5-mile downstream reach of the San Pedro River above its confluence with the Babocomari River over the 100-year simulation period. About half of the simulated recharge goes to satisfy demands for riparian ET and replenishment of aquifer storage, and the remainder translates into increased baseflow. Baseflows downstream of the Babocomari site show short-term increases in response to the 500 AF/yr-recharge simulation, but this response quickly diminishes after 2030. The expanding simulated cone of depression under the site depresses groundwater levels and consumes most (72%) of the simulated recharge water by 2111.

In the variable-rate recharge simulation, Palominas recharge increases from 500 to 700 AF/yr between 2012 and 2030, and then stabilizes at a maximum rate of 700 AF/yr. This maximum simulated rate represents the balance between what the site can absorb (limited by hydraulic conductivity and depth to water) and the rate of consumption of the recharged water by riparian ET (95%) and aquifer storage demand (5%).

For the Garden Canyon site, simulated recharge at 500 AF/yr successfully maintains downstream baseflows at 2003 levels until 2060. Recharge increases of 100 AF/yr in 2060 and again in 2090 are necessary to sustain downstream baseflows for the remainder of the simulation period. The timing of this increased recharge demand reflects the evolving dynamics of the simulated cone of depression, which appears to capture baseflow at this site more rapidly in the second half of the 21st Century. Of the added recharge applied in the last half of the simulation period, roughly 58% translates directly into increased downstream baseflows, while 17% satisfies growing aquifer storage demand and 25% goes to riparian ET demand.

The Babocomari site lies just west of a major silt and clay unit that extends along the length of the model area, primarily west of the San Pedro River. Because it does not overlie the silt and clay unit as do the Palominas and Garden Canyon Sites, this surface site is in more direct hydrologic communication with the underlying regional aquifer than the other two sites (Pool and Dickinson, 2007). As a result, simulated recharge must increase steadily by 100 to 400 AF every 10 years (to a peak of 2,600 AF/yr by 2100) in order to maintain downstream baseflows at 2003 levels over the 100-year simulation period. Fifty-six percent (56%) of the additional recharge in the variable-rate recharge simulation supports downstream baseflows, while 42% replenishes aquifer storage, and just 2% satisfies riparian ET demand.

Simulating concurrent variable-rate recharge at all three sites successfully maintains baseflows throughout the Sierra Vista subbasin at levels higher than those observed in 2003 throughout the 100-year simulation period. The greatest impact of the concurrent recharge scenario

appears in increased simulated baseflows along the SPR downstream (north) of the Garden Canyon site. Subsequent simulations explored the potential for reducing recharge at the Garden Site while maintaining the same variable-rate recharge distributions at the Babocomari and Palominas sites. Iterative reduction in recharge rates at the Garden Canyon site reveals the new minimum recharge rate required to sustain 2003 baseflows throughout the Sierra Vista subbasin. The resulting recharge configuration at the Garden Canyon site consists of 100 AF/yr from 2012-2085, increasing to 500 AF/yr by 2090, and stabilizing there until 2111. Ultimately, simulation of concurrent recharge at the three sites allows a reduction in recharge of roughly 350 AF/yr at the Garden Canyon site, and results in a maximum recharge demand of 3,800 AF/yr (200 AF/yr less than the combined independent sites) by 2111.

The simulations in this study demonstrate that strategic recharge of water near the San Pedro River and its major tributary, the Babocomari River, may successfully maintain baseflows at 2003 levels and increased riparian ET demand by maintaining required near-stream hydraulic heads in the presence of an expanding regional cone of depression in the basin-fill aquifer. The large-scale model used in this study provides a good tool for comparing various basin-wide recharge strategies, but significantly more detail will be required for more accurate predictions of local-scale effects at each recharge site.

FMC000961

ABBREVIATIONS AND ACRONYMS

AF	acre-feet
AF/yr	acre-feet per year
cfs	cubic-feet per second
EOP	Environmental Operations Facility (City of Sierra Vista)
ET	evapotranspiration
ft	feet
SPR	San Pedro River
SPRNCA	San Pedro River National Conservation Area
US	United States
USGS	United States Geological Survey
USPB	Upper San Pedro River Basin
USPP	Upper San Pedro Partnership

TABLE OF CONTENTS

LIST OF FIGURES 7
LIST OF TABLES 11
INTRODUCTION 12
Purpose of Study 12
Methods 14
CONSTANT-RATE RECHARGE SIMULATION RESULTS 17
Palominas Site 17
Garden Canyon Site 23
Babocomari Site 29
VARIABLE-RATE RECHARGE SIMULATION RESULTS 36
Palominas Site 37
Garden Canyon Site 41
Babocomari Site 45
CONCURRENT RECHARGE AT ALL THREE SITES 49
Initial Variable-Rate Recharge 49
Optimized Variable-Rate Recharge 52
SUMMARY AND CONCLUSIONS 56
Summary 56
Conclusions 61
REFERENCES CITED 62

LIST OF FIGURES

Figure 1. Map of the Upper San Pedro Basin showing extent of the USGS' groundwater flow model (Pool and Dickinson, 2007) and the San Pedro Riparian National Conservation Area. The Sierra Vista subbasin is the area north of the international boundary with Mexico (from Figure 1 in Pool and Dickinson, 2007) 13
Figure 2. Simulated recharge sites in the Sierra Vista subbasin of the Upper San Pedro River basin. Sites are overlain on Map of riparian condition class and Streamflow Presence in June 2002 (from Figure 42 in Stromberg, et al (2006)). River reaches 2, 4, 6, and 7 are Class

FMC000963

3 ("WET"), while The remaining reaches in the Sierra Vista Subbasin are Class 2 ("INTERMEDIATE"). 15
FIGURE 3. Conceptualized cross section of USPB showing model layers (from Figure 3 in Pool and Dickinson (2007)). 16
Figure 4. Palominas recharge site in model layer 1. Stream cell used for illustration in Figure 9 is shown in yellow. Wet and dry reaches of the SPR reflect conditions recorded during June 2002 (after Figure 42 in Stromberg, et al, 2006). 18
Figure 5. Palominas recharge site (red oval) and simulated extent of positive baseflow effects downstream in response to 500 AF/yr constant-rate recharge four years after the onset of artificial recharge. 19
Figure 6. Simulated change in spring baseflow resulting from 500 AF/yr of recharge at the Palominas site applied from October 2012 to March 2111 for the years: a) 2016, b) 2030, c) 2060, and d) 2090. 20
Figure 7. Cumulative changes in simulated basin-wide model water budget resulting solely from 500 AF/yr recharge applied at the Palominas site from October 2012 to March 2111. 21
Figure 8. Schematic diagram of conceptualization of head-dependent ET rates in MODFLOW (McDonald and Harbaugh, 1988). 22
Figure 9. Depth to groundwater (ft) at the Palominas site over the period 2003-2111 with constant-rate recharge of 500 AF/yr starting in October 2012. 23
Figure 10. Map of Garden Canyon recharge site and the Sierra Vista Environmental Operations Park (EOP) recharge facility overlain on riparian condition class map by Stromberg, et al (2006). The stream cell used for illustration in Figure 13 is shown in yellow. Wet and dry stream reaches reflect conditions observed in June 2002 (after Figure 42 in Stromberg, et al, 2006). 24
Figure 11. Garden Canyon recharge site (red oval) and extent and magnitude of baseflow increase downstream of site by March 2016, four years after the onset of simulated recharge. Riparian condition class and stream flow presence from Figure 42 in Stromberg, et al (2006). 25
Figure 12. Simulated change in spring baseflow resulting from 500 AF/yr of recharge at the Garden Canyon site applied from October 2012 to March 2111 for the years: a) 2016, b) 2030, c) 2060, and d) 2090. 26
Figure 13. Depth to groundwater (ft) at Garden Canyon site under constant-rate recharge of 500 AF/yr from 2012-2111. 27
Figure 14. Cumulative changes in simulated basin-wide model water budget resulting solely from 500 AF/yr recharge applied at the Garden Canyon site from October 2012 to March 2111. 28
Figure 15. Map of Babocomari recharge site and the Sierra Vista Environmental Operations Park (EOP) recharge facility. The stream cell used for illustration in Figure 20 is shown in

yellow. Wet and dry stream reaches reflect conditions recorded in June 2002 (after Figure 42 in Stromberg, et al, 2006). 30
Figure 16. Extent and altitude of top of the thick silt and clay interval in the basin fill, USPB, United States and Mexico (from Pool and Dickinson (2007) Figure 4A). Recharge sites indicated by red ovals. 31
Figure 17. Extent and altitude of bottom of the thick silt and clay interval in the basin fill, USPB, United States and Mexico (from Pool and Dickinson (2007) Figure 4B). Recharge sites indicated by red ovals. 32
Figure 18. Babocomari recharge site (red oval) and lineal extent and amount of baseflow increase as of March 2016 due to 500 AF/yr constant recharge applied at Babocomari site from October 2012 to March 2016. Riparian condition class and stream flow presence from Figure 42 in Stromberg, et al (2006). 33
Figure 19. Simulated change in spring baseflow resulting from 500 AF/yr of recharge at the Babocomari site applied from October 2012 to March 2111 for the years: a) 2016, b) 2030, c) 2060, and d) 2090. 34
Figure 20. Depth to groundwater (ft) under stream immediately adjacent to the Babocomari recharge site under constant-rate recharge conditions of 500 AF/yr starting in October 2012. 35
Figure 21. Cumulative changes in simulated basin-wide model water budget resulting solely from 500 AF/yr recharge applied at the Babocomari site from October 2012 to March 2111. 35
Figure 22. Simulated difference in baseflow (cfs) from 2003 baseflow conditions with variable-rate recharge at the Palominas Site from 2012 through 2111. 38
Figure 23. Simulated variable recharge rate at Palominas Site (blue line) and DTW in stream cell immediately downstream of Palominas recharge site (see Figure 4) for both constant-rate (500 AF/yr) and variable-rate recharge scenarios. 39
Figure 24. Cumulative changes in simulated water budget relative to constant-rate recharge scenario resulting from variable-rate recharge at the Palominas site. 41
Figure 25. Simulated difference in baseflow (cfs) from 2003 baseflow conditions with variable-rate recharge at the Garden Canyon Site from 2012 through 2111. 42
Figure 26. Simulated variable recharge rate at Garden Canyon site and DTW in stream cell immediately downstream of Garden Canyon recharge site (see Figure 10) from March 2003 to March 2111 for both constant-rate (500 af/yr) and variable-rate recharge scenarios. 43
Figure 27. Cumulative changes in simulated water budget relative to the constant-rate recharge scenario resulting from variable-rate recharge at the Garden Canyon site. 44
Figure 28. Simulated variable recharge rate at Babocomari Site and DTW in stream cell immediately downstream of Babocomari recharge site (see Figure 15) from March 2003 To March 2111 for both constant-rate (500 af/yr) and variable-rate recharge scenarios. 45

FMC000965

Figure 29. Simulated difference in baseflow (cfs) from 2003 conditions with variable-rate recharge at the Babocomari site from 2012 through 2111. 47
Figure 30. Cumulative changes in simulated water budget relative to the constant-rate recharge scenario resulting from variable-rate recharge at the Babocomari site. 48
Figure 31. Simulated difference in baseflow (cfs) from 2003 baseline conditions with concurrent initial variable-rate recharge at the Palominas, Garden Canyon, and Babocomari sites at four points in time: a) March 2030, B) March 2050, C) March 2070, and D) March 2111. 50
Figure 32. Simulated cumulative change (af) in water budget (vs. baseline scenario) for initial variable-rate recharge at Palominas, Garden Canyon, and Babocomari sites, 2012-2111.... 51
Figure 33. Original and reduced variable-rate recharge distributions at the Garden Canyon Site. 53
Figure 34. Simulated cumulative change (af) in water budget (vs. baseline scenario) for optimized variable-rate recharge at Palominas, Garden Canyon, and Babocomari sites, 2012-2111. 53
Figure 35. Simulated difference in baseflow (cfs) from 2003 baseline conditions with optimized concurrent variable-rate recharge at the Palominas, Garden Canyon, and Babocomari sites at four points in time: a) March 2030, B) March 2050, C) March 2070, and D) March 2111. Recharge was optimized by reducing recharge at the Garden Canyon Site. 55
Figure 36. Comparison of simulated groundwater levels at the three recharge sites in response to 500 af/yr of constant-rate recharge at each site applied from October 2012 to March 2111. 57
Figure 37. Comparison of cumulative changes in simulated water budgets (relative to baseline) at the three recharge sites in response to 500 af/yr of constant-rate recharge applied from October 2012 to March 2111. 57
Figure 38. Comparison of simulated recharge rates required to sustain 2003 baseflow conditions in the affected reach downstream of each of the three recharge sites. 59
Figure 39. Comparison of cumulative water budget changes (AF) at the Babocomari, Garden Canyon, and Palominas sites resulting from additional recharge (above 500 af/yr) applied in the variable-rate recharge scenarios. 59
Figure 40. Comparison of simulated groundwater levels at the three independent recharge sites in response to variable-rate recharge at each site applied from October 2012 to March 2111. 60
Figure 41. Simulated distribution of combined required recharge at Palominas, Garden Canyon, and Babocomari recharge sites to maintain 2003-level baseflows downstream of all three sites, 2012-2111. 61

LIST OF TABLES

Table 1. Simulated change in cumulative water budget resulting from constant-rate recharge at the Palominas site, 2012-2111. 21
Table 2. Simulated water budget for constant-rate recharge at the Garden Canyon site..... 28
Table 3. Simulated water budget for constant-rate recharge at the Babocomari site. 36
Table 4. Comparison of ET characteristics relative to ground surface at Babocomari, Garden Canyon, and Palominas sites as defined in the USGS groundwater model (Pool and Dickinson, 2007). 36
Table 5. Cumulative changes in simulated water budget relative to constant-rate recharge scenario resulting from variable-rate recharge at the Palominas site. 40
Table 6. Cumulative changes in simulated water budget relative to the constant-rate recharge scenario resulting from variable-rate recharge at the Garden Canyon site..... 44
Table 7. Cumulative changes in simulated water budget relative to the constant-rate recharge scenario resulting from variable-rate recharge at the Babocomari Site. 48
Table 8. Water budget for initial concurrent variable-rate recharge simulation at Palominas, Garden Canyon, and Babocomari Recharge Sites, 2012-2111. 51
Table 9. Water budget for optimized concurrent variable-rate recharge simulation at Palominas, Garden Canyon, and Babocomari Recharge Sites, 2012-2111. 54

FMC000967

SIMULATED NEAR-STREAM RECHARGE AT THREE SITES IN THE SIERRA VISTA SUBBASIN, ARIZONA

INTRODUCTION

This study is part of a larger effort to define feasible options for protecting and enhancing riparian habitat along the Upper San Pedro River (SPR) and its major tributary, the Babocomari River, in the Sierra Vista subbasin of the Upper San Pedro River Basin (USPB) in southeastern Arizona (Figure 1). In particular, the projects contemplated in this study aim to have a reasonable chance of improving riparian conditions by the year 2020. The projects described in this study utilize the concept of near-stream recharge to sustain stream baseflows in the face of anticipated ongoing and increasing pumping-induced depletion of aquifer storage. While identifying sources of recharge water is beyond the scope of this study, the projects described herein assume that these projects will have no net impact on the basin-wide water budget within the 100-year simulation time period.

The purpose of near-stream recharge is similar to that of a salt water-intrusion barrier used in coastal areas. Such a hydrologic "barrier" consists of an artificially created groundwater mound that maintains the necessary pressure to prevent sea water from flowing into a nearby fresh-water aquifer, even as pumping from that aquifer reduces freshwater levels to below sea level. A near-stream recharge project can also form a groundwater mound that maintains baseflow in spite of pumping-related depletion of the underlying aquifer. Although the mound does not prevent pumping from depleting baseflows, the groundwater mound provides a source of water under adequate pressure to move it into the river as well as supplying a source of aquifer storage replenishment.

PURPOSE OF STUDY

The Upper San Pedro Partnership (USPP) and others seek to evaluate the potential for recharging water at the surface in locations across the basin in order to sustain or improve existing riparian condition classes as defined by Stromberg, et al (2006) and critical habitat for the Huachuca water umbel that is currently defined within the San Pedro Riparian National Conservation Area (SPRNCA).

FMC000968

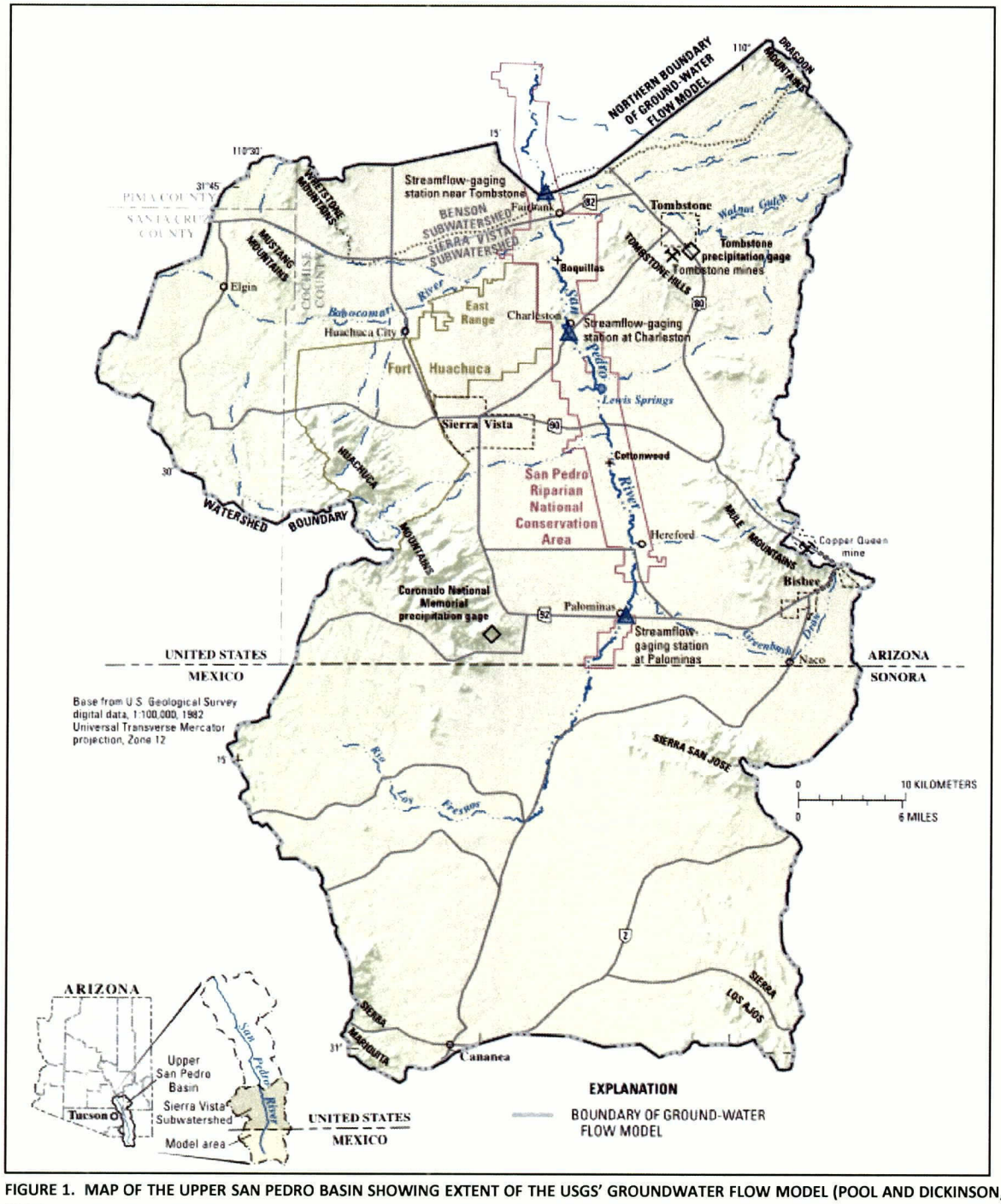

FIGURE 1. MAP OF THE UPPER SAN PEDRO BASIN SHOWING EXTENT OF THE USGS' GROUNDWATER FLOW MODEL (POOL AND DICKINSON, 2007) AND THE SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA. THE SIERRA VISTA SUBBASIN IS THE AREA NORTH OF THE INTERNATIONAL BOUNDARY WITH MEXICO (FROM FIG. 1 IN POOL AND DICKINSON, 2007).

METHODS

This study used an updated (Lacher, 2011)[2] version of the Upper San Pedro Basin groundwater model published by the USGS in 2007 (Pool and Dickinson, 2007) to compare and contrast the simulated hydrologic impacts of near-stream recharge at three sites in the Sierra Vista subbasin. The groundwater model uses the public-domain computer code known as MODFLOW-2000 (Harbaugh, et al, 2000), and was run with the Groundwater Modeling System (GMS v.7.1) software developed by the U.S. Army Corps of Engineers and supported by AQUAVEO™ as a graphical user interface. Figure 2 illustrates the three site locations selected by consensus among members of the USPP Technical Advisory Committee in the summer of 2011. All three sites lie west of the mainstem of the San Pedro River.

The southernmost site, Palominas, lies north of Highway 92 in "the Gap" between two separate sections of the SPRNCA, and between the communities of Palominas and Hereford. The central site, Garden Canyon, lies just northwest of the confluence of Garden Canyon Creek and the SPR within the SPRNCA. The Babocomari site is the northernmost site and is on Fort Huachuca's East Range, south of the Babocomari River at its confluence with Soldier Creek. The sites satisfy various geopolitical criteria as well as two hydrogeologic simulation criteria: 1) at least 500 acre-feet per year (AF/yr) can be recharged from the surface without producing flooding (groundwater at or above the ground surface) during the 100-year simulation period, and 2) surface recharge at the site produces measurable impacts on downstream baseflows within the first 20 years. Each site covers four model cells (roughly 62 acres), and is located adjacent to stream cells in the numerical groundwater model, either in the young alluvium of model layer 1 (Palominas) or on the surface of model layer 2 (Garden Canyon and Babocomari) where layer 1 is not present.

The USPB groundwater model consists of 5 layers in a "stacked bowl" configuration, with layer 5 representing the lower basin fill and bedrock of the east and west bounding mountain ranges as well as the deepest aquifer in the model (Figure 3). Layer 4 (above and recessed within layer 5) represents the primary, or upper basin-fill aquifer, and has surface exposures primarily west of the SPR across the entire longitudinal extent of the model from north of the Babocomari River down to near the copper-mining town of Cananea, Mexico. Model layers 2 and 3 lie above, and are recessed within, layer 4 and represent primarily silt and clay with very low to moderate hydraulic conductivities on the west side of the SPR within the Sierra Vista subbasin. Layer 2 has surface exposures in the Sierra Vista subbasin, but layer 3 lies entirely underneath layer 2 with no surface exposure. Layer 1 represents stream alluvium associated with the SPR

[2] Lacher (2011) updated pumping and artificial recharge for 2003-2010. An additional update to the model used in this study includes the reconfiguration of surface recharge at the City of Sierra Vista's Environmental Operations Park to more accurately reflect existing conditions.

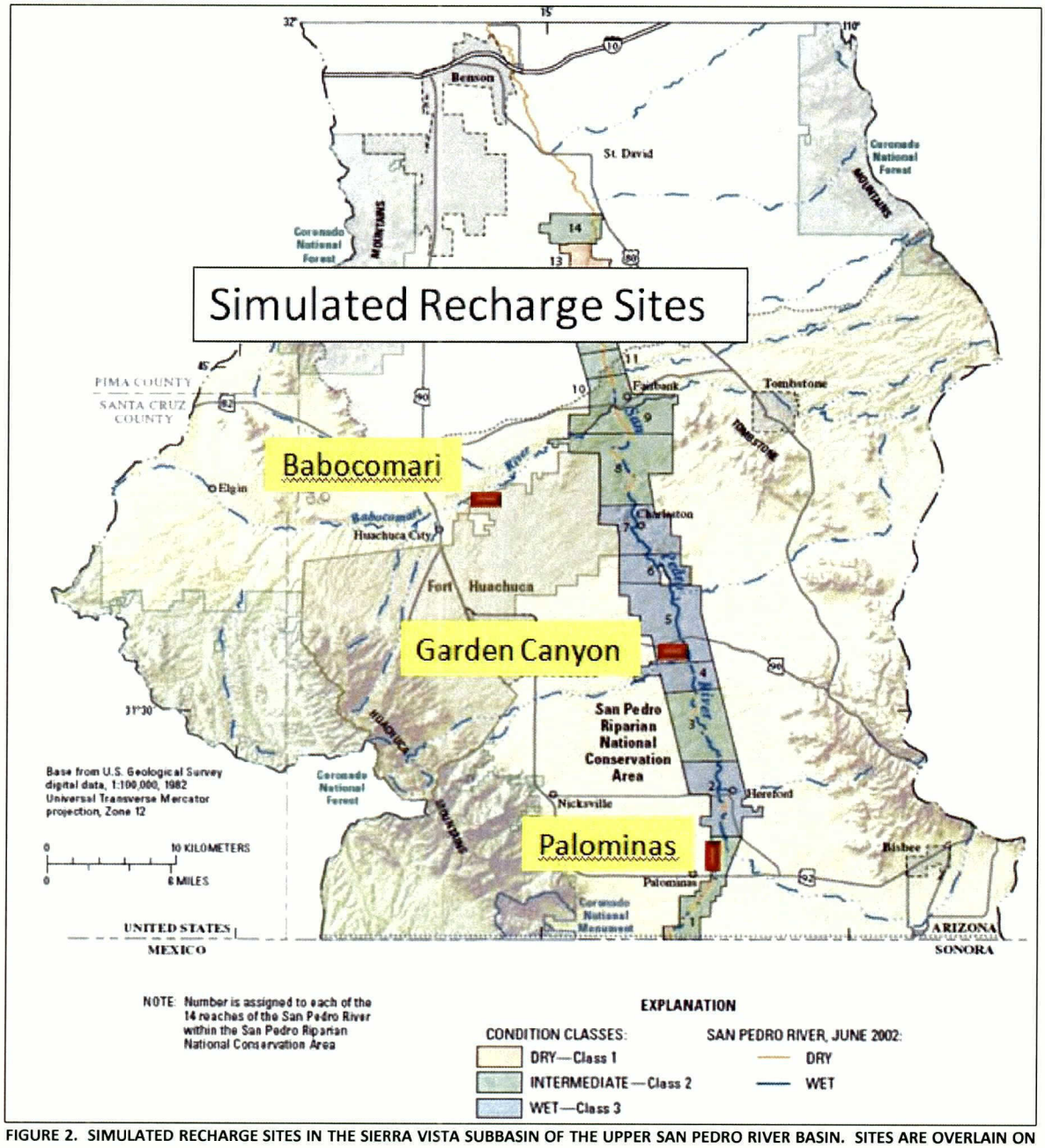

FIGURE 2. SIMULATED RECHARGE SITES IN THE SIERRA VISTA SUBBASIN OF THE UPPER SAN PEDRO RIVER BASIN. SITES ARE OVERLAIN ON MAP OF RIPARIAN CONDITION CLASS AND STREAMFLOW PRESENCE IN JUNE 2002 (FROM FIGURE 42 IN STROMBERG, ET AL (2006)). RIVER REACHES 2, 4, 6, AND 7 ARE CLASS 3 ("WET"), WHILE THE REMAINING REACHES IN THE SIERRA VISTA SUBBASIN ARE CLASS 2 ("INTERMEDIATE").

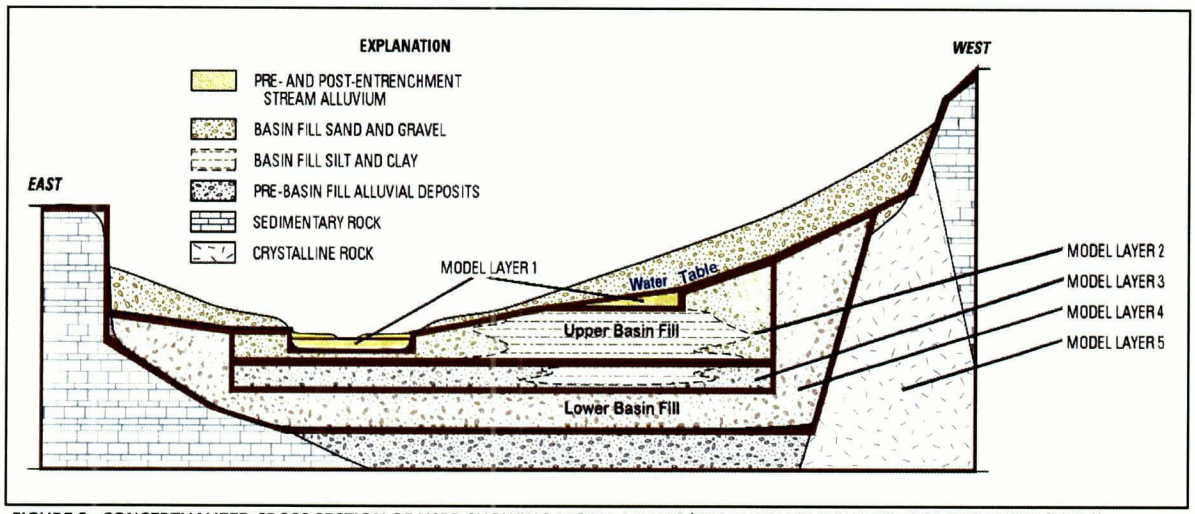

FIGURE 3. CONCEPTUALIZED CROSS SECTION OF USPB SHOWING MODEL LAYERS (FROM FIGURE 3 IN POOL AND DICKINSON (2007)).

covering only a small area of the model's surface, and does not extend south across the international boundary with Mexico. Additional details on the model structure and development are available in Pool and Dickinson (2007).

This study simulated two recharge scenarios for each of the three near-stream sites as well as one scenario with all three sites recharging concurrently. All recharge scenarios were built from a "baseline" scenario which simulates historic, current, and projected future artificial recharge and pumping from 1902-2111, but includes no artificial recharge at the three near-stream sites discussed in this study. The simulated recharge water originates from an unspecified source (see Introduction). Examples of such sources may include stormwater, treated wastewater, or water imported from outside the basin. Importantly, existing incidental recharge from urban-enhanced runoff in stream channels and stormwater detention facilities is accounted for in the groundwater model, so any water destined for the types of projects described in this study would entail development of new sources water.

The first scenario ("constant-rate recharge") applied water at a constant rate of 500 AF/yr at the surface of each the three sites, independently, from October 2012 through March 2111. The second scenario ("variable-rate recharge") iteratively increased recharge rates at each site from the initial 500 AF/yr, as necessary, to sustain simulated baseflows downstream of each site at or above 2003[3] levels throughout the 100-year simulation period. In this scenario, recharge was increased by increments of 100 AF/yr in 10-year (minimum) blocks, as needed, to sustain downstream flows at or above 2003 levels. Simulated recharge was also limited to rates

[3] March of 2003 marks the end of the transient calibration period for the USGS groundwater model by Pool and Dickinson (2007) used for this study, and baseflows at that time represent a widely accepted "status quo" condition for the Upper SPR.

that did not produce flooding of model cells at the near-stream recharge sites. The third modeling scenario ("concurrent variable-rate recharge") applies the same variable-rate recharge to all three sites concurrently, then optimizes that recharge to define the minimum cumulative near-stream recharge required to maintain 2003-level baseflows throughout the Sierra Vista subbasin.

The modified[4] groundwater model by Pool and Dickinson (2007) has two stress periods per year. The summer stress period runs from mid-March to mid-October, while the winter stress period covers the mid-October to mid-March period. The model computes baseflows as streamflow resulting from groundwater at or above the bottom elevation of the streambed. No storm flows or bank-storage-related flows are included in the model, but simulated baseflows fluctuate in response to seasonal pumping and ET demands. In order to isolate the effects of near-stream recharge simulated in this study, cumulative water budget numbers from the baseline model were subtracted from the water budget values in the near-stream recharge scenarios for the 2012-2111 simulation period.

CONSTANT-RATE RECHARGE SIMULATION RESULTS

PALOMINAS SITE

The Palominas constant-rate recharge simulation applied 500 AF/yr of surface recharge from 2012 to 2111 across a 62-acre area in model layer 1 (recent alluvium) immediately west of the SPR at the site shown in Figure 4. The simulated effects of this recharge can be characterized in terms of impacts to baseflow downstream of the site as well as impacts to the basin-wide water budget. Figure 5 shows the lineal extent of simulated baseflow response in the SPR by March 2016, less than four years after the onset of artificial recharge. Significantly, simulated recharge at this site affects a small part of the SPR presently rated as Class 2 ("intermediate") riparian condition (Stromberg, et al, 2006), as opposed to the more robust ("wet") Class 3 riparian conditions farther downstream (north) on the SPR.

Figure 6 compares baseflow increases (relative to baseline) in response to simulated recharge at the Palominas site in March of simulation years 2016, 2030, 2060, and 2090. This figure indicates that the maximum baseflow increase occurs around 2030 and then wanes throughout the rest of the simulation period. The downstream extent of the increase in baseflow is limited to about 1.25 miles throughout the simulation period. The graphics in Figure 6 provide no information about the overall status of baseflows relative to their historic values. Rather, they only reveal changes to baseflow resulting from the addition of 500 AF/yr at the Palominas site.

[4] Refer to footnote 2.

FMC000973

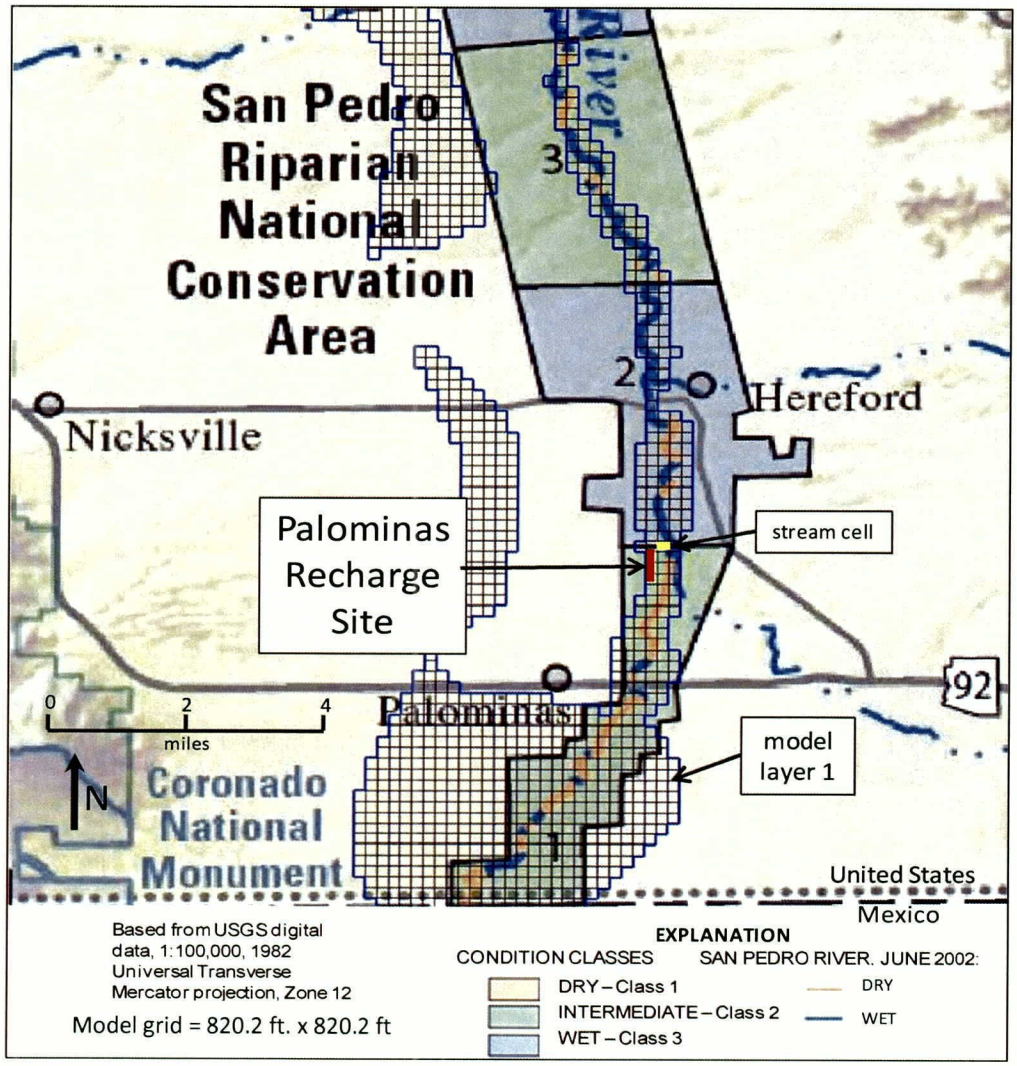

FIGURE 4. PALOMINAS RECHARGE SITE IN MODEL LAYER 1. STREAM CELL USED FOR ILLUSTRATION IN FIGURE 9 IS SHOWN IN YELLOW. WET AND DRY REACHES OF THE SPR REFLECT CONDITIONS RECORDED DURING JUNE 2002 (AFTER FIGURE 42 IN STROMBERG, ET AL, 2006).

Figure 7 shows the cumulative effect of simulated constant-rate recharge at the Palominas site on the basin-wide water budget by the end of the simulation period in March 2111. Values used to derive this chart are provided in column 4 of Table 1, and represent the *difference* in the water budget (compared with baseline) due solely to the addition of 500 AF/yr of recharge at the Palominas site from 2012-2111.[5] The positive and negative signs on the water budget values reflect MODFLOW sign conventions. In general, Figure 7 shows that virtually all of the recharge added to the model (nearly 50,000 AF over 100 years) is partitioned into three water

[5] Water budget values for the same period in the baseline model were subtracted from constant-rate recharge simulation water budget values.

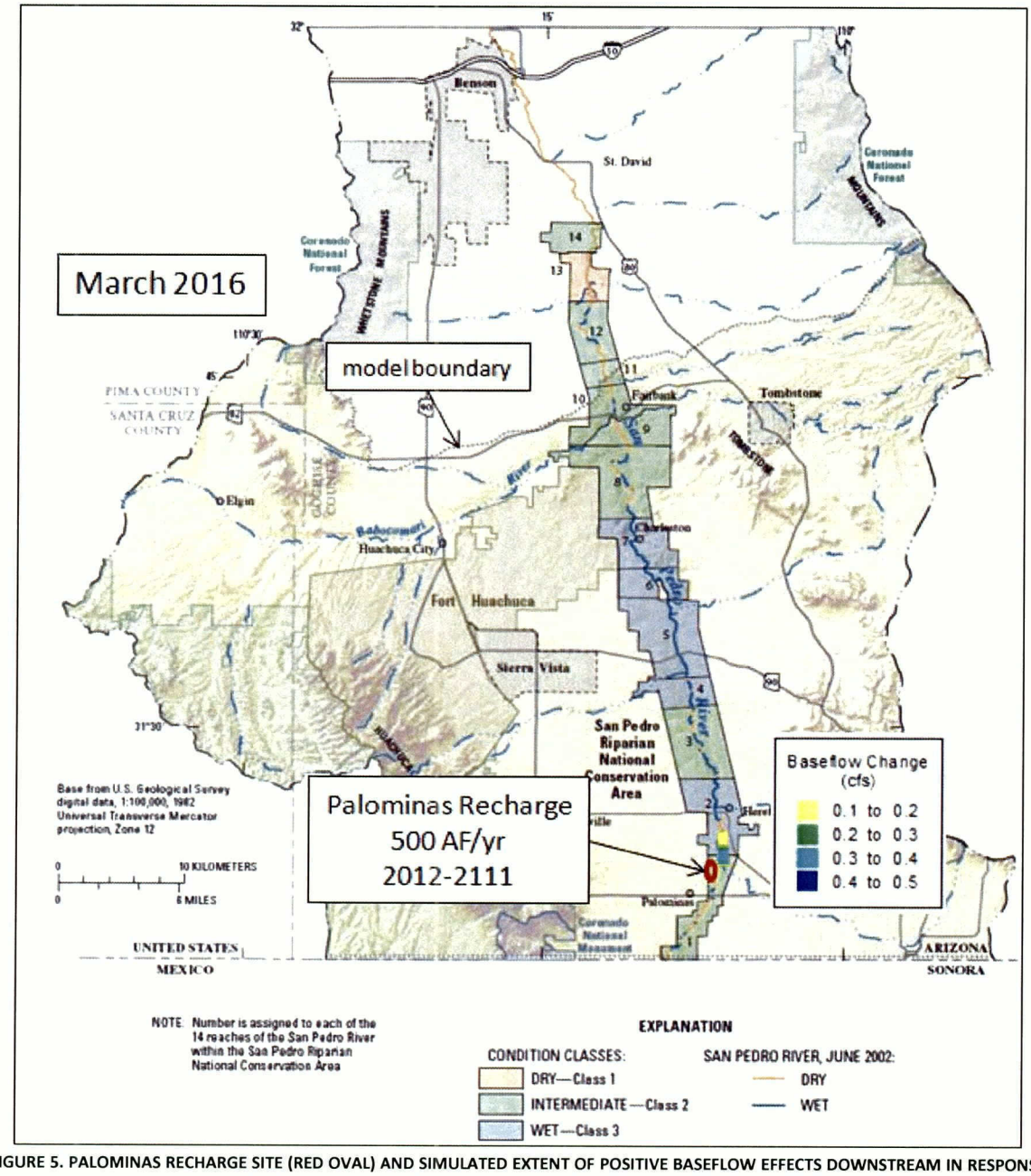

FIGURE 5. PALOMINAS RECHARGE SITE (RED OVAL) AND SIMULATED EXTENT OF POSITIVE BASEFLOW EFFECTS DOWNSTREAM IN RESPONSE TO 500 AF/YR CONSTANT-RATE RECHARGE FOUR YEARS AFTER THE ONSET OF ARTIFICIAL RECHARGE.

budget components: aquifer storage replenishment, riparian evapotranspiration (ET), and baseflow. While the model computes some differences in pumping, constant-head boundary, and drain components of the water budget (see column 4 of Table 1), these difference values are so small (≤0.1%) relative to the water budget component totals in the baseline model (refer to column 5 of Table 1), that they may be considered negligible.

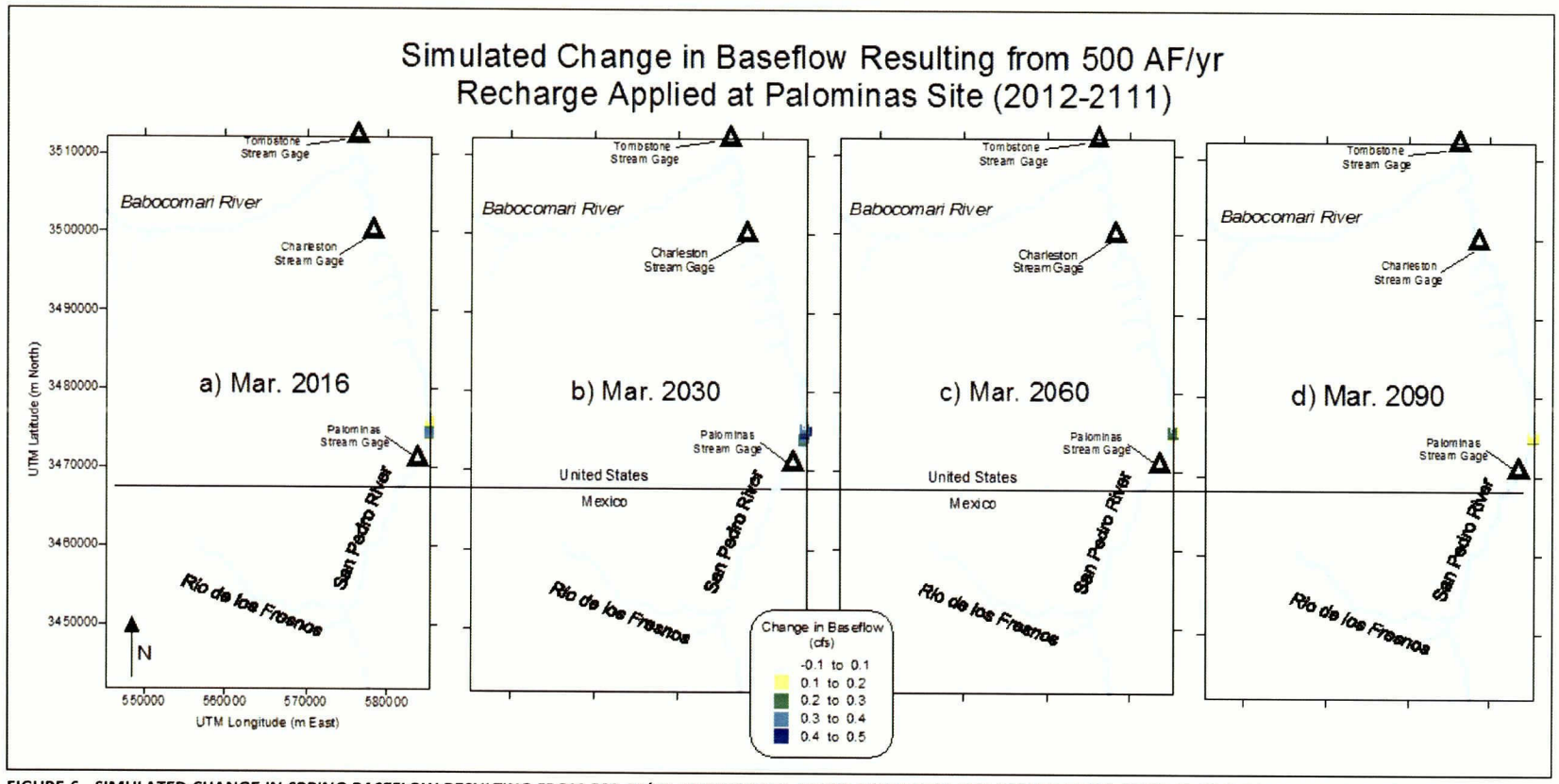

FIGURE 6. SIMULATED CHANGE IN SPRING BASEFLOW RESULTING FROM 500 AF/YR OF RECHARGE AT THE PALOMINAS SITE APPLIED FROM OCTOBER 2012 TO MARCH 2111 FOR THE YEARS: A) 2016, B) 2030, C) 2060, AND D) 2090.

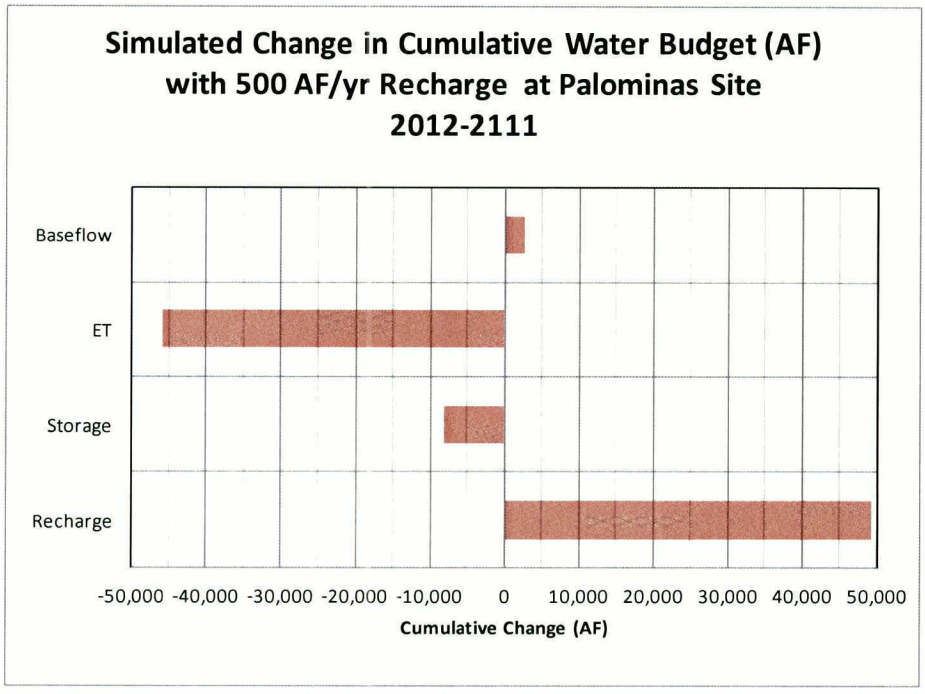

FIGURE 7. CUMULATIVE CHANGES IN SIMULATED BASIN-WIDE MODEL WATER BUDGET RESULTING SOLELY FROM 500 AF/YR RECHARGE APPLIED AT THE PALOMINAS SITE FROM OCTOBER 2012 TO MARCH 2111.

TABLE 1. SIMULATED CHANGE IN CUMULATIVE WATER BUDGET RESULTING FROM CONSTANT-RATE RECHARGE AT THE PALOMINAS SITE, 2012-2111.

Palominas Constant-Rate Recharge Model					
Cumulative Net Water Budget: 2012-2111[1]					
Budget Element	**Palominas Recharge Model (AF)**	**Baseline Model (AF)**	**Difference** (Palominas Recharge Model - Baseline Model) **(AF)**	**Difference as % of Baseline Element**	**Difference as % of Added Recharge[2]**
Recharge	2,203,772	2,154,530	49,242	2.3%	100%
Storage	3,808,056	3,816,244	(8,188)	-0.2%	-17%
ET	(781,051)	(735,029)	(46,022)	6.3%	-93%
Baseflow	(282,950)	(285,695)	2,745	-1.0%	6%
Pumping	(4,827,233)	(4,829,314)	2,081	0.0%	4%
Constant Head Boundary	(76,478)	(76,498)	21	0.0%	0%
Drains	(41,880)	(41,913)	34	-0.1%	0%
Palominas Recharge Model Water Budget Summary, 2012-2111 (AF)					
TOTAL IN		TOTAL OUT		IN-OUT	% ERROR
7,213,661		7,211,423		2238	0.03%

[1] Cumlative IN - Cumulative OUT at the end of the 100-year simulation period in March 2111.
[2] Difference value as a percentage of cumulative recharge at the Palominas site (49,242 AF).

In the Palominas constant-recharge simulation, essentially all of the simulated recharge is consumed by increased riparian ET and replenishment of aquifer storage. In this case, the simulated net cumulative[6] change in simulated baseflow is slightly positive. Interpreting the MODFLOW sign convention, this result means that, in spite of the addition of 50,000 AF of recharge at the Palominas site, simulated baseflow actually decreases slightly *relative to baseline* over the 100-year simulation period. This simulated relative decrease results from strong competition for this recharge from riparian ET and vadose zone[7] storage related to growing local and regional cones of depression.[8]

Understanding the connection between increasing recharge and increasing ET requires knowledge of how MODFLOW calculates ET. Figure 8 illustrates the conceptual model for computing head-dependent ET rates in the MODFLOW groundwater model (McDonald and Harbaugh, 1988). An "ET surface" is prescribed in the model (refer to Pool and Dickinson, 2007) at some point within a few feet (6 to 8 feet in the Palominas area) of ground surface. Above this ET surface, ET occurs at the maximum rate defined in the model. When the groundwater level in a model cells drops below the ET surface, the ET rate for that cell is calculated as a linear function of the distance between the ET surface and the "extinction depth" in that cell. Pool and Dickinson (2007) defined the extinction depth at and near the Palominas recharge site as 20 ft. Below the extinction depth, ET ceases because water is then considered to be inaccessible to riparian-obligate flora.

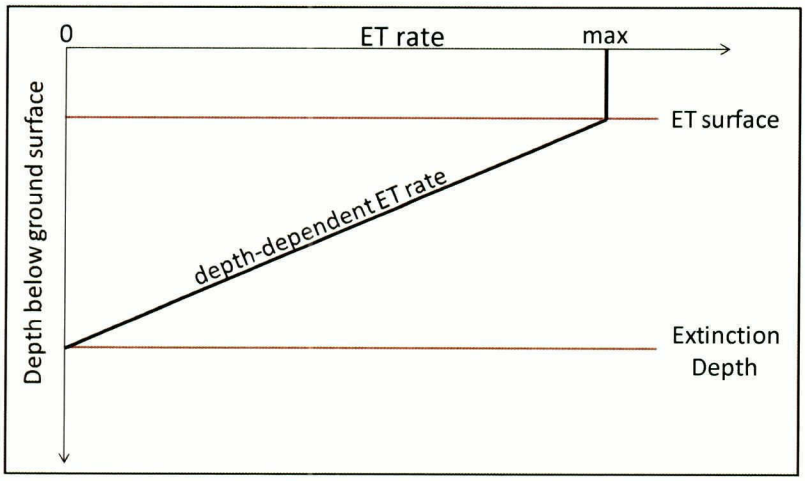

FIGURE 8. SCHEMATIC DIAGRAM OF CONCEPTUALIZATION OF HEAD-DEPENDENT ET RATES IN MODFLOW (MCDONALD AND HARBAUGH, 1988).

[6] "Net" refers to total flows IN minus total flows OUT in MODFLOW water budget elements. "Cumulative" implies all changes added up over the 100-year recharge simulation period.

[7] The vadose zone is the unsaturated area of the aquifer above the water table. As pumping lowers the water table, the vadose zone grows and the aquifer has a greater capacity to absorb recharge.

[8] "Cone of depression" refers to a contiguous area of groundwater depletion caused by pumping. In this case, the regional cone of depression emanates from the Sierra Vista/Fort Huachuca area.

Figure 9 shows simulated depth to groundwater (DTW) in a stream cell immediately downstream of the Palominas recharge site (see stream cell location in Figure 4). As the figure indicates, simulated DTW under the stream at this location decreases from about 22 ft. to an average of about 14.5 ft. in the first 10 years after the onset of simulated recharge in 2012. Most of the change in water level occurs by 2016, and water levels stabilize by about 2030. Significantly, the DTW rises above the critical "ET extinction depth" of 20 ft. in response to recharge at the Palominas site. Since 20 ft. is the prescribed extinction depth at this location in the model, ET "turns on" any time water levels rise above this threshold. In this case, the DTW stabilizes between the ET surface and the extinction depth, so ET occurs at something less than the maximum ET rate prescribed for this area in the model. The larger seasonal oscillations shown in the DTW graph in Figure 9 after the onset of simulated near-stream recharge in 2012 reflect higher ET demand resulting from shallower groundwater.

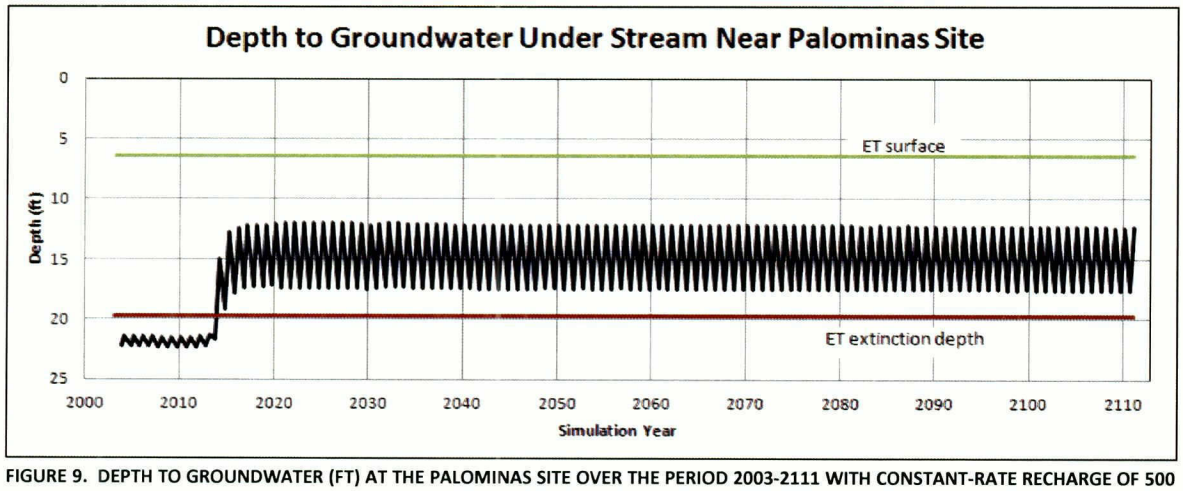

FIGURE 9. DEPTH TO GROUNDWATER (FT) AT THE PALOMINAS SITE OVER THE PERIOD 2003-2111 WITH CONSTANT-RATE RECHARGE OF 500 AF/YR STARTING IN OCTOBER 2012.

GARDEN CANYON SITE

The simulated Garden Canyon recharge site lies northwest of the Garden Canyon Creek-SPR confluence within the SPRNCA (Figure 10), about 17 miles upstream of the northern model boundary at the downstream end of the Sierra Vista subbasin. The City of Sierra Vista's Environmental Operations Park (EOP) wastewater recharge facility is located about four miles northwest of the Garden Canyon recharge site. Baseline simulations support observations that recharge at the EOP since 2002 has produced a significant groundwater mound under the EOP and that this mound is contributing to SPR baseflows in reaches 5 through 8 (Figure 10) (Brown and Caldwell, 2009).

FMC000979

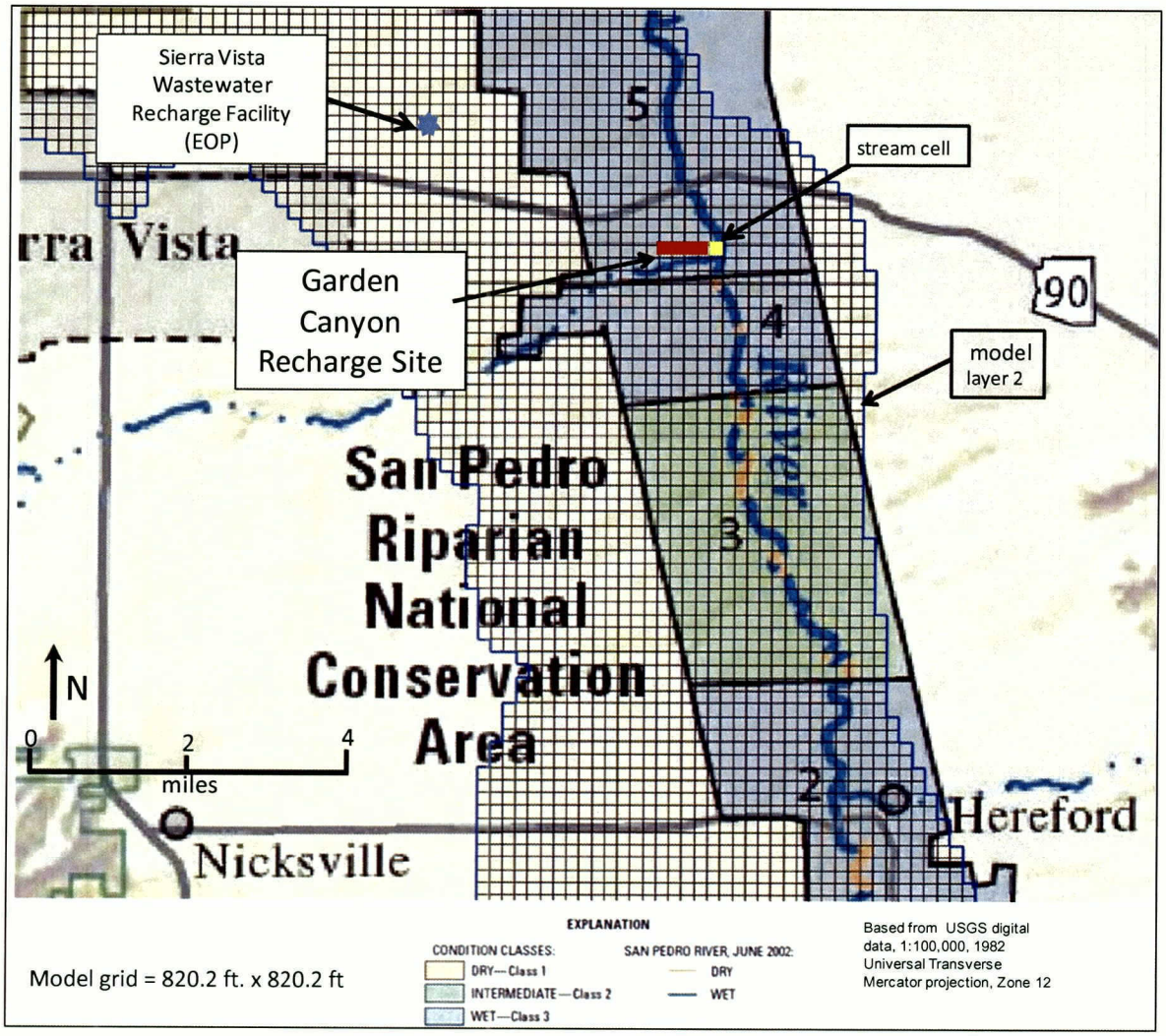

FIGURE 10. MAP OF GARDEN CANYON RECHARGE SITE AND THE SIERRA VISTA ENVIRONMENTAL OPERATIONS PARK (EOP) RECHARGE FACILITY OVERLAIN ON RIPARIAN CONDITION CLASS MAP BY STROMBERG, ET AL (2006). THE STREAM CELL USED FOR ILLUSTRATION IN FIGURE 13 IS SHOWN IN YELLOW. WET AND DRY STREAM REACHES REFLECT CONDITIONS OBSERVED IN JUNE 2002 (AFTER FIGURE 42 IN STROMBERG, ET AL, 2006).

By virtue of its position just upstream from the EOP in a reach of the SPR that is presently gaining water from the regional aquifer, the Garden Canyon site overlies a very shallow vadose zone where aquifer storage is already near capacity under the SPR. Furthermore, since groundwater is fairly shallow at this site, simulated ET is at or near its maximum prescribed rate prior to the addition of near-stream recharge (see Figure 8).

Figure 11 shows the maximum extent of simulated baseflow improvement (relative to baseline) downstream of the Garden Canyon site four years after the simulated onset of recharge. The combined simulated effects of the EOP and Garden Canyon recharge are additive, producing a

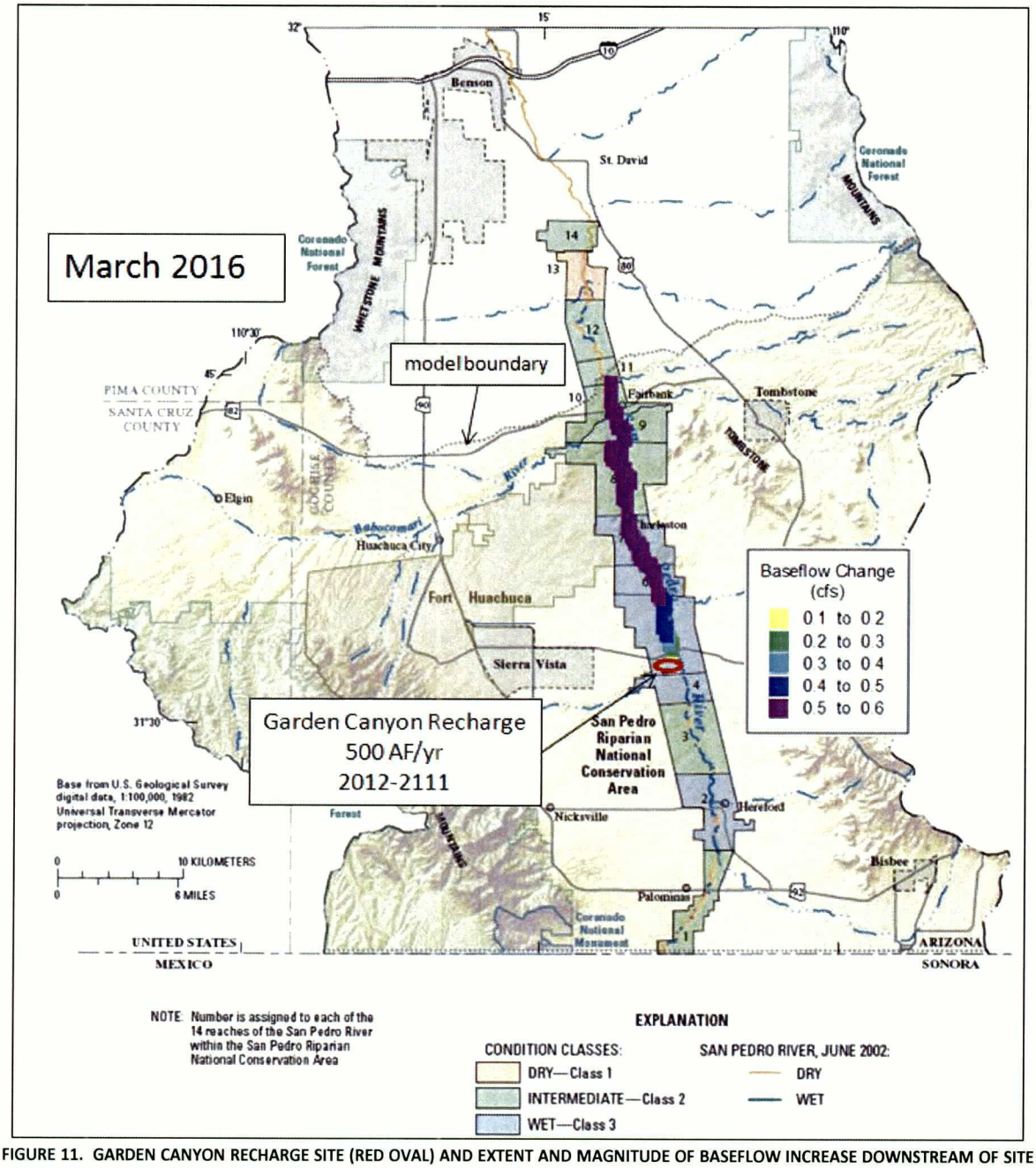

FIGURE 11. GARDEN CANYON RECHARGE SITE (RED OVAL) AND EXTENT AND MAGNITUDE OF BASEFLOW INCREASE DOWNSTREAM OF SITE BY MARCH 2016, FOUR YEARS AFTER THE ONSET OF SIMULATED RECHARGE. RIPARIAN CONDITION CLASS AND STREAM FLOW PRESENCE FROM FIGURE 42 IN STROMBERG, ET AL (2006).

significant (0.5 to 0.6 cubic-feet per second (cfs)) response in baseflows on many miles of the SPR in just four years. Figure 12 illustrates the evolution of the simulated baseflow increase downstream of the Garden Canyon site at four points in time (2016, 2030, 2060, and 2090) over

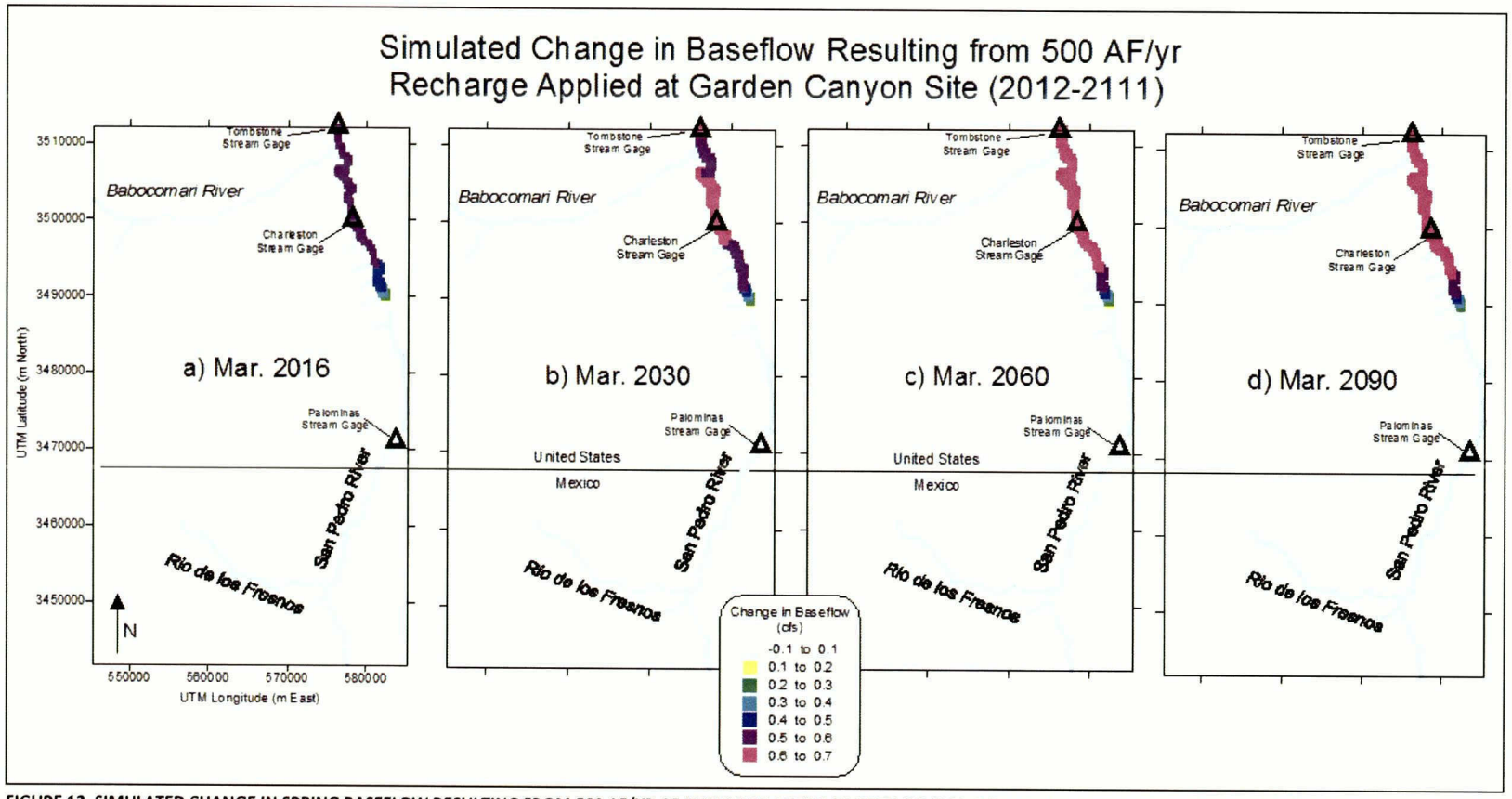

FIGURE 12. SIMULATED CHANGE IN SPRING BASEFLOW RESULTING FROM 500 AF/YR OF RECHARGE AT THE GARDEN CANYON SITE APPLIED FROM OCTOBER 2012 TO MARCH 2111 FOR THE YEARS: A) 2016, B) 2030, C) 2060, AND D) 2090.

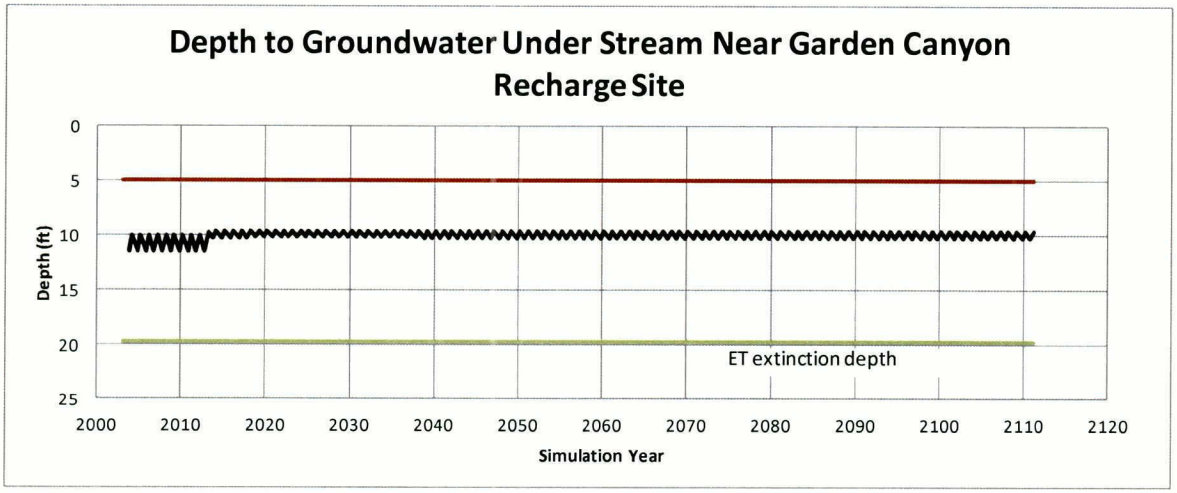

FIGURE 13. DEPTH TO GROUNDWATER (FT) AT GARDEN CANYON SITE UNDER CONSTANT-RATE RECHARGE OF 500 AF/YR FROM 2012-2111.

the next century. These graphics reveal that simulated baseflows increase fastest near the EOP (just southwest of the Charleston gaging station) and spread both up and downstream from there over time. Similar to the Palominas groundwater response, groundwater levels at the Garden Canyon site rise immediately upon the onset of simulated recharge in 2012, as shown in Figure 13. The oscillatory pattern in the DTW curve reflects seasonal ET demand. Unlike the Palominas graph in Figure 9, however, the ET signal in the Garden Canyon graph does not change significantly following the onset of simulated near-stream recharge in October 2012. In this case, groundwater is shallower (less than 12 ft. vs. 22 ft. at Palominas), and within the ET zone (between the extinction depth and ET surface) prior to the initiation of recharge.

The simulated basin-wide cumulative water budget changes resulting from the addition of 500 AF/yr of recharge at the Garden Canyon site are shown in Figure 14, and data used to produce the graph are provided in Table 2. About half of the simulated recharge at this site translates into increased baseflow,[9] with the remaining recharge partitioned between riparian ET (30%) and aquifer replenishment (20%).

[9] In MODFLOW sign convention, negative baseflow means flow from aquifer into stream.

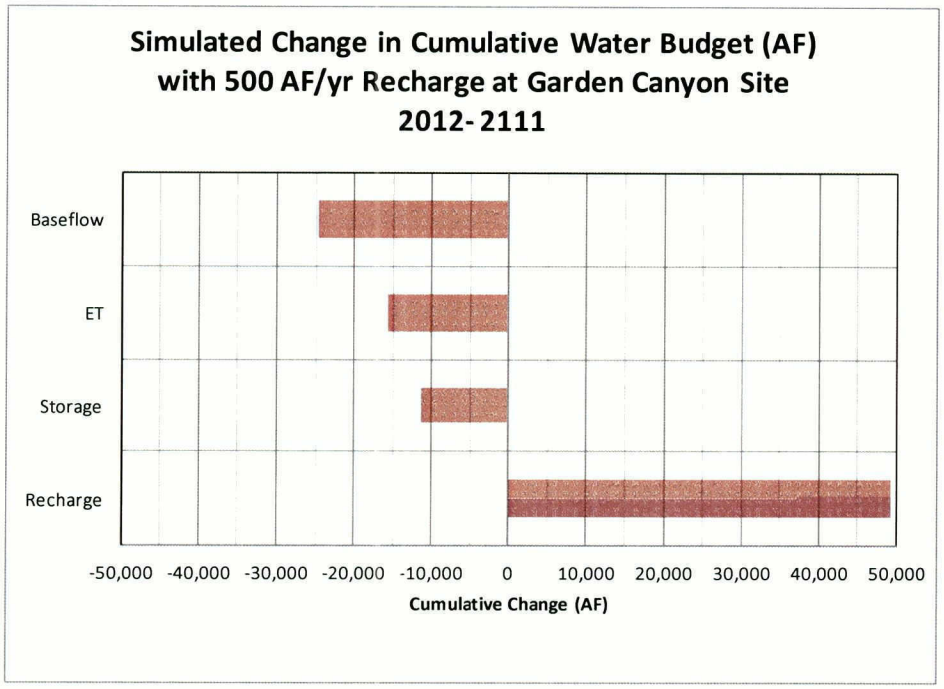

FIGURE 14. CUMULATIVE CHANGES IN SIMULATED BASIN-WIDE MODEL WATER BUDGET RESULTING SOLELY FROM 500 AF/YR RECHARGE APPLIED AT THE GARDEN CANYON SITE FROM OCTOBER 2012 TO MARCH 2111.

TABLE 2. SIMULATED WATER BUDGET FOR CONSTANT-RATE RECHARGE AT THE GARDEN CANYON SITE.

Garden Canyon Constant-Rate Recharge Model					
Cumulative Net Water Budget: 2012-2111[1]					
Budget Element	**Garden Canyon Recharge Model (AF)**	**Baseline Model (AF)**	**Difference** (Garden Canyon Recharge Model - Baseline Model) **(AF)**	**Difference as % of Baseline Element**	**Difference as % of Added Recharge[2]**
Recharge	2,203,772	2,154,530	49,242	2.3%	100%
Storage	3,804,983	3,816,244	(11,261)	-0.3%	-23%
ET	(750,652)	(735,029)	(15,623)	2.1%	-32%
Baseflow	(310,348)	(285,695)	(24,653)	8.6%	-50%
Pumping	(4,827,228)	(4,829,314)	2,086	0.0%	4%
Constant Head Boundary	(76,470)	(76,498)	28	0.0%	0%
Drains	(41,880)	(41,913)	33	-0.1%	0%
Garden Canyon Recharge Model Water Budget Summary, 2012-2111 (AF)					
TOTAL IN		TOTAL OUT		IN-OUT	% ERROR
7,186,718		7,184,540		2178	0.03%

[1] Cumlative IN - Cumulative OUT at the end of the 100-year simulation period in March 2111.
[2] Difference value as a percentage of cumulative recharge at the Garden Canyon site (49,242 AF).

BABOCOMARI SITE

The Babocomari recharge site lies at the mouth of Soldier Creek at its confluence with the Babocomari River (Figure 15). Unlike the Garden Canyon and Palominas sites, the extensive silt and clay unit in the USGS groundwater model that extends along the west side of the SPR over most of its length in the Sierra Vista subbasin (Figure 16 andFigure 17) does not underlie this site in the model (Pool and Dickinson, 2007). Instead, this site lies immediately west of the thick silt and clay unit, and the site itself has high simulated infiltration capacity.

Figure 18 presents the extent and magnitude of simulated baseflow increase downstream of the Babocomari recharge site four years after the onset of recharge at this site. The end of the highlighted stream segment below the Babocomari-SPR confluence marks the northern limit of the model area and the watershed divide between the Sierra Vista and Benson subbasins. As Figure 18 shows, simulated baseflows downstream of the Babocomari recharge site increase by 0.3 to 0.4 cfs for more than 10 miles downstream within the first 4 years of applied constant-rate recharge (500 AF/yr starting in October 2012).

Figure 19 shows this same plot at 4 different points in time over the next century: a) 2016, b) 2030, c) 2060, and d) 2090. The peak effect of the simulated constant-rate recharge at the Babocomari site occurs around the year 2030, then diminishes to 2012 levels by 2060, and by 2090, the effect of simulated near-stream recharge is completely gone (Figure 19d).

The DTW graph in Figure 20 illustrates the simulated groundwater response in the stream immediately adjacent to the Babocomari recharge site under constant-rate recharge conditions of 500 AF/yr from October 2012 to March 2111. Simulated groundwater levels rise (DTW decreases) from 20.9 to 18.8 ft. by March 2016, then taper off and decline more rapidly over time under the influence of the expanding simulated cone of depression in this area of the model (Lacher, 2011).

The cumulative changes in the basin-wide water budget resulting from the application of 500 AF/yr of recharge at the Babocomari site from 2012 to 2111 are shown Figure 21 and Table 3. Simulated recharge at the Babocomari site is partitioned entirely between increased baseflow (30%) and aquifer storage demand (70%), with essentially no change in basin-wide cumulative ET over the 100-year simulation.

The lack of ET response can be explained by the model's prescribed ET rates for each model cell. In the immediate vicinity of the Babocomari recharge site, the maximum ET rate in the model is set to zero (Pool and Dickinson, 2007), so raising simulated groundwater levels has no impact on ET in those specific cells. Prescribed maximum ET rates in the model increase downstream from the site, but never reach rates approaching those at the Palominas or Garden

FMC000985

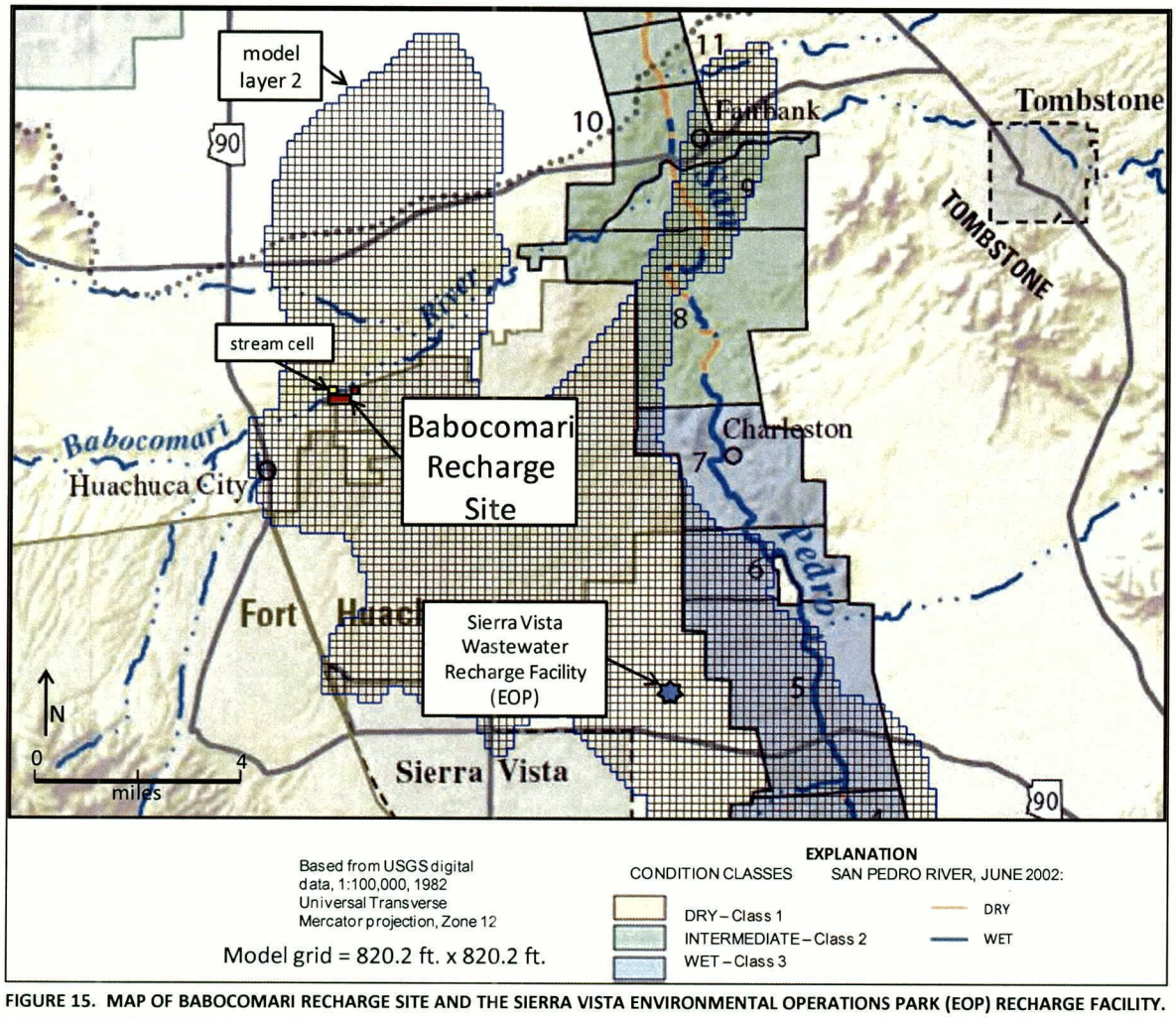

FIGURE 15. MAP OF BABOCOMARI RECHARGE SITE AND THE SIERRA VISTA ENVIRONMENTAL OPERATIONS PARK (EOP) RECHARGE FACILITY. THE STREAM CELL USED FOR ILLUSTRATION IN FIGURE 20 IS SHOWN IN YELLOW. WET AND DRY STREAM REACHES REFLECT CONDITIONS RECORDED IN JUNE 2002 (AFTER FIG. 42 IN STROMBERG, ET AL, 2006).

Canyon sites (see Table 4). While these ET conditions are intended to approximate observed vegetation at the time of the model's creation, a detailed site investigation would be required to refine simulations in the area of this (and other) recharge sites.

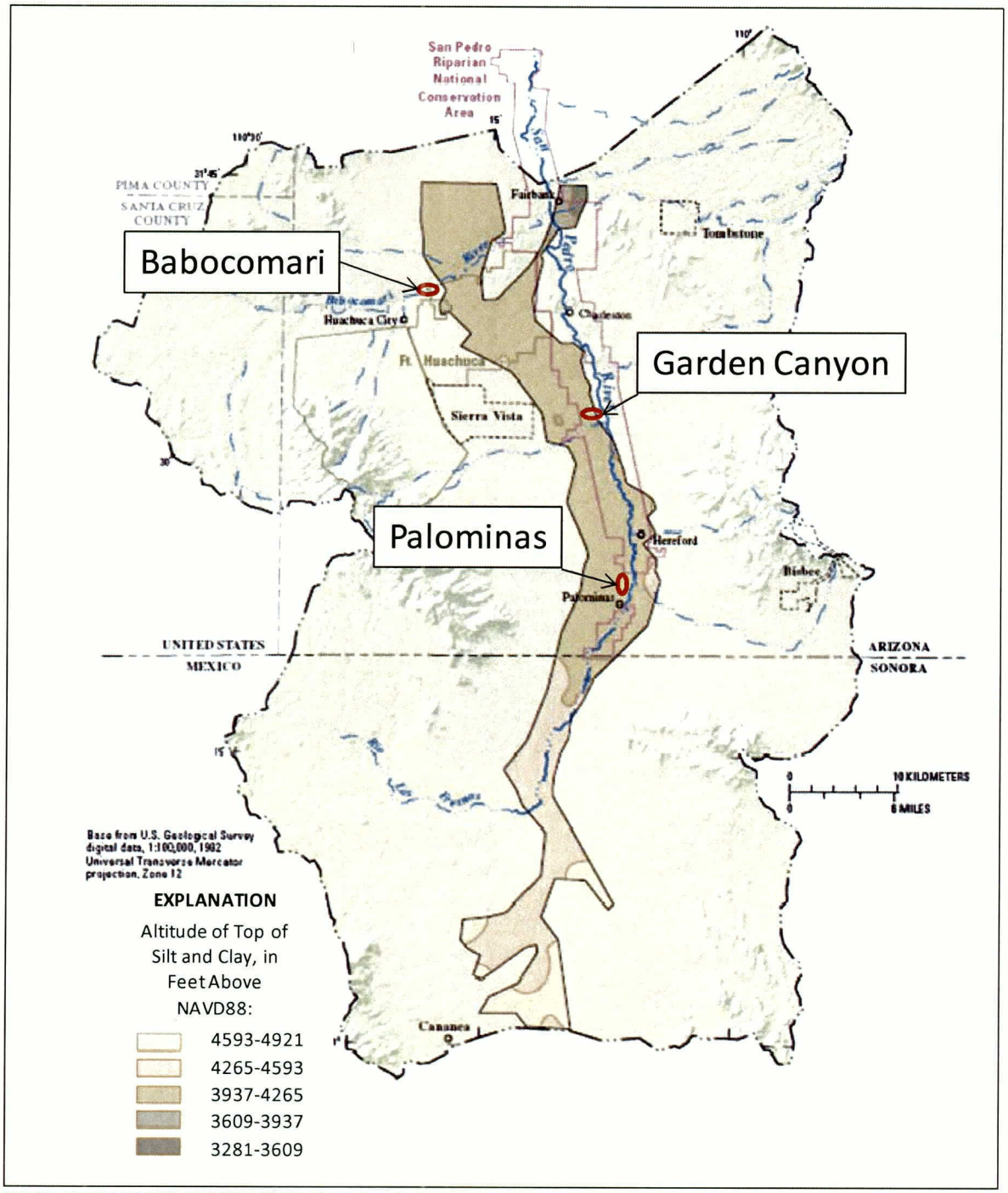

FIGURE 16. EXTENT AND ALTITUDE OF TOP OF THE THICK SILT AND CLAY INTERVAL IN THE BASIN FILL, USPB, UNITED STATES AND MEXICO (FROM POOL AND DICKINSON (2007) FIGURE 4A). RECHARGE SITES INDICATED BY RED OVALS.

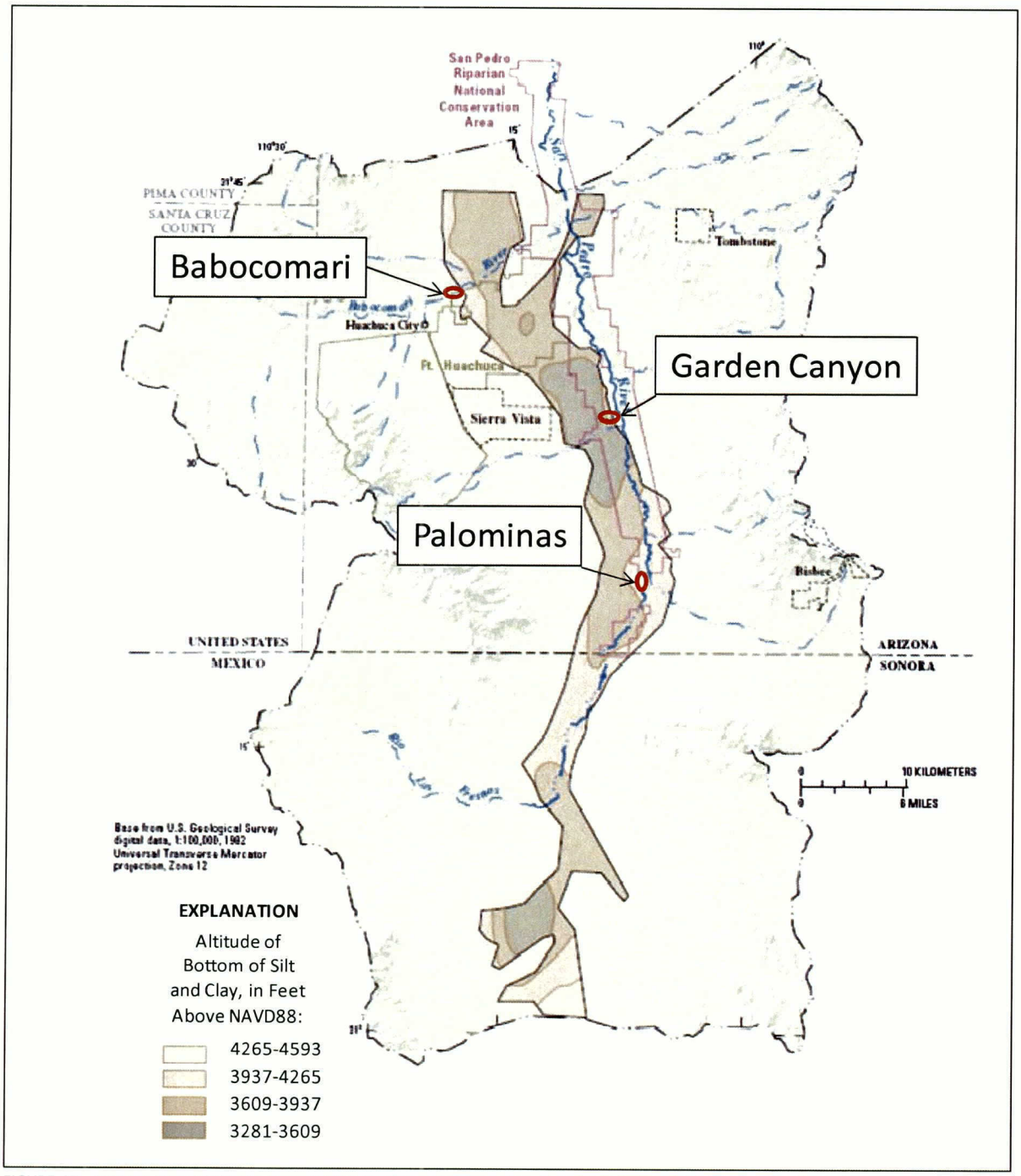

FIGURE 17. EXTENT AND ALTITUDE OF BOTTOM OF THE THICK SILT AND CLAY INTERVAL IN THE BASIN FILL, USPB, UNITED STATES AND MEXICO (FROM POOL AND DICKINSON (2007) FIGURE 4B). RECHARGE SITES INDICATED BY RED OVALS.

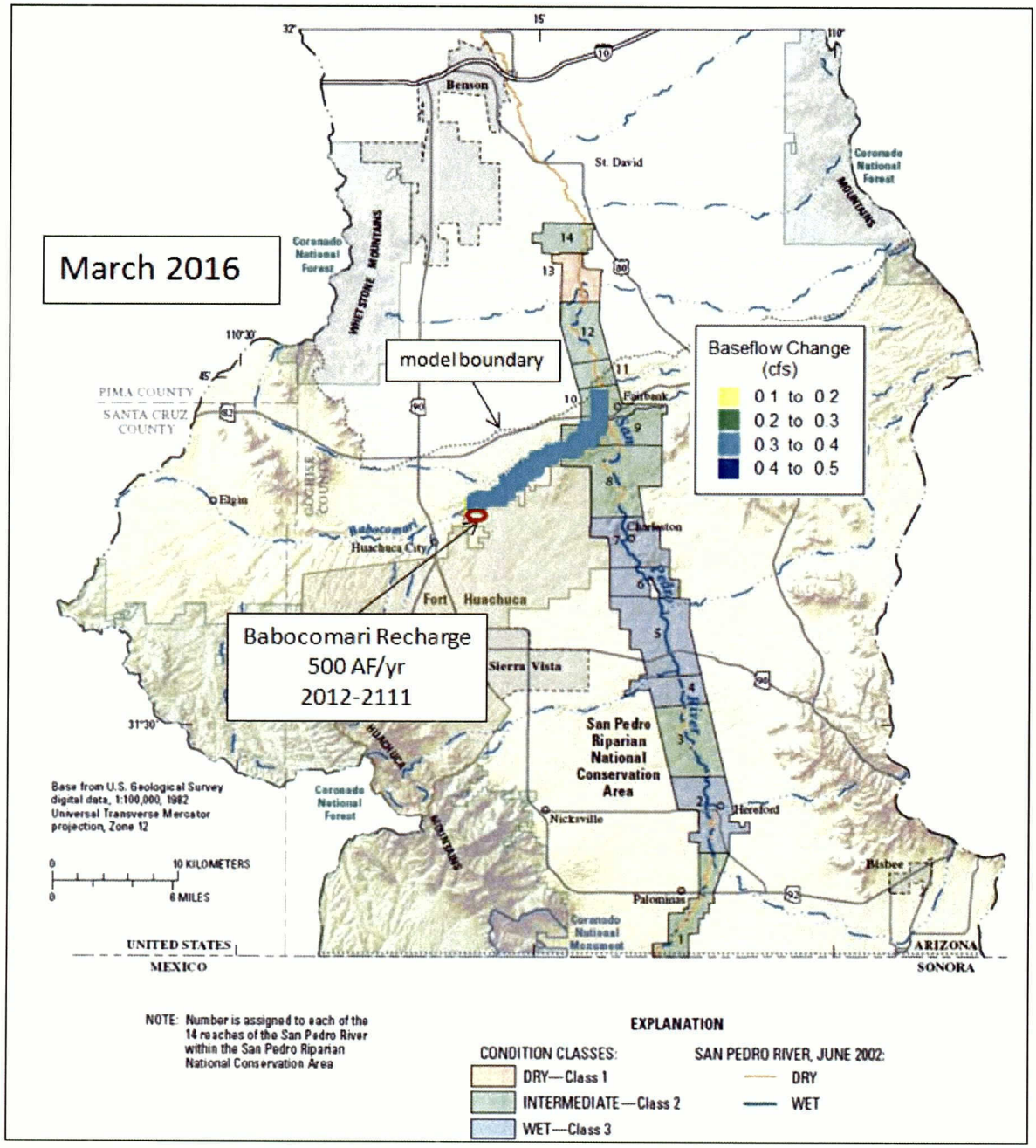

FIGURE 18. BABOCOMARI RECHARGE SITE (RED OVAL) AND LINEAL EXTENT AND AMOUNT OF BASEFLOW INCREASE AS OF MARCH 2016 DUE TO 500 AF/YR CONSTANT RECHARGE APPLIED AT BABOCOMARI SITE FROM OCTOBER 2012 TO MARCH 2016. RIPARIAN CONDITION CLASS AND STREAM FLOW PRESENCE FROM FIGURE 42 IN STROMBERG, ET AL (2006).

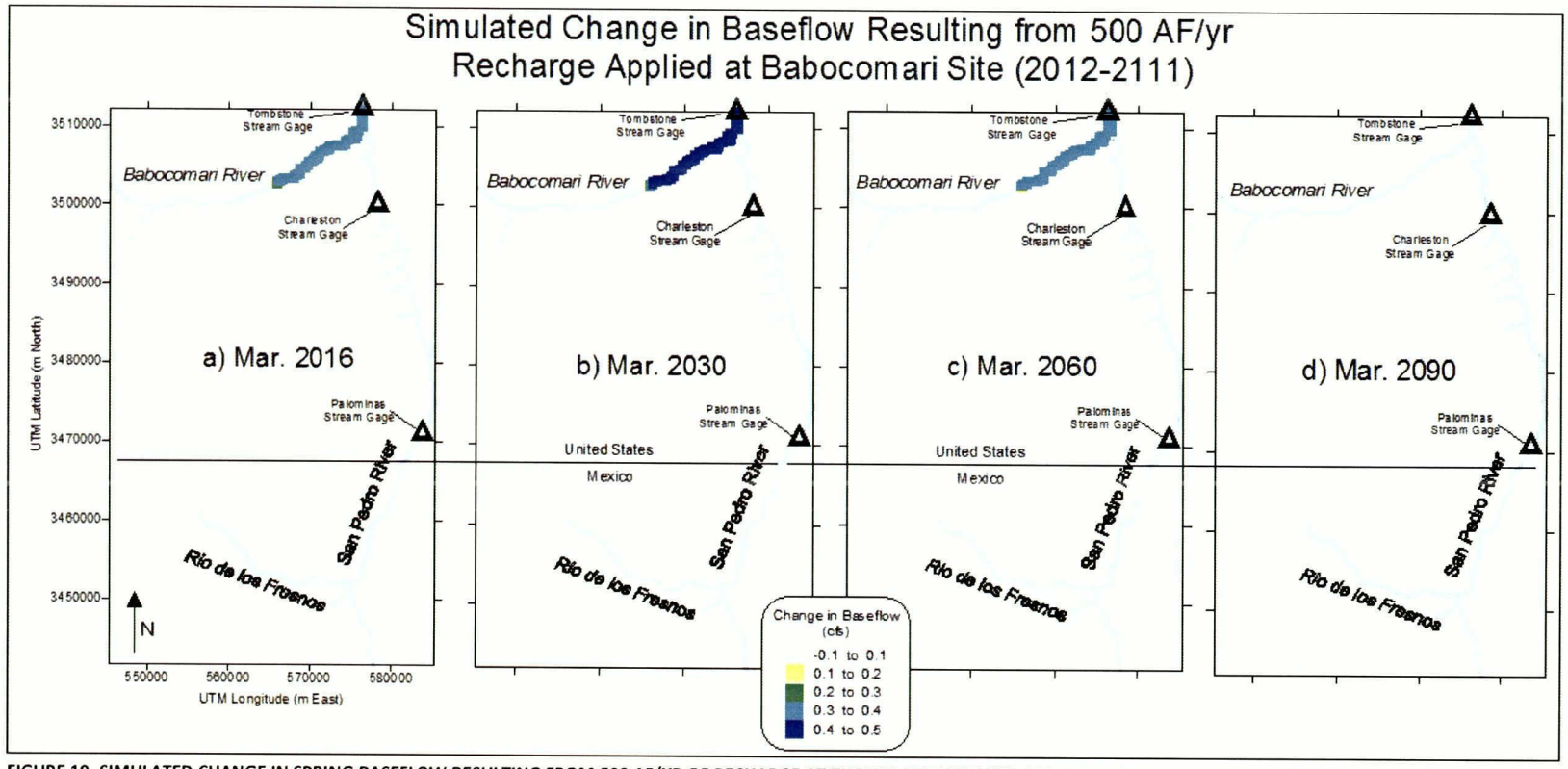

FIGURE 19. SIMULATED CHANGE IN SPRING BASEFLOW RESULTING FROM 500 AF/YR OF RECHARGE AT THE BABOCOMARI SITE APPLIED FROM OCTOBER 2012 TO MARCH 2111 FOR THE YEARS: A) 2016, B) 2030, C) 2060, AND D) 2090.

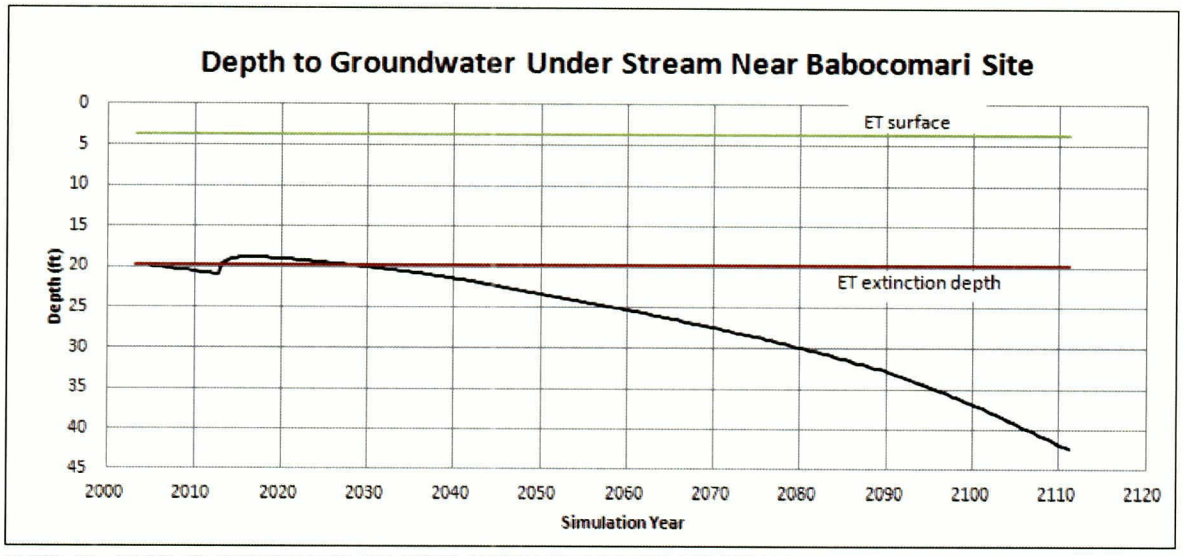

FIGURE 20. DEPTH TO GROUNDWATER (FT) UNDER STREAM IMMEDIATELY ADJACENT TO THE BABOCOMARI RECHARGE SITE UNDER CONSTANT-RATE RECHARGE CONDITIONS OF 500 AF/YR STARTING IN OCTOBER 2012.

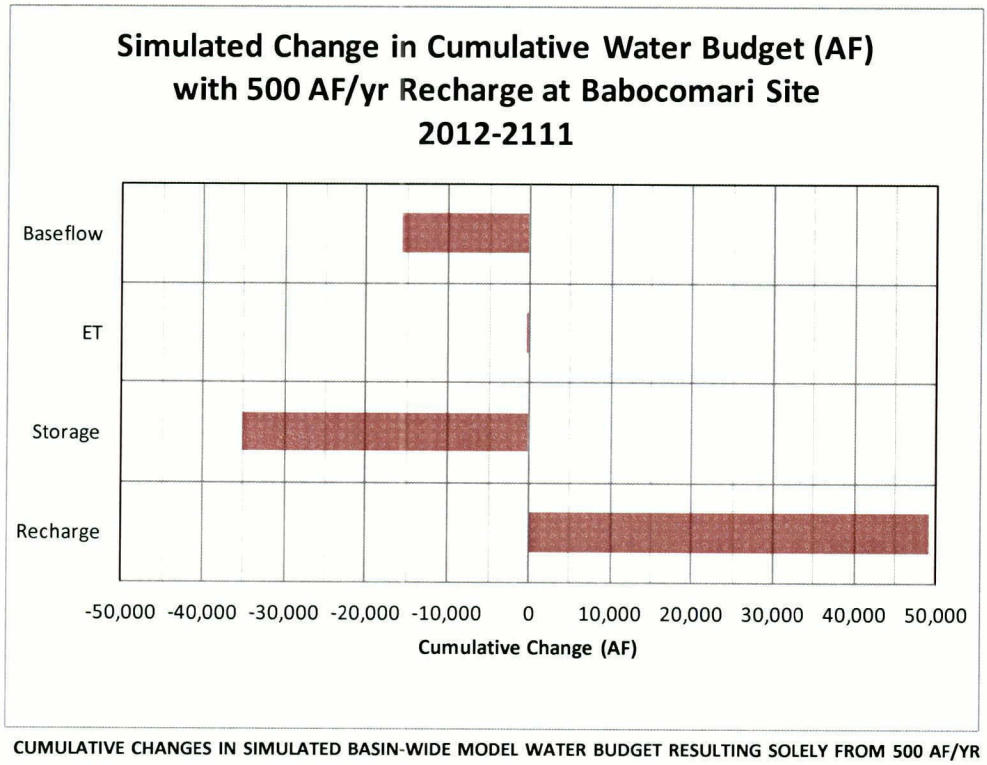

FIGURE 21. CUMULATIVE CHANGES IN SIMULATED BASIN-WIDE MODEL WATER BUDGET RESULTING SOLELY FROM 500 AF/YR RECHARGE APPLIED AT THE BABOCOMARI SITE FROM OCTOBER 2012 TO MARCH 2111.

TABLE 3. SIMULATED WATER BUDGET FOR CONSTANT-RATE RECHARGE AT THE BABOCOMARI SITE.

Babocomari Constant-Rate Recharge Model					
Cumulative Net Water Budget: 2012-2111[1]					
Budget Element	Babocomari Recharge Model (AF)	Baseline Model (AF)	Difference (Babocomari Recharge Model - Baseline Model) (AF)	Difference as % of Baseline Element	Difference as % of Added Recharge[2]
Recharge	2,203,772	2,154,530	49,242	2.3%	100%
Storage	3,781,015	3,816,244	(35,230)	-0.9%	-72%
ET	(735,323)	(735,029)	(294)	0.0%	-1%
Baseflow	(301,314)	(285,695)	(15,619)	5.5%	-32%
Pumping	(4,827,243)	(4,829,314)	2,071	0.0%	4%
Constant Head Boundary	(76,582)	(76,498)	(83)	0.1%	0%
Drains	(41,966)	(41,913)	(53)	0.1%	0%

Babocomari Recharge Model Water Budget Summary, 2012-2111 (AF)			
TOTAL IN	TOTAL OUT	IN-OUT	% ERROR
7,162,022	7,159,662	2359	0.03%

[1] Cumlative IN - Cumulative OUT at the end of the 100-year simulation period in March 2111.

[2] Difference value as a percentage of cumulative recharge at the Babocomari site (49,242 AF).

TABLE 4. COMPARISON OF ET CHARACTERISTICS RELATIVE TO GROUND SURFACE AT BABOCOMARI, GARDEN CANYON, AND PALOMINAS SITES AS DEFINED IN THE USGS GROUNDWATER MODEL (POOL AND DICKINSON, 2007).

Site Name	Ground Surface (ft)	ET Surface (ft)	Extinction Depth (ft)	ET Rate (ft/d)
Babocomari	4186	4182	20	0.0000
Garden Canyon	4062	4057	20	0.0213
Palominas	4184	4179	20	0.0213

VARIABLE-RATE RECHARGE SIMULATION RESULTS

Building on the constant-rate recharge simulations, the variable-rate recharge simulations started from an initial rate of 500 AF/yr at each of the three near-stream recharge sites. Recharge rates were then increased iteratively to determine the minimum rate of recharge required to maintain simulated baseflows downstream of each recharge site at or above 2003 levels.

PALOMINAS SITE

Figure 22 illustrates the spatial distribution of baseflow changes from 2003 conditions resulting from the variable-rate recharge simulation at the Palominas site. In the maps in Figure 22, the narrow light blue lines (small hollow circles) represent areas of the stream where simulated baseflow is essentially unchanged from 2003 conditions. The warm colors (small red, brown, and orange filled circles) indicate areas where simulated baseflow is less than it was in 2003, and the cooler colors (green and blue filled squares) mark stream reaches where simulated baseflow exceeds that for 2003. The 1.25-mile stream segment immediately downstream (north) of the Palominas site (0.1 to 0.5 cfs increase from 2003 baseflow) is the only portion of the river affected by recharge at the Palominas site during the 100-year simulation period. The end of this affected segment corresponds roughly with the southern end of the Class 3 riparian condition area (reach 2 in Stromberg, et al, 2006) that contains the community of Hereford (see Figure 5). Downstream of the affected reach, simulated baseflows remain unchanged from 2003 conditions throughout the simulation period, as indicated in Figure 22(a-d).

Simulated baseflows in the northern portion of the basin (Figure 22) illustrate the beneficial effects of the City of Sierra Vista's EOP along the mainstem of the SPR through the Charleston reach. These beneficial effects peak at approximately 1.0 to 1.5 cfs of added baseflow in 2030 (Figure 22(a)), then diminish over time to 0.5 to 1 cfs by 2070 (Figure 22(c)). By 2111, the simulated baseflow impacts from EOP recharge are overwhelmed by pumping-induced depletions, leaving baseflows in the Charleston reach at 0.1 to 1.0 cfs below 2003 levels, and up to 1.5 to 2.5 cfs below 2003 levels downstream of the Babocomari confluence (Figure 22(d)). Simulated baseflows on the Babocomari decline over time in this scenario from 0.1 to 0.5 cfs below 2003 levels in 2030 (Figure 22(a)) to 1.0 to 1.5 cfs below 2003 levels in 2111 (Figure 22(d)).

Interpreting the lack of response in baseflows in the SPR reach between the Palominas site and the Garden Canyon site roughly 12 miles downstream is complex and appears to reflect the combined influence of three important factors. First, low simulated hydraulic conductivity at the Palominas site limits the rate of recharge that can be applied to the site as it is defined in this study without producing surface flooding.

Figure 23 illustrates the rate of recharge required to support 2003 baseflows in the 1.25-mile reach of river adjacent to the Palominas recharge site, and the resulting DTW in a stream cell immediately downstream of the site (see Figure 4). This varying rate of recharge adds a net total of more than 17,000 AF over the 100-year simulation period relative to the constant-rate recharge scenario (see Table 5). It is also the maximum recharge that the site would accept without producing flooding. The maximum recharge rate increases over time as simulated

FMC000993

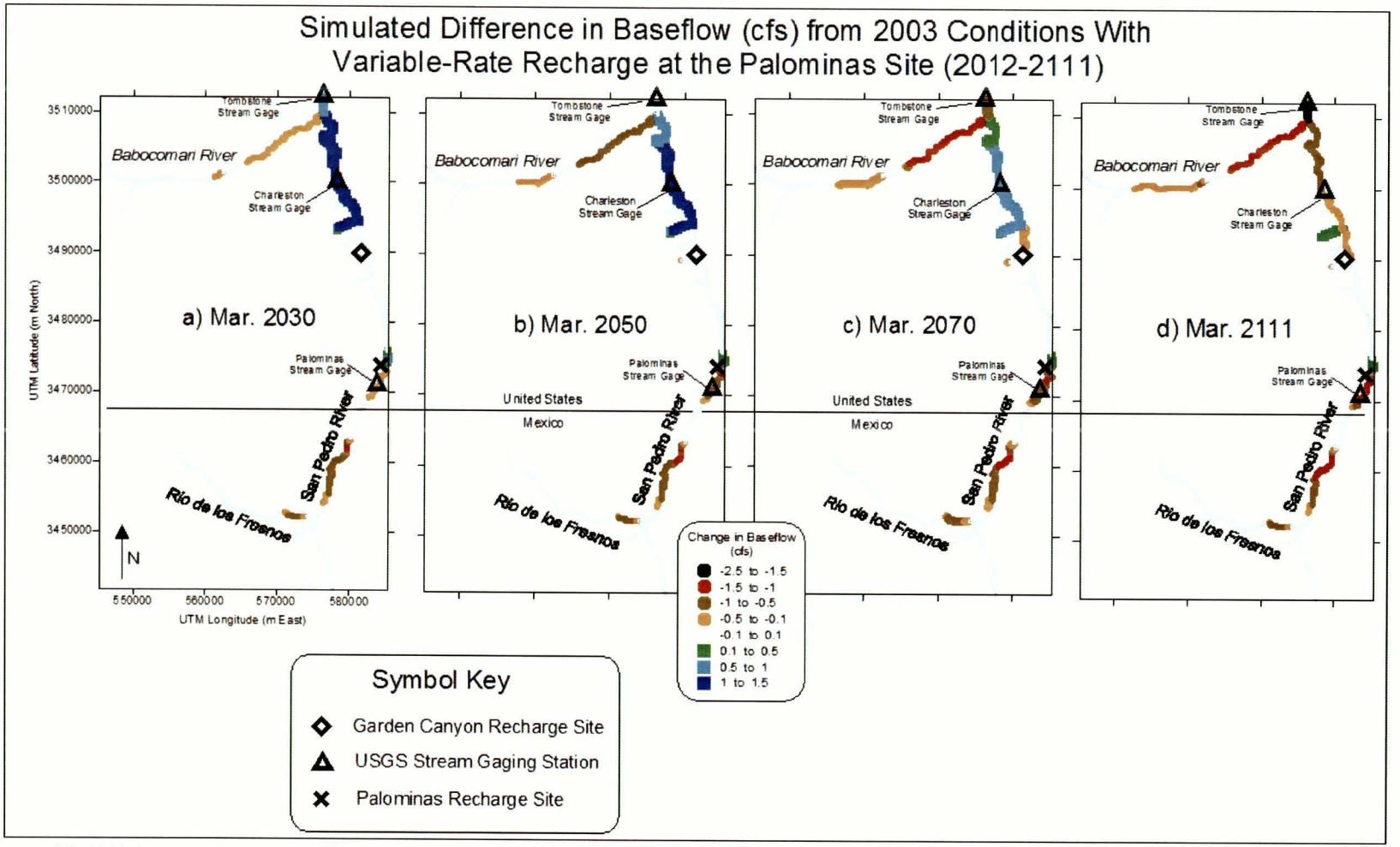

FIGURE 22. SIMULATED DIFFERENCE IN BASEFLOW (CFS) FROM 2003 BASEFLOW CONDITIONS WITH VARIABLE-RATE RECHARGE AT THE PALOMINAS SITE FROM 2012 THROUGH 2111.

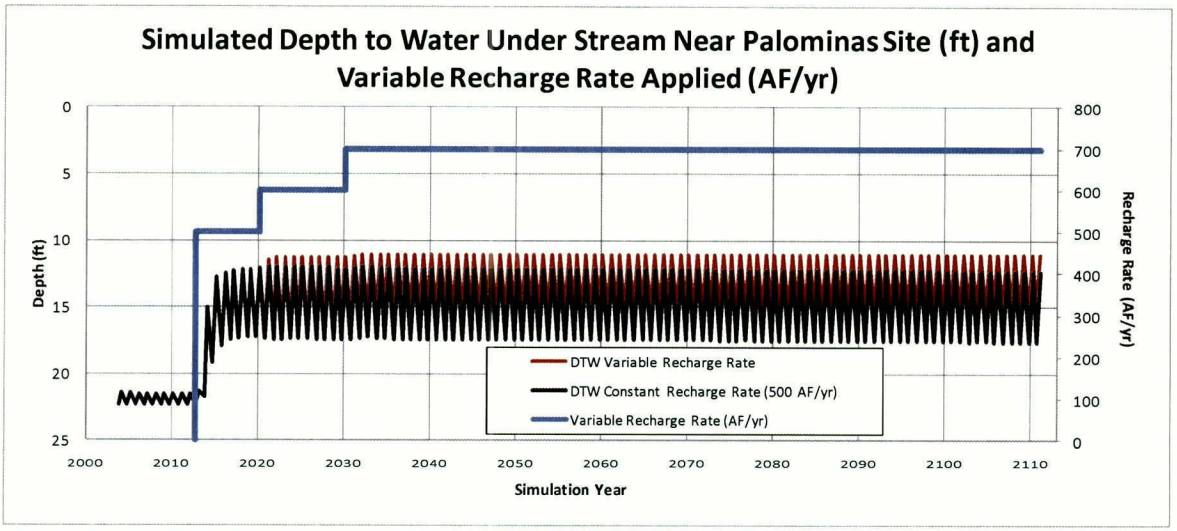

FIGURE 23. SIMULATED VARIABLE RECHARGE RATE AT PALOMINAS SITE (BLUE LINE) AND DTW IN STREAM CELL IMMEDIATELY DOWNSTREAM OF PALOMINAS RECHARGE SITE (SEE FIGURE 4) FOR BOTH CONSTANT-RATE (500 AF/YR) AND VARIABLE-RATE RECHARGE SCENARIOS.

groundwater levels under the site are eventually impacted by the expanding regional cone of depression. As water levels decline, additional space is available in the vadose zone under the recharge site for accepting more water.

Figure 23 plots DTW for the constant-rate and variable-rate recharge simulations for the Palominas site. Increasing the recharge from 500 AF/yr to 700 AF/yr over time as described in Figure 23 has the effect of reducing the average simulated DTW under the stream just downstream of the recharge site from 14.5 ft. (constant 500 AF/yr recharge rate scenario) to about 12.5 ft. This additional two feet of groundwater elevation has the effect of further increasing riparian ET while maintaining baseflows at 2003 levels from 2016 to 2111.

The increasing ET demand associated with higher groundwater levels at the Palominas site as described above is the second limiting factor for the influence of surface recharge at the Palominas site. Simulation results indicate that the riparian ET demand essentially keeps pace with all available added recharge (see Figure 24 and Table 5), thereby limiting the downstream extent of the recharge's impacts. Again, the accuracy of this projected increase in riparian ET demand is unknown, and more detailed study would be needed to assess the validity of this result.

Finally, the third factor affecting the insensitivity of the reach of the SPR between the Palominas and Garden Canyon recharge sites involves the interconnection between the regional (basin-fill) aquifer and the river. The thick silt and clay unit underlying much of the river reach south of the Garden Canyon site thickens to nearly 1,000 feet in the center of the subbasin near the Garden Canyon site (see Figure 16 and Figure 17). This thick, low-

permeability unit limits hydraulic communication between the regional aquifer and this reach of river, thereby providing some protection against pumping-related depletions associated with the regional cone of depression over the simulation period. By contrast, the silt and clay unit under the Palominas site is much thinner (and likely more permeable), thereby increasing the hydrologic response between the stream and the regional aquifer in this area (see Leake, Pool, and Leenhouts, 2008).

TABLE 5. CUMULATIVE CHANGES IN SIMULATED WATER BUDGET RELATIVE TO CONSTANT-RATE RECHARGE SCENARIO RESULTING FROM VARIABLE-RATE RECHARGE AT THE PALOMINAS SITE.

Simulated Change in Water Budget: Variable Recharge Rate - Constant Recharge Rate (500 AF/yr) at Palominas Site 2012-2111*			
Budget Element	Change from Constant-Rate Recharge Scenario (AF)	% of Additional Recharge (Above Constant-Rate Recharge of 500 AF/yr)	
Recharge	17,224	100.0%	
Storage	(889)	-5.2%	
ET	(16,384)	-95.1%	
Baseflow	23	0.1%	
Pumping	0	0.0%	
Constant Head Boundary	11	0.1%	
Drains	0	0.0%	
Total Water Budget Summary, 2012-2111 (AF)			
TOTAL IN	TOTAL OUT	IN-OUT	% ERROR
7,245,731	7,243,506	2224	0.03%

*Values are differences (Palominas variable recharge rate vs. Palominas constant recharge rate (500 AF/yr)) in cumulative net (IN-OUT) totals at the end of the 100-year simulation period in March 2111.

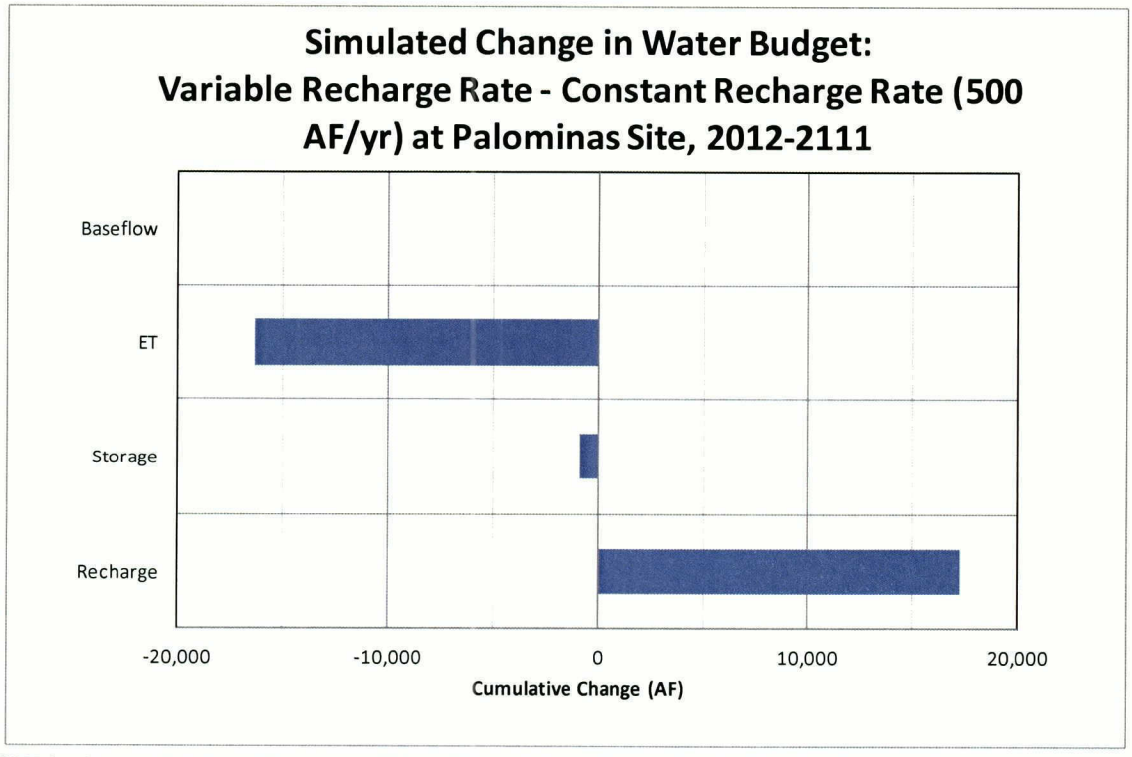

FIGURE 24. CUMULATIVE CHANGES IN SIMULATED WATER BUDGET RELATIVE TO CONSTANT-RATE RECHARGE SCENARIO RESULTING FROM VARIABLE-RATE RECHARGE AT THE PALOMINAS SITE.

GARDEN CANYON SITE

Figure 25 shows the spatial distribution of simulated differences in baseflow with variable-rate recharge at the Garden Canyon site compared to baseline over the 100-year simulation period. Comparing simulated baseflows on the Charleston reach of the SPR in Figure 25 with those in Figure 22 highlights the incremental increase in flow in this reach produced by variable rate recharge at the Garden Canyon site. In 2030, simulated baseflows downstream of the Garden Canyon site in Figure 25(a) are mostly in the range of 1.5 to 2.0 cfs above 2003 levels. Simulated baseflows in the same reach in Figure 22(a)[10] fall into the range of 1.0 to 1.5 cfs above 2003 levels, largely because of recharge at the EOP. By 2050 (Figure 22(b) and Figure 25(b)), simulated baseflows for the Charleston reach are roughly equal and range from 0.5 to 1.5 cfs above 2003 levels in both scenarios. By 2070 (Figure 25(c)), the Garden Canyon variable-rate recharge scenario produces simulated baseflows that exceed those in Figure 22(c) by 0.5 to 1.0 cfs, and by 2111, simulated baseflows in the Garden Canyon scenario (Figure 25(d)) remain slightly above 2003 baseflow levels, while those in the Palominas scenario (Figure 22(d)) fall significantly below (-1.0 to -0.5 cfs) 2003 levels in the Charleston reach.

[10] Because the Palominas recharge had no discernable impact on baseflows downstream of Garden Canyon, the northern half of Figure 22 is equivalent to the baseline model.

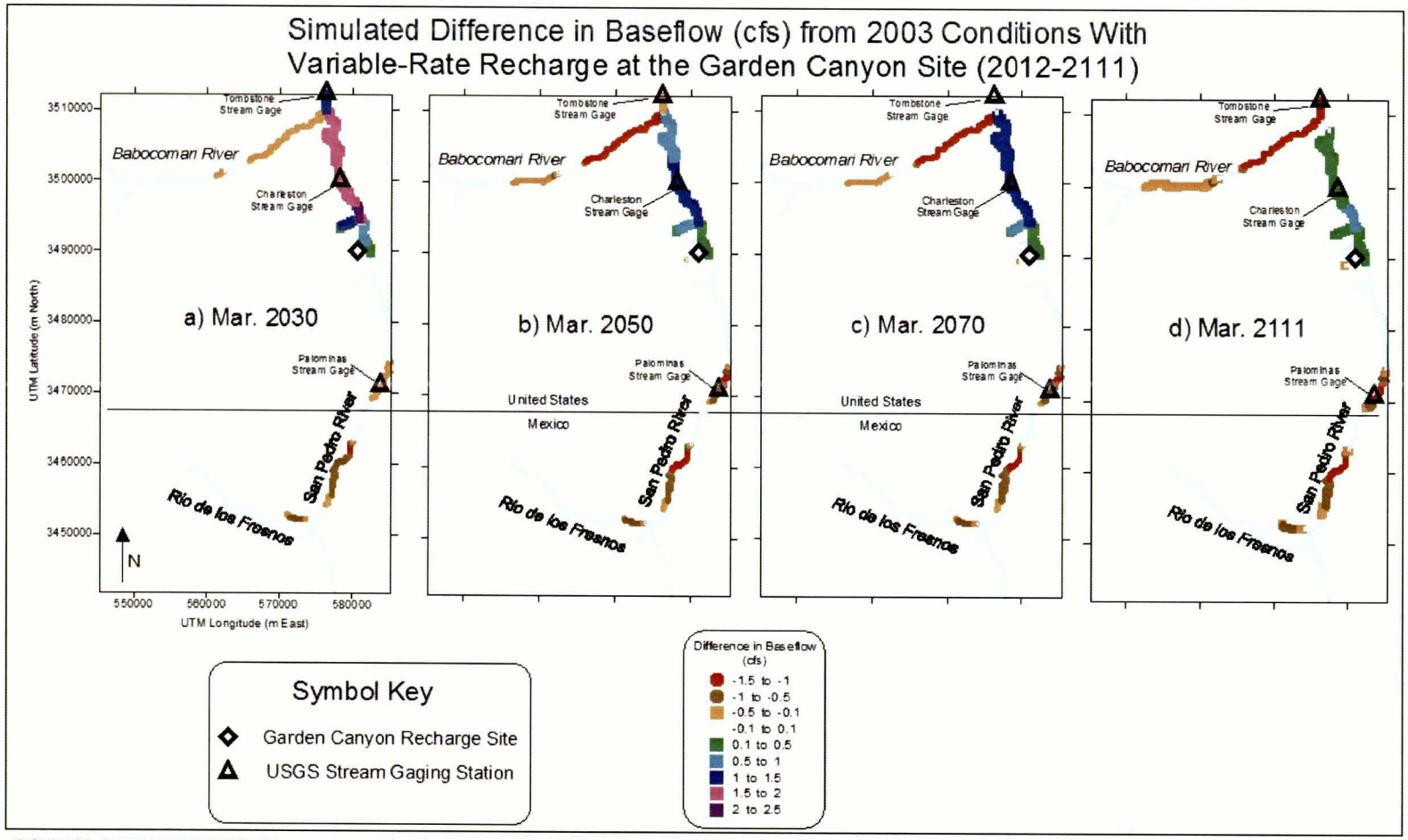

FIGURE 25. SIMULATED DIFFERENCE IN BASEFLOW (CFS) FROM 2003 BASEFLOW CONDITIONS WITH VARIABLE-RATE RECHARGE AT THE GARDEN CANYON SITE FROM 2012 THROUGH 2111.

FMC000998

Figure 26 illustrates the simulated near-stream recharge distribution at the Garden Canyon site required to maintain downstream baseflows at 2003 levels throughout the 100-year simulation period. Until 2060, applying 500 AF/yr of simulated recharge at the Garden Canyon site successfully maintained 2003-level baseflows all the way to the Babocomari confluence (16.5 miles) and sustained riparian ET at or above current levels. Roughly one-third of this downstream reach is presently classified as Class 2 (moderate) riparian condition, indicating some riparian stress (Stromberg, et al, 2006). After 2060, the simulated groundwater level declines as a result of the expanding cone of depression from the Sierra Vista/Fort Huachuca area. This decline necessitated 100-AF/yr increases in simulated near-stream recharge in 2060 and again in 2090 to maintain 2003 baseflow rates throughout the downstream reach and meet riparian ET demands through March 2111.

Figure 26 also plots DTW for the constant-rate and variable-rate recharge simulations. The two DTW curves diverge slightly starting in about 2060 as the regional cone of depression starts to affect heads at the Garden Canyon recharge site. Recharge increases in 2060 and 2090 maintain the DTW at a fairly constant average level of about 9.8 ft. until the end of the simulation period.

Changes in the cumulative water budget from the constant-rate to the variable-rate recharge simulation at the Garden Canyon site are shown in Figure 27 and Table 6. The additional 5,000 AF recharged in the variable-recharge rate simulation (compared with the constant-rate recharge scenario) is partitioned between baseflow (58%), ET demand (25%), and aquifer replenishment (storage) (17%). Notably, the amount of additional recharge required at the

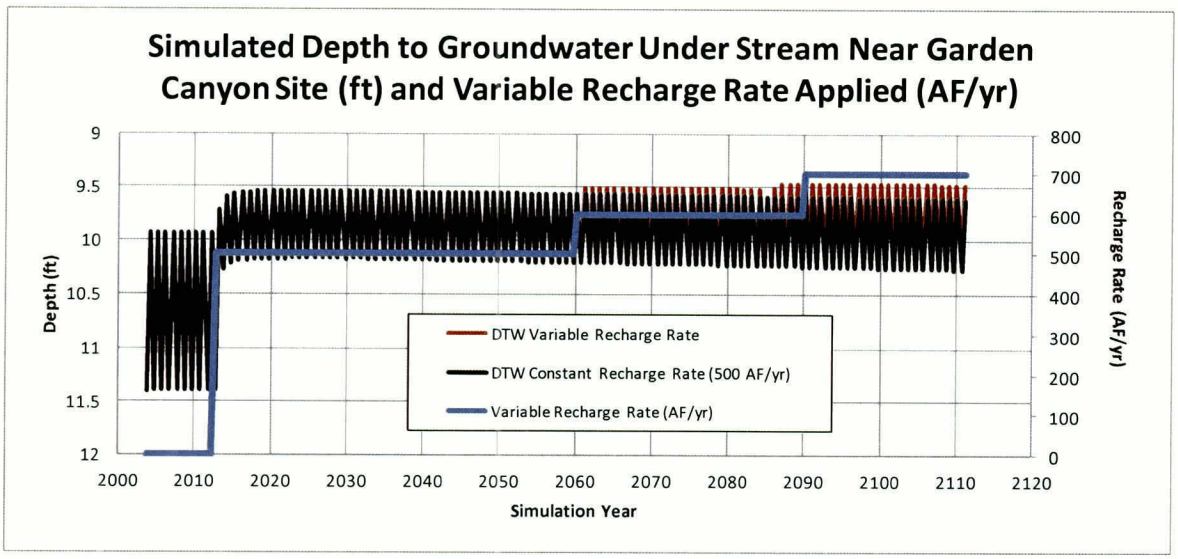

FIGURE 26. SIMULATED VARIABLE RECHARGE RATE AT GARDEN CANYON SITE AND DTW IN STREAM CELL IMMEDIATELY DOWNSTREAM OF GARDEN CANYON RECHARGE SITE (SEE FIGURE 10) FROM MARCH 2003 TO MARCH 2111 FOR BOTH CONSTANT-RATE (500 AF/YR) AND VARIABLE-RATE RECHARGE SCENARIOS.

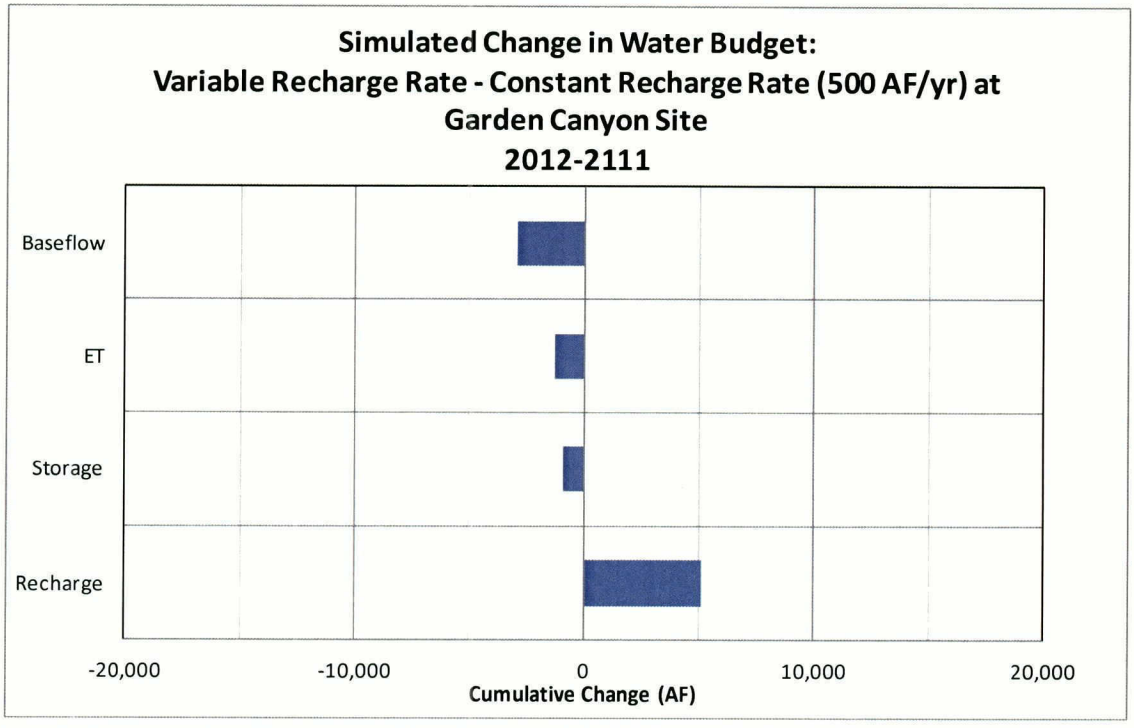

FIGURE 27. CUMULATIVE CHANGES IN SIMULATED WATER BUDGET RELATIVE TO THE CONSTANT-RATE RECHARGE SCENARIO RESULTING FROM VARIABLE-RATE RECHARGE AT THE GARDEN CANYON SITE.

TABLE 6. CUMULATIVE CHANGES IN SIMULATED WATER BUDGET RELATIVE TO THE CONSTANT-RATE RECHARGE SCENARIO RESULTING FROM VARIABLE-RATE RECHARGE AT THE GARDEN CANYON SITE.

Simulated Change in Water Budget: Variable Recharge Rate - Constant Recharge Rate (500 AF/yr) at Garden Canyon Site 2012-2111*			
Budget Element	Change from Constant-Rate Recharge Scenario (AF)	% of Additional Recharge (Above Constant-Rate Recharge of 500 AF/yr)	
Recharge	5,088	100.0%	
Storage	(886)	-17.4%	
ET	(1,312)	-25.8%	
Baseflow	(2,959)	-58.1%	
Pumping	0	0.0%	
Constant Head Boundary	(0)	0.0%	
Drains	0	0.0%	
Total Water Budget Summary, 2012-2111 (AF)			
TOTAL IN	TOTAL OUT	IN-OUT	% ERROR
7,191,145	7,189,035	2110	0.03%
*Values are differences (Garden Canyon variable recharge rate vs. Garden Canyon constant recharge rate (500 AF/yr)) in cumulative net (IN-OUT) totals at the end of the 100-year simulation period in March 2111.			

Garden Canyon site (5,000 AF over 100 years) is less than one-third the amount required at the Palominas site (see Table 5) to maintain 2003-level baseflows, and the length of the affected river reach is much greater.

BABOCOMARI SITE

High permeability and a 20-ft. DTW at the Babocomari recharge site permit much higher rates of simulated recharge than the Garden Canyon or Palominas site. As shown in Figure 28, a steady increase in simulated recharge applied at the Babocomari site is required after the year 2030 in order to overcome the competing demand of pumping-induced aquifer storage depletion. Lacher (2011) illustrated the significant projected expansion of the regional cone of depression under the Babocomari River over the 21st Century. Thus, recharge at this site must first satisfy the ever-increasing storage demand of the underlying aquifer in order to create a groundwater mound sufficient to sustain baseflows at 2003 levels for the 10.5 river miles downstream. The recharge distribution shown in Figure 28 successfully strikes this balance by increasing simulated recharge by an average of 100 to 400 AF/yr every 10 years from 2030 to 2111. For the last decade of simulation (2100-2111), required recharge is 2,600 AF/yr at this site.

Figure 28 also compares the resulting simulated DTW from the variable-rate recharge scenario (red line) at the Babocomari site with DTW from the constant-rate recharge scenario (black line). At this site, maintaining a simulated water level at or above 20 ft. is a necessary condition for sustaining downstream baseflows at or above 2003 levels.

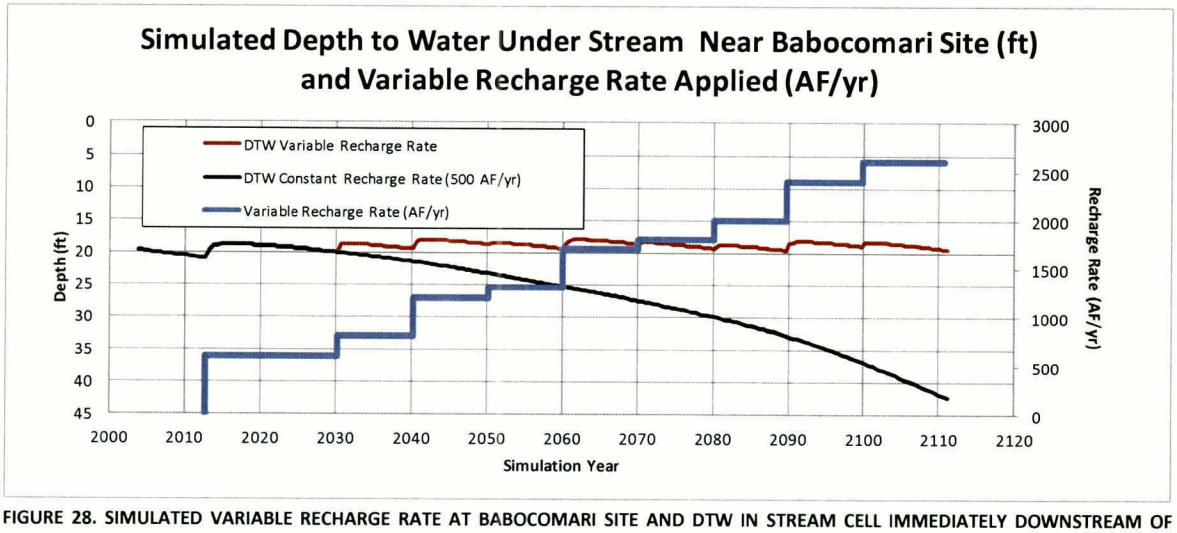

FIGURE 28. SIMULATED VARIABLE RECHARGE RATE AT BABOCOMARI SITE AND DTW IN STREAM CELL IMMEDIATELY DOWNSTREAM OF BABOCOMARI RECHARGE SITE (SEE FIGURE 15) FROM MARCH 2003 TO MARCH 2111 FOR BOTH CONSTANT-RATE (500 AF/YR) AND VARIABLE-RATE RECHARGE SCENARIOS.

FMC001001

Figure 29 shows the spatial distribution of baseflow changes (relative to baseline) resulting from variable-rate recharge at the Babocomari site. Figure 29 shows the westward (upstream) progression of declining baseflows upstream of the Babocomari recharge site. Downstream of the site, the simulated variable-rate recharge applied in this simulation (see Figure 28) successfully maintains baseflows at or above 2003 levels. Simulated baseflows remain at 0.1 to 0.5 cfs above 2003 levels in this reach from 2050 (Figure 29(b)) through 2070 (Figure 29(c)), then diminish slightly by 2111 (Figure 29(d)). Comparing these predicted flow differences on the Babocomari River between the simulated recharge site and the SPR confluence with those in Figure 25 (Garden Canyon scenario) or Figure 22 (Palominas scenario) shows that the variable-rate recharge scenario at the Babocomari site provides a net increase in flow of 0.5 to 2.0 cfs in this downstream reach between 2030 and 2111. Notably, the westward progression of declining baseflows upstream of the recharge site appears relatively unaffected by recharge at the Babocomari site (compare Figure 29 with Figure 25, for example).

Figure 30 and Table 7 provide details on the partitioning of the extra 102,000 AF of water recharged at the Babocomari site under the variable-rate recharge simulation relative to the constant-rate scenario. Slightly more than half (56%) of the additional recharge translates into baseflows, 42% replenishes aquifer storage, and about 2% is consumed by ET. Notably, this volume of added recharge is 1 to 2 orders of magnitude greater than that added to the Palominas and Garden Canyon sites under the variable-rate recharge scenarios.

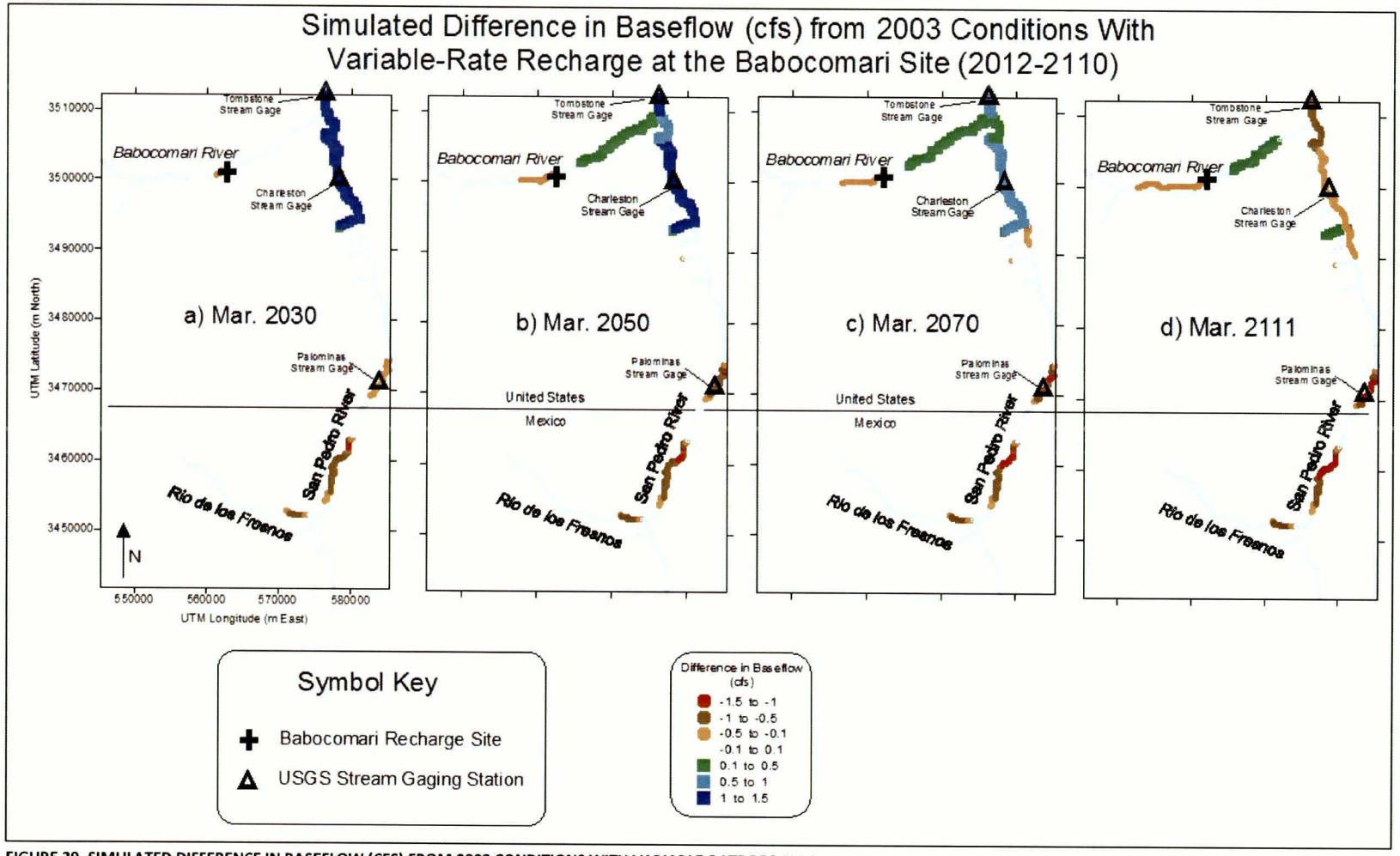

FIGURE 29. SIMULATED DIFFERENCE IN BASEFLOW (CFS) FROM 2003 CONDITIONS WITH VARIABLE-RATE RECHARGE AT THE BABOCOMARI SITE FROM 2012 THROUGH 2111.

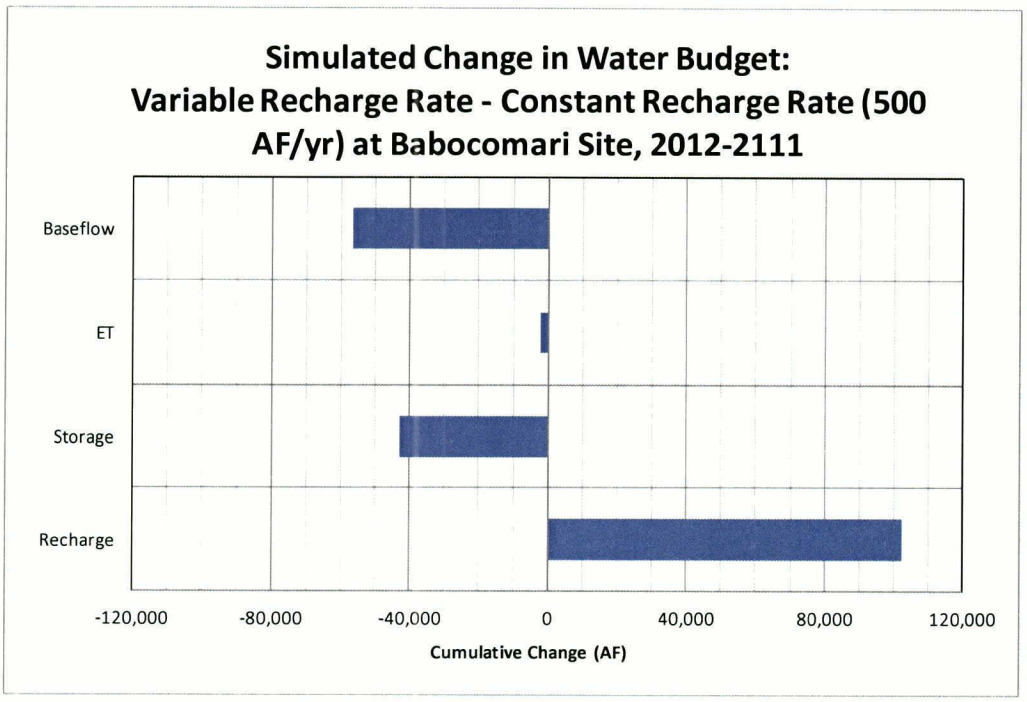

FIGURE 30. CUMULATIVE CHANGES IN SIMULATED WATER BUDGET RELATIVE TO THE CONSTANT-RATE RECHARGE SCENARIO RESULTING FROM VARIABLE-RATE RECHARGE AT THE BABOCOMARI SITE.

TABLE 7. CUMULATIVE CHANGES IN SIMULATED WATER BUDGET RELATIVE TO THE CONSTANT-RATE RECHARGE SCENARIO RESULTING FROM VARIABLE-RATE RECHARGE AT THE BABOCOMARI SITE.

Simulated Water Budget with Variable Recharge at Babocomari Site 2012-2111*			
Budget Element	Change from Constant-Rate Recharge Scenario (AF)	% of Additional Recharge over Constant-Rate Recharge of 500 AF/yr	
Storage	(43,073)	-42.1%	
ET	(2,078)	-2.0%	
Recharge	102,201	100.0%	
Baseflow	(56,892)	-55.7%	
Pumping	(1)	0.0%	
Constant Head Boundary	(89)	-0.1%	
Drains	(82)	-0.1%	
Water Budget Summary, 2012-2111 (AF)			
TOTAL IN	TOTAL OUT	IN-OUT	% ERROR
7,226,949	7,224,603	2346	0.03%

*Values are differences (Babocomari variable recharge rate vs. Babocomari constant recharge rate (500 AF/yr)) in cumulative net (IN-OUT) totals at the end of the 100-year simulation period in March 2111.

CONCURRENT RECHARGE AT ALL THREE SITES

INITIAL VARIABLE-RATE RECHARGE

The preceding sections described the simulated hydrologic impacts of applying recharge at each of three separate sites (Palominas, Garden Canyon, and Babocomari) in isolation, while all other basin-wide conditions remained as they were in the baseline model. This section presents results of simulating concurrent recharge at the three sites. The initial simulation for this scenario applied the variable-rate recharge distributions shown in Figure 23, Figure 26, and Figure 28 concurrently at the three sites over the period 2012 to 2111.

Figure 31 shows the spatial distribution of simulated changes in baseflow (from baseline) with concurrent initial variable-rate recharge at the three near-stream sites (Palominas, Garden Canyon, and Babocomari). Simulated baseflows exceed 2003 levels by as much as 2.5 cfs (just below the Garden Canyon site) in 2030 (Figure 31(a)), but by 2111, the maximum increase over 2003 baseflows is 0.5 to 1 cfs in the reach just upstream of the Charleston gaging station (Figure 31(d)). The greatest impact of the initial concurrent recharge scenario manifests in simulated baseflows along the SPR downstream (north) of the Garden Canyon site. Comparing Figure 31(b) (three sites - March 2050) with Figure 25(b) (Garden Canyon – March 2050) shows that concurrent recharge sustains significantly higher levels of baseflow (up to 2.5 cfs) in the Charleston reach and below the Babocomari confluence than with any site operating independently. By 2111, simulated baseflows below the confluence of the SPR and the Babocomari are as much as 3 cfs higher with all three sites operating concurrently (Figure 31(d)) than with any of the sites operating independently (Figure 22(d), Figure 25(d), and Figure 29(d)).

Figure 32 illustrates the changes in the simulated water budget elements for the initial concurrent recharge simulation vs. the baseline scenario over the 100-year simulation period. Details of the water budget for this combined recharge simulation are provided in

Table 8. Over the 100-year simulation period, a net total of 272,242 AF (average 2,722 AF/yr) of water were recharged at the three sites (Palominas, Garden Canyon, and Babocomari). Of this recharge, about 38% supported increased baseflow, while the remaining 62% was split equally between aquifer storage replenishment and riparian ET (see

Table 8). As shown in the fourth column of

Table 8, this change in simulated baseflow represents an increase of more than 36% over the baseline value.

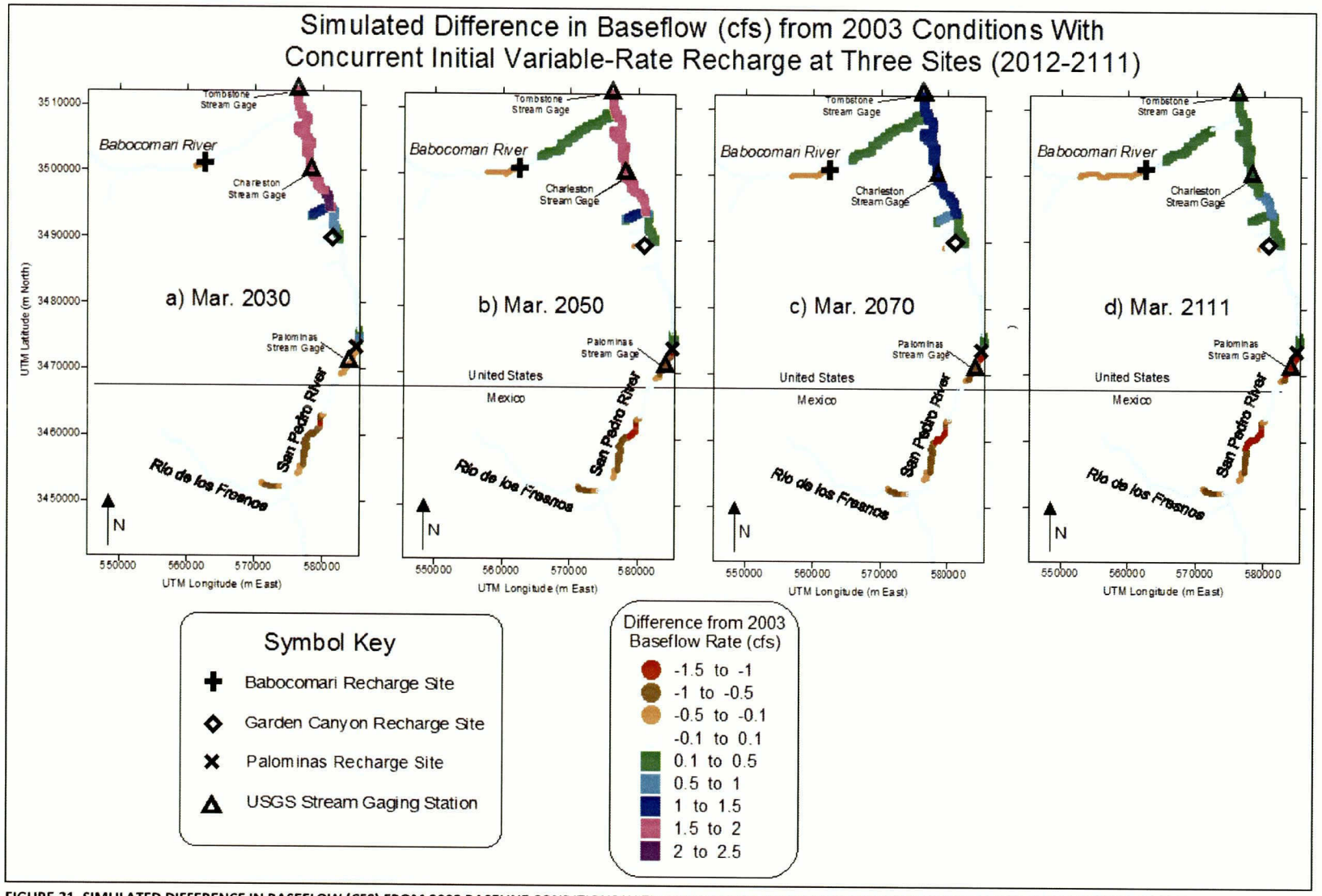

FIGURE 31. SIMULATED DIFFERENCE IN BASEFLOW (CFS) FROM 2003 BASELINE CONDITIONS WITH CONCURRENT INITIAL VARIABLE-RATE RECHARGE AT THE PALOMINAS, GARDEN CANYON, AND BABOCOMARI SITES AT FOUR POINTS IN TIME: A) MARCH 2030, B) MARCH 2050, C) MARCH 2070, AND D) MARCH 2111.

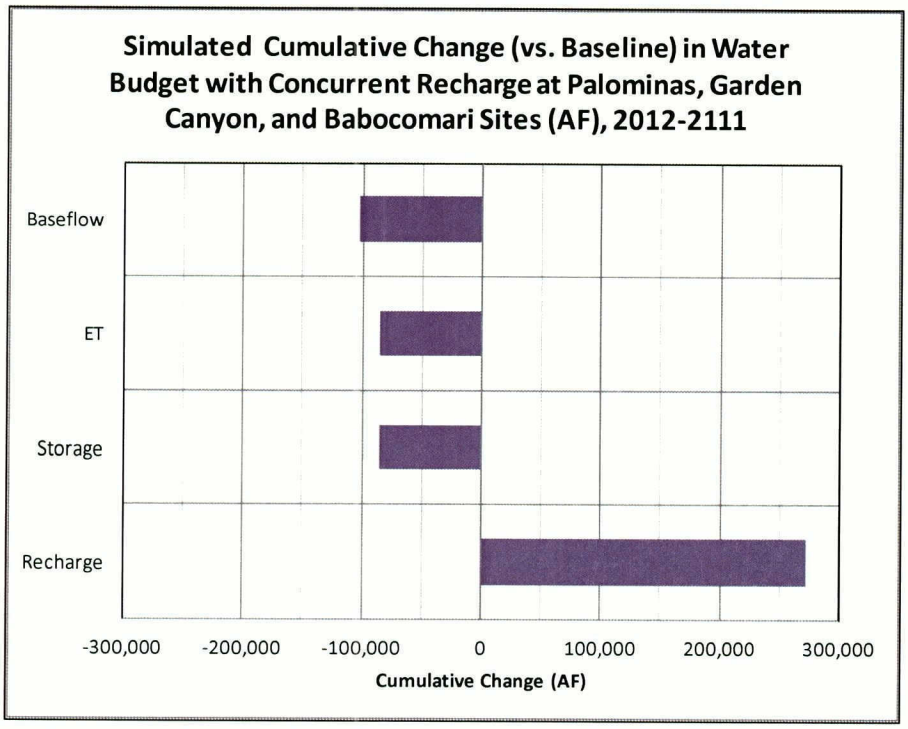

FIGURE 32. SIMULATED CUMULATIVE CHANGE (AF) IN WATER BUDGET (VS. BASELINE SCENARIO) FOR INITIAL VARIABLE-RATE RECHARGE AT PALOMINAS, GARDEN CANYON, AND BABOCOMARI SITES, 2012-2111.

TABLE 8. WATER BUDGET FOR INITIAL CONCURRENT VARIABLE-RATE RECHARGE SIMULATION AT PALOMINAS, GARDEN CANYON, AND BABOCOMARI RECHARGE SITES, 2012-2111.

Simulated Change in Water Budget: Concurrent Variable-Rate Recharge At Three Sites vs. Baseline				
Cumulative Net Water Budget: 2012-2011[1]				
Budget Element	Change from Baseline (AF)	Baseline Model (AF)	% of Baseline Element[2]	% of Combined Recharge[3]
Recharge	272,242	2,154,530	12.6%	100.0%
Storage	(85,530)	3,816,244	-2.2%	-31%
ET	(85,651)	(735,029)	11.7%	-31%
Baseflow	(103,248)	(285,695)	36.1%	-37.9%
Pumping	2,070	(4,829,314)	0.0%	0.8%
Constant Head Boundary	(190)	(76,498)	0.2%	-0.1%
Drains	(135)	(41,913)	0.3%	0.0%
Water Budget Summary, 2012-2111 (AF)				
TOTAL IN	TOTAL OUT	IN-OUT		% ERROR
7,384,268	7,382,386	1882		0.03%

[1]Values are differences (with recharge at three sites vs. baseline scenario) in cumulative net (IN-OUT) totals at the end of the 100-year simulation period in March 2111.

[2] Budget element for three concurrent recharge sites simulation as a percentage of same budget element in baseline simulation.

[3]Each budget element as a percentage of the cumulative recharge for three concurrent recharge sites (272,242 AF).

Optimized Variable-Rate Recharge

The results shown in Figure 31 suggest that simulated 2003-level baseflows in the Sierra Vista subbasin could be sustained with less recharge than the 272,242 AF applied in the initial concurrent recharge simulation (Table 8). In an effort to optimize the rate of simulated near-stream recharge, subsequent simulations explored the potential for reducing recharge at the Garden Site from the initial rates shown in Figure 26 while maintaining the same variable-rate recharge distributions at the Palominas and Babocomari sites as described in Figure 23 and Figure 28, respectively. Figure 33 compares the original and reduced recharge distributions for the Garden Canyon site. Notably, in the reduced-recharge case, a sharp increase in simulated recharge (from 100 to 500 AF/yr) is required between 2080 and 2090 to sustain baseflows downstream of that site through 2111. Figure 34 illustrates the nearly equal partitioning of simulated near-stream recharge in this scenario into the water budget elements of baseflow, riparian ET, and aquifer storage. Table 9 presents the data used to generate Figure 34. In this case, cumulative near-stream recharge of 237,579 AF increased cumulative simulated baseflow by approximately 9% over the baseline scenario (compared with 36% greater in the initial concurrent variable-rate recharge scenario). Another interpretation of these results is that the baseline model projects that baseflow across the Sierra Vista subbasin will decline by 9% from 2003 levels over the next century without any intervention such as the near-stream recharge strategy presented in this study. This projected decline in baseflow includes only the effects represented in the groundwater model (primarily pumping, ET, mountain-front recharge, and artificial recharge), and does not include any changes that might result from drought or climate change. Over the 100-year simulation period, reducing recharge at the Garden Canyon site saved a net total of 34,663 AF (272,242 AF – 237,579 AF), or an average of nearly 350 AF/yr compared with the initial concurrent variable-rate recharge simulations (see Table 8).

Figure 35 illustrates the new spatial distribution of simulated baseflows as differences from 2003 baseflows with optimized recharge at the Garden Canyon site. Comparison with Figure 31 shows that baseflows downstream of the Garden Canyon site decreased by roughly 0.5 cfs on average from 2030 to 2070 as a result of the reduced recharge applied at the Garden Canyon site. By 2111 (Figure 31(d) and Figure 35(d)), the simulated baseflows in the initial concurrent recharge case are only slightly higher than those in the reduced recharge case.

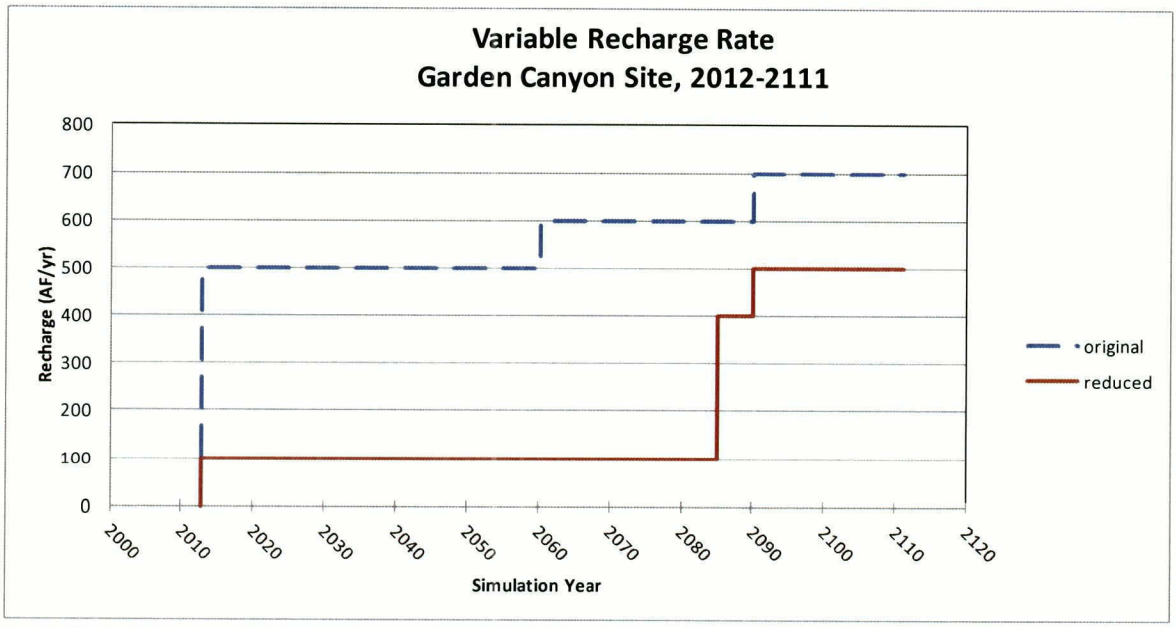

FIGURE 33. ORIGINAL AND REDUCED VARIABLE-RATE RECHARGE DISTRIBUTIONS AT THE GARDEN CANYON SITE.

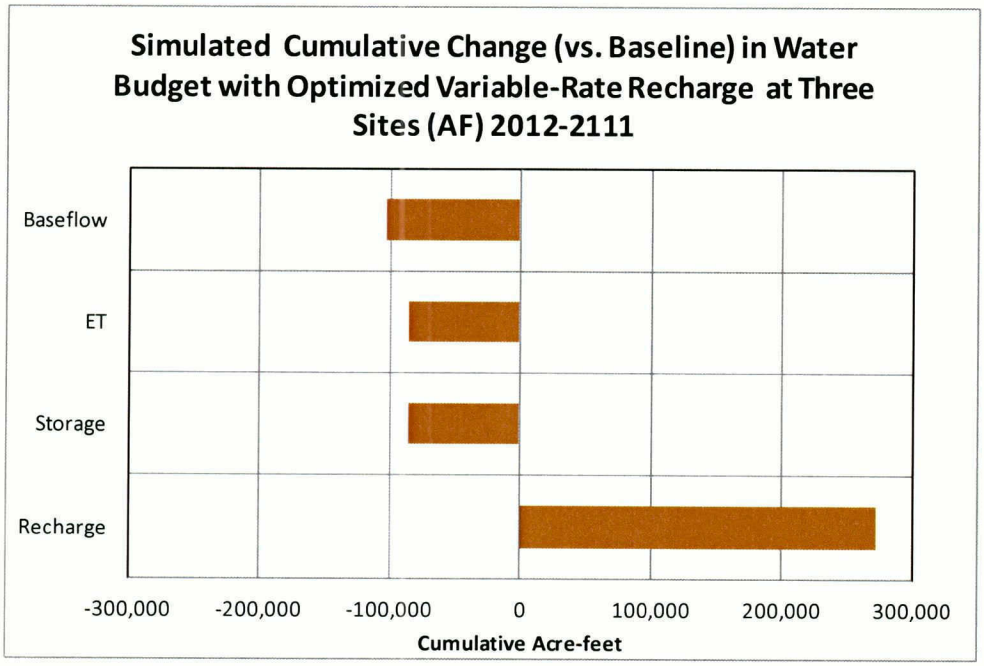

FIGURE 34. SIMULATED CUMULATIVE CHANGE (AF) IN WATER BUDGET (VS. BASELINE SCENARIO) FOR OPTIMIZED VARIABLE-RATE RECHARGE AT PALOMINAS, GARDEN CANYON, AND BABOCOMARI SITES, 2012-2111.

TABLE 9. WATER BUDGET FOR OPTIMIZED CONCURRENT VARIABLE-RATE RECHARGE SIMULATION AT PALOMINAS, GARDEN CANYON, AND BABOCOMARI RECHARGE SITES, 2012-2111.

Simulated Change in Water Budget: Optimized Concurrent Variable-Rate Recharge At Three Sites vs. Baseline			
Cumulative Water Budget Changes from Baseline[1]			
Budget Element	AF	% of Baseline Element[2]	% of Added Recharge[3]
Recharge	237,579	5.2%	100.0%
Storage	(83,879)	-1.7%	-35%
ET	(73,312)	4.5%	-31%
Baseflow	(82,399)	8.7%	-34.7%
Pumping	2,188	0.0%	0.9%
Constant Head Boundary	(168)	0.1%	-0.1%
Drains	(133)	0.1%	-0.1%
Water Budget Summary, 2012-2111 (AF)			
TOTAL IN	TOTAL OUT	IN-OUT	% ERROR
7,351,905	7,349,704	2201	0.03%

[1]Values are differences (with recharge at three sites vs. baseline scenario) in cumulative net (IN-OUT) totals
[2] Budget element for three recharge sites simulation as a percentage of same budget element in baseline
[3]Each budget element as a percentage of the cumulative recharge for three recharge sites (237,579 AF).

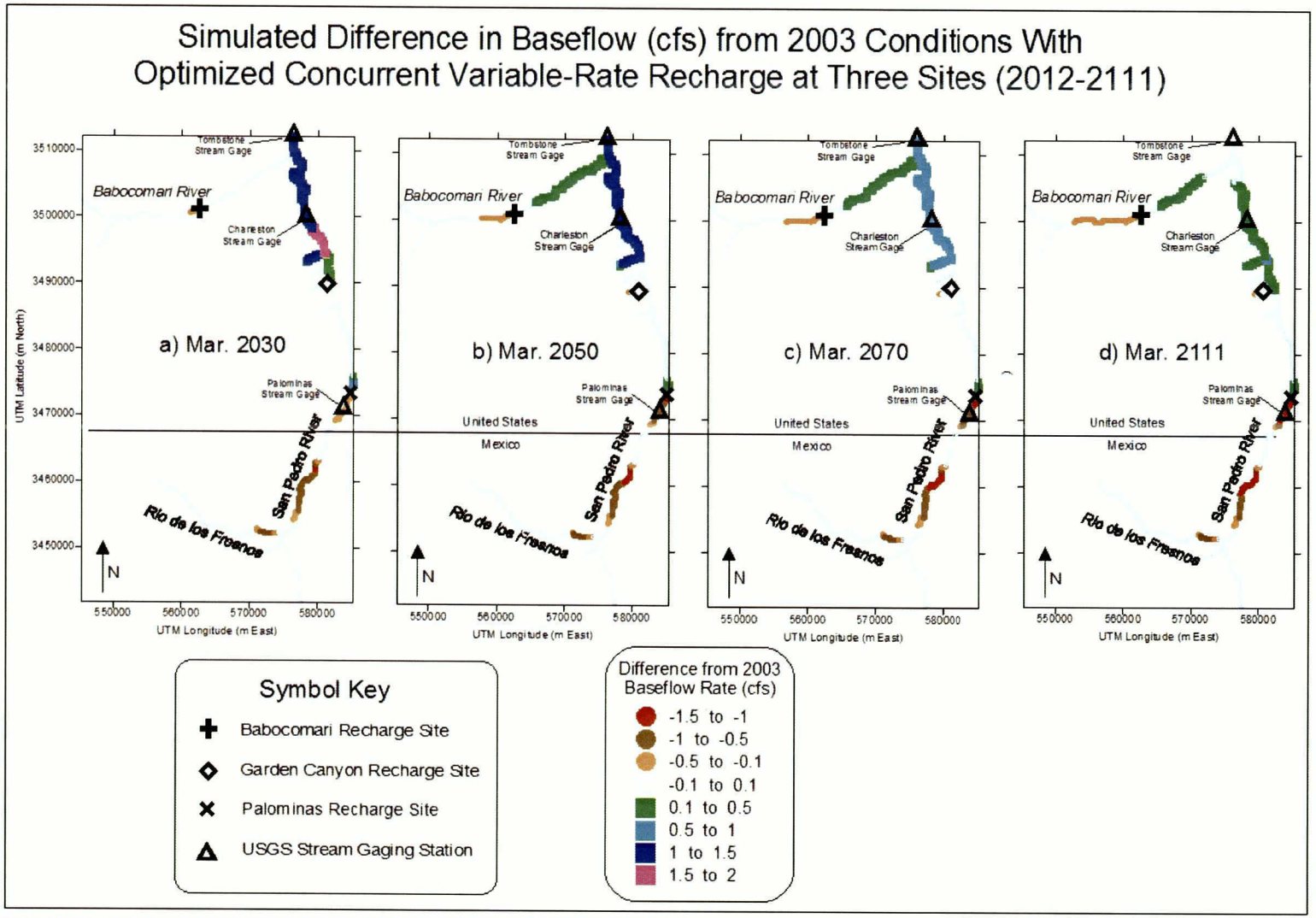

FIGURE 35. SIMULATED DIFFERENCE IN BASEFLOW (CFS) FROM 2003 BASELINE CONDITIONS WITH OPTIMIZED CONCURRENT VARIABLE-RATE RECHARGE AT THE PALOMINAS, GARDEN CANYON, AND BABOCOMARI SITES AT FOUR POINTS IN TIME: A) MARCH 2030, B) MARCH 2050, C) MARCH 2070, AND D) MARCH 2111. RECHARGE WAS OPTIMIZED BY REDUCING RECHARGE AT THE GARDEN CANYON SITE.

SUMMARY AND CONCLUSIONS

SUMMARY

Simulations using the most current groundwater model of the USPB (Lacher, 2011; Pool and Dickinson, 2007) explored the potential use of near-stream surface recharge at three sites in the Sierra Vista subbasin to protect baseflows and riparian habitat in the Upper San Pedro and Babocomari rivers from pumping-induced depletions over the next century. In addition to demonstrating measurable improvements in simulated baseflows within the first 20 years, the study addressed three objectives: 1) to compare and contrast the hydrologic effects of near-stream recharge at three different sites; 2) to determine the minimum rate of recharge required at each site to sustain simulated downstream baseflows at or above 2003 levels for 100 years considering each site independently, and 3) to evaluate the potential water savings afforded by operating all three recharge sites concurrently.

Simulated recharge began in October 2012 and continued until March 2111 using water of unspecified origin, but assumed to have no negative impact on the basin-wide water budget within the 100-year simulation period. Examples of such sources may include captured stormwater, treated effluent, or water imported from outside the basin. Importantly, existing incidental recharge from urban-enhanced runoff in stream channels and stormwater detention facilities is already accounted for in the groundwater model, so any water destined for the types of projects described in this study would entail development of new sources.

The constant-rate recharge simulations applied 500 AF/yr of water on the surface of each 62-acre recharge site: Babocomari in the north, Garden Canyon near the center, and Palominas near the south end of the Sierra Vista subbasin. The reaches downstream of each recharge site were divided as follows: a) Babocomari site to San Pedro River confluence (10.5 miles), b) Garden Canyon site to Babocomari confluence (16.5 miles), and c) Palominas site to Garden Canyon site (12 miles). Aside from the surface recharge, all other elements of the baseline model remained unchanged. These simulations revealed how antecedent hydrogeologic and riparian conditions at each site governed the fate of water recharged at each site. Figure 36 and Figure 37 compare depth to groundwater over time and cumulative water budget changes for each the three sites in response to 500 AF/yr of surface recharge over the 100-year simulation period. In general, the recharged water was partitioned among three elements of the water budget: 1) baseflow, 2) riparian ET demand, and 3) aquifer storage. Underlying geology (e.g., presence or absence of an extensive silt and clay unit under the site), initial depth to groundwater, ET criteria, and proximity to the regional cone of depression in the basin-fill aquifer determined the fate of recharge at each site.

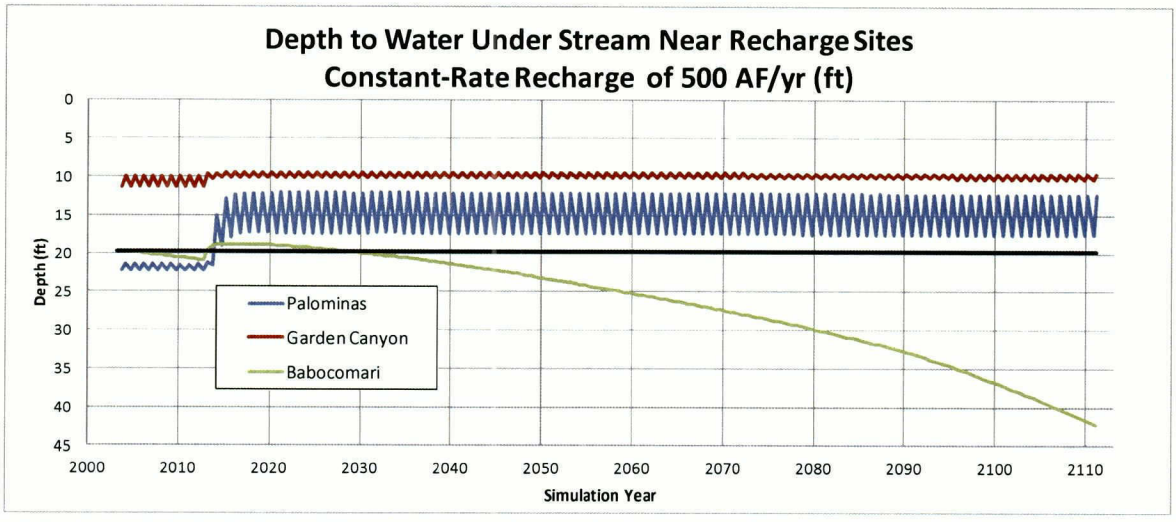

FIGURE 36. COMPARISON OF SIMULATED GROUNDWATER LEVELS AT THE THREE RECHARGE SITES IN RESPONSE TO 500 AF/YR OF CONSTANT-RATE RECHARGE AT EACH SITE APPLIED FROM OCTOBER 2012 TO MARCH 2111.

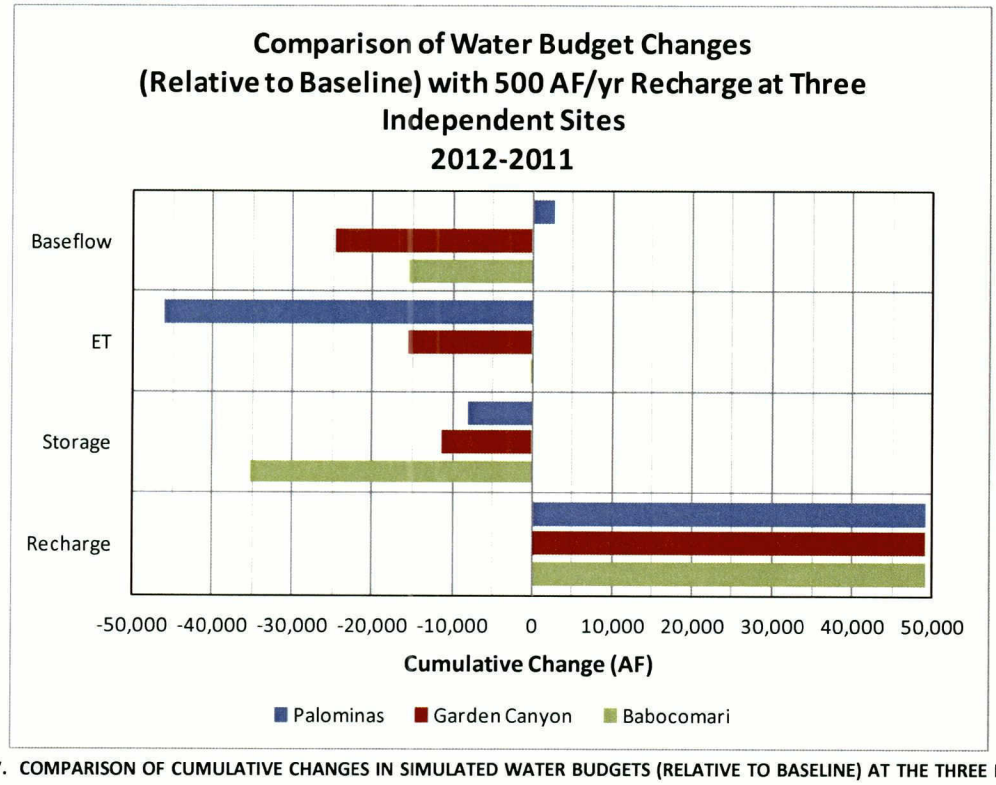

FIGURE 37. COMPARISON OF CUMULATIVE CHANGES IN SIMULATED WATER BUDGETS (RELATIVE TO BASELINE) AT THE THREE RECHARGE SITES IN RESPONSE TO 500 AF/YR OF CONSTANT-RATE RECHARGE APPLIED FROM OCTOBER 2012 TO MARCH 2111.

At the Palominas site, high riparian ET demand consumed more than 90% of the 500 AF/yr recharged at the site as the simulated recharge process successfully raised groundwater levels above the ET extinction depth after 2012 (see Figure 36). The remaining available recharge replenished aquifer storage in response to pumping-induced depletions. Recharging 500 AF/yr at this site produced a dramatic increase in simulated riparian ET, but also a slight decrease in total baseflow in the basin (relative to the baseline model) by the end of the 100-year simulation period. At the Garden Canyon site, shallow antecedent groundwater levels and a thick underlying silt and clay unit translated roughly half of the simulated 500 AF/yr recharged at the site into baseflow, while about 30% satisfied riparian ET demand, and 20% replenished aquifer storage. This simulated recharge increased baseflows in 16.5 miles of the SPR downstream of the site by 0.5 to 0.7 cfs, with impacts steadily increasing over the 100-year period. The absence of a protective silt and clay unit under the Babocomari site and its proximity to the heart of the regional cone of depression make it vulnerable to pumping-induced depletions (Leake, Pool, and Leenhouts, 2008). Consequently, the simulated demand for aquifer storage replenishment consumed over 70% of the 500 AF/yr recharged at the site, with the remaining water supporting downstream baseflow. As a result of this recharge, simulated baseflow in the 10.5-mile reach below the Babocomari site increased by 0.3 to 0.5 cfs until 2030, then began to decline so that no discernable improvement in baseflow remained by 2090.

The constant-rate recharge simulation results demonstrated that 500 AF/yr of recharge at each site was not sufficient to maintain downstream simulated baseflows at 2003 levels for next 100 years. In order to keep pace with the simulated expanding regional cone of depression (Lacher, 2011), the variable-rate recharge scenario increased recharge at each site over time as shown in Figure 38. Figure 39 illustrates the partitioning of the additional recharge at each of the three independent sites (above the 500 AF/yr constant rate) among water budget components of baseflow, riparian ET, and aquifer storage. The total additional recharge at the Babocomari site totaled 102,000 AF by 2111, compared with just over 5,000 AF at the Garden Canyon site, and 17,000 AF at the Palominas site. The largest change (relative to the constant-rate recharge scenario) in simulated downstream baseflow under the variable-rate recharge scenario occurred below the Babocomari site, followed by the Garden Canyon site. Simulated baseflow downstream of the Palominas site declined slightly (relative to baseline) with the added recharge, while riparian ET increased by more than 16,000 AF over the 100-year simulation period (see Table 5). Figure 40 illustrates the resulting simulated DTW under the stream adjacent to each of the three recharge sites in the variable-rate recharge scenario.

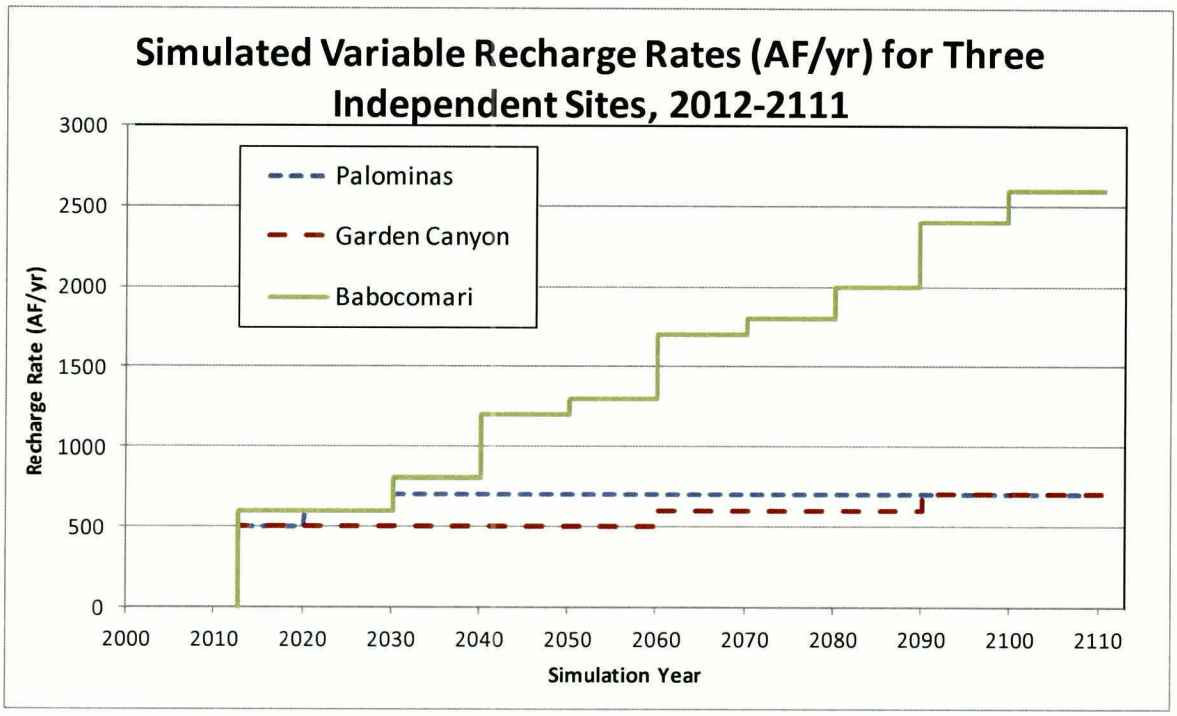

FIGURE 38. COMPARISON OF SIMULATED RECHARGE RATES REQUIRED TO SUSTAIN 2003 BASEFLOW CONDITIONS IN THE AFFECTED REACH DOWNSTREAM OF EACH OF THE THREE RECHARGE SITES.

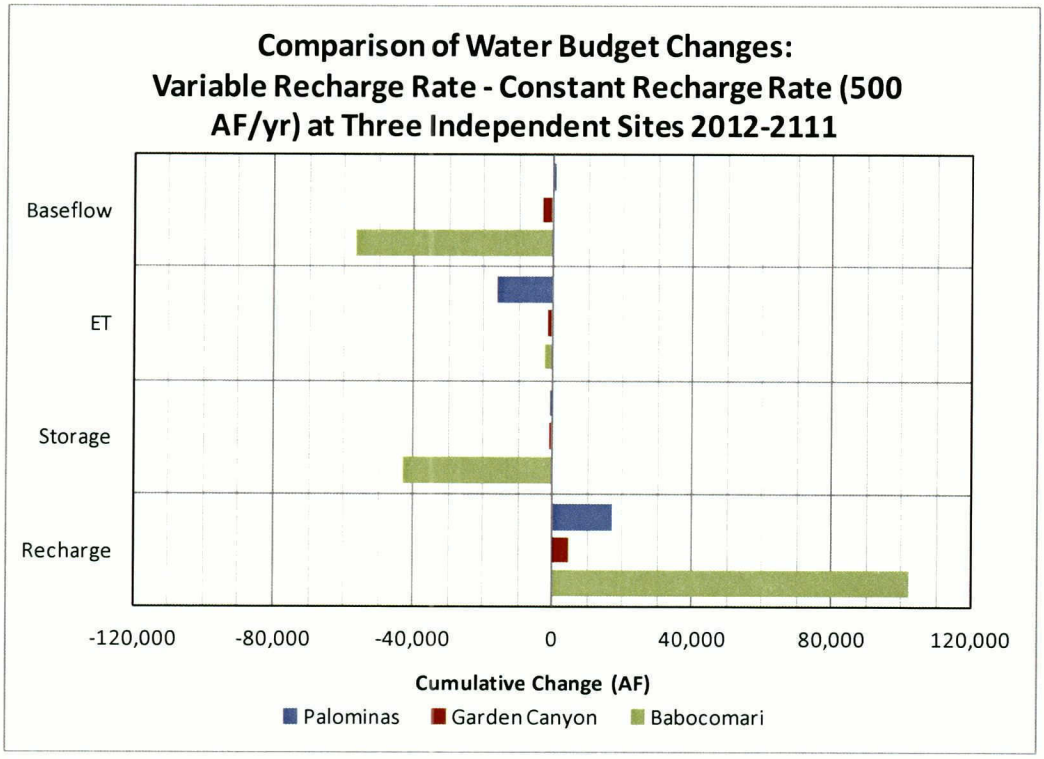

FIGURE 39. COMPARISON OF CUMULATIVE WATER BUDGET CHANGES (AF) AT THE BABOCOMARI, GARDEN CANYON, AND PALOMINAS SITES RESULTING FROM ADDITIONAL RECHARGE (ABOVE 500 AF/YR) APPLIED IN THE VARIABLE-RATE RECHARGE SCENARIOS.

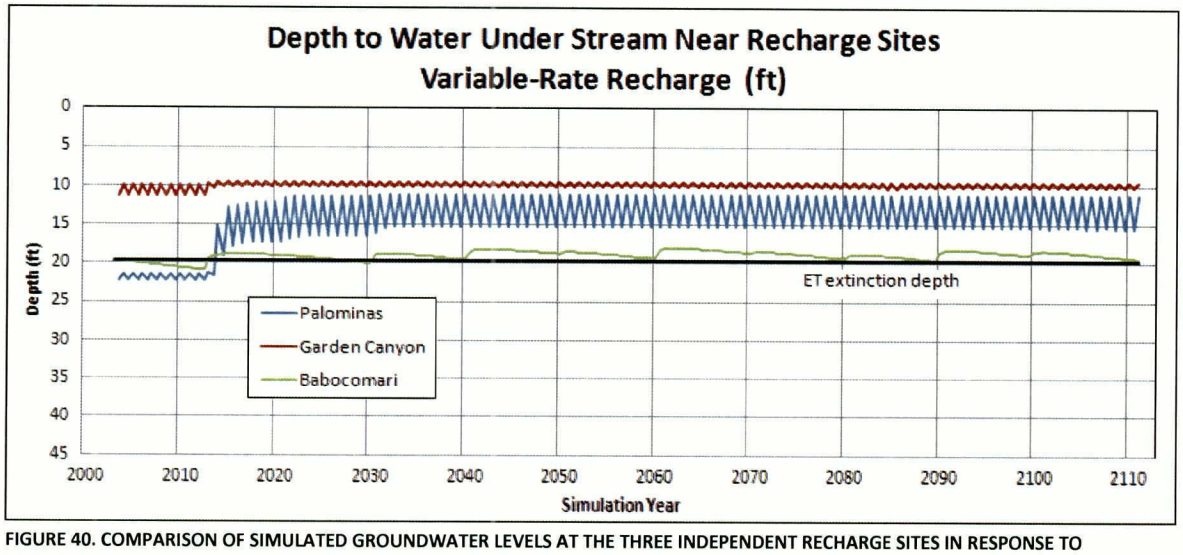

FIGURE 40. COMPARISON OF SIMULATED GROUNDWATER LEVELS AT THE THREE INDEPENDENT RECHARGE SITES IN RESPONSE TO VARIABLE-RATE RECHARGE AT EACH SITE APPLIED FROM OCTOBER 2012 TO MARCH 2111.

Applying the variable recharge rates shown in Figure 38 to all three sites concurrently over the 100-year simulation period produced a 36% increase in simulated baseflows across the Sierra Vista subbasin with a total of 272,242 AF more recharge than the baseline model (Table 8). This level of concurrent recharge resulted in simulated baseflows up to 2.5 cfs higher than those observed in 2003 in 2030, but that difference diminished to a maximum of 1 cfs by 2111 (Figure 31). The largest increases in simulated baseflow occurred downstream of the Garden Canyon site.

In order to capitalize on the additive effects of concurrent recharge, successive simulations reduced the rate of near-stream recharge at the Garden Canyon site until the minimum concurrent rate of recharge required to sustain 2003 baseflows was identified. Figure 41 illustrates the benefits of recharging at all three sites concurrently using an optimized (reduced) variable rate at the Garden Canyon site (Figure 33), and maintaining the initial variable rates at the Palominas and Babocomari sites (Figure 23 and Figure 28). The blue area of the chart in Figure 41 shows the total recharge required to support baseflow throughout the Sierra Vista subbasin at 2003 levels with each site operating independently. The red area of the chart shows the amount of recharge required to sustain 2003-level baseflows when all three sites recharge concurrently. Simulating concurrent recharge at all three sites permits an average reduction of about 350 AF/yr at the Garden Canyon site, and reduces total recharge demand at the three near-stream sites by almost 35,000 AF over the 100-year simulation period. Under this configuration, the total near-stream recharge required to maintain 2003-level baseflows ranges from 1,200 AF/yr in the 2012 to 3,800 AF/yr in 2111, with the sharpest increase in required recharge rate occurring between 2085 and 2100. Total cumulative recharge in this optimized scenario is 237,579 AF over the 100-year simulation period (average 2,376 AF/yr).

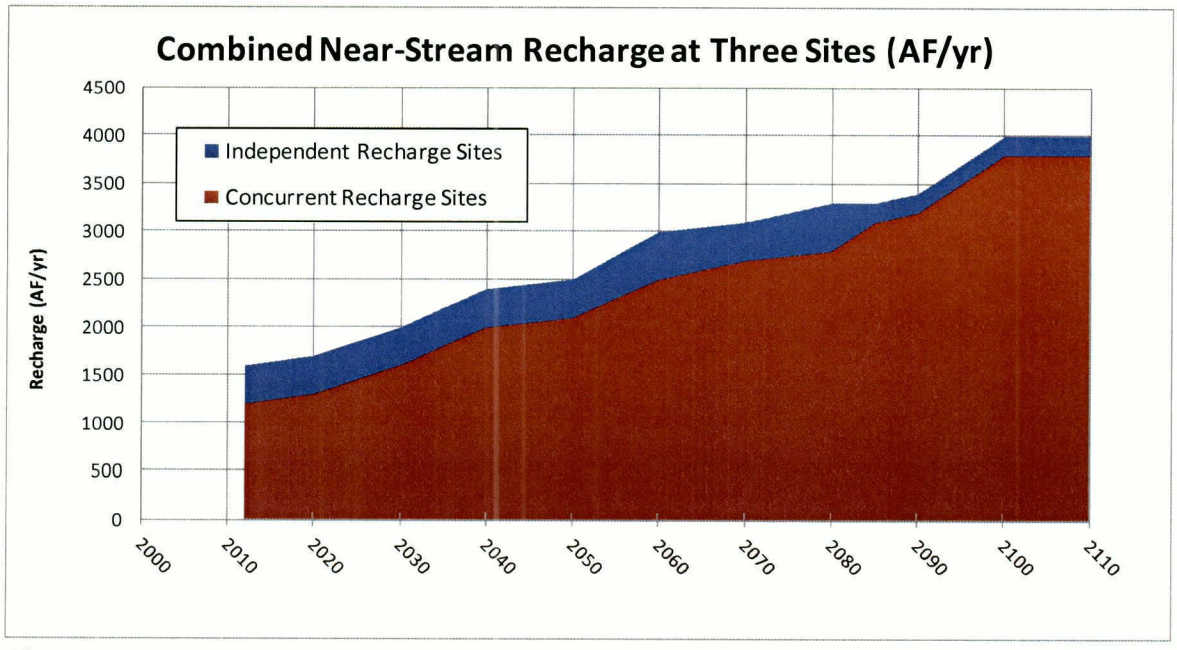

FIGURE 41. SIMULATED DISTRIBUTION OF COMBINED REQUIRED RECHARGE AT PALOMINAS, GARDEN CANYON, AND BABOCOMARI RECHARGE SITES TO MAINTAIN 2003-LEVEL BASEFLOWS DOWNSTREAM OF ALL THREE SITES, 2012-2111.

CONCLUSIONS

Different antecedent hydrological and ecological conditions at each of the three simulated near-stream sites in this study produce significantly varied baseflow responses to recharge among the three sites. Recharging at all three sites concurrently provides substantial additive benefits, and reduces the simulated requirement for near-stream recharge by roughly 13% or 35,000 AF over 100 years. This work demonstrates that, even in the face of projected growth and increasing demand for groundwater within the existing regional cone of depression, strategic near-stream recharge averaging less than 2,400 AF/yr may be capable of supporting baseflows and riparian habitat at 2003 levels in most of the Sierra Vista subbasin for the next century. Notably, the USPP estimated the aquifer storage deficit in 2010 at roughly 6,100 AF (USPP, 2010). While considerably more detailed study will be required for any proposed recharge site in order to evaluate the accuracy of the basin-wide model predictions, the simulations outlined in this study demonstrate that riparian health in the USPB may be sustainable with strategic use of continuous near-stream recharge at an average rate considerably lower than the current annual storage deficit in the Sierra Vista subbasin.

REFERENCES CITED

Brown and Caldwell, 2009, Sierra Vista Water Reclamation Facility Groundwater Modeling Study, prepared for City of Sierra Vista.

Harbaugh, A.W., Banta, E.R., Hill, M.C. and M.G. McDonald, 2000, MODFLOW-2000, The U.S. Geological Survey Modular Ground-water Model – User Guide to Modularization Concepts and the Ground-water Flow Process, Open-file Report 00-92, 121 p.

Lacher, L.J., 2011, Simulated Groundwater and Surface Water Conditions In the Upper San Pedro Basin, 1902-2105 – Preliminary Baseline Results, Task 1 Report prepared for the Friends of the San Pedro River and the Walton Family Foundation, June, 51 p. + App.

Leake, S.A., Pool, D.R., and J.M. Leenhouts, 2008, Simulated Effects of Ground-Water Withdrawals and Artificial Recharge on Discharge to Streams, Springs, and Riparian Vegetation in the Sierra Vista Subwatershed of the Upper San Pedro Basin, Southeastern Arizona, prep. in coop. with the Upper San Pedro Partnership, U.S. Geological Survey Sci. Inv. Rpt. 2008-5207, 14 p.

McDonald, M.G. and A.W. Harbaugh, 1988, A Modular Three-dimensional Finite-difference Ground-water Flow Model, Techniques of Water Resources Investigations of the United States Geological Survey, United States Geological Survey, Reston, VA, Jan.

Pool, D.R. and J.E. Dickinson, 2007, Ground-Water Flow Model of the Sierra Vista Subwatershed and Sonoran Portions of the Upper San Pedro Basin, Southeastern Arizona, United States, and Northern Sonora, Mexico, in cooperation with the Upper San Pedro Partnership and U.S. Bureau of Land Management, U.S. Dept. of Interior, U.S. Geological Survey Scientific Investigations Report 2006-5228, 47 p.

Stromberg, J.C., Lite, S.J., Dixon, M., Rychener, T., and E. Makings, 2006, Relations between Streamflow Regime and Riparian Vegetation Composition, Structure, and Diversity within the San Pedro Riparian National Conservation Area, Arizona, Chapter C *in* Hydrologic Requirements of and Consumptive Ground-Water Use by Riparian Vegetation along the San Pedro River, Arizona, U.S. Geological Survey Sci. Inv. Rpt. 2005-5163, pp. 57-106.

Upper San Pedro Partnership (USPP), 2010, Water Management of the Regional Aquifer in the Sierra Vista Subwatershed, Arizona—2010 Report to Congress Washington, D.C., U.S. Department of Interior, 20 p.

FMC001018