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Prepared in consultation with the Secretaries of Agriculture and Defense and in cooperation with the Upper San Pedro Partnership in response to Public Law 108-136, Section 321

2010 Appendix A: Progress Toward Achieving and Maintaining Sustainable Yield of the Regional Aquifer of the Sierra Vista Subwatershed, Arizona

Upper SanPedro Partnership

U.S. Department of the Interior
U.S. Geological Survey

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Appendix A: Progress Toward Achieving and Maintaining Sustainable Yield of the Regional Aquifer of the Sierra Vista Subwatershed, Arizona

Forward

As in the 2009[1] 321 report to Congress, the bulk of the background text and figures for the 2010 321 Report are found here in Appendix A of this report. The intent is to make the 321 report more understandable, a simpler matter to review, and of greater value to both Members of Congress and the general public than earlier editions of the report. As with all editions of the 321 Report to Congress, the Upper San Pedro Partnership welcomes and encourages feedback with regard to the format of the 2010 report.

Introduction

Groundwater is the primary source of water for the residents of the Sierra Vista Subwatershed, Cochise County, Arizona, including Fort Huachuca, Huachuca City, and the cities of Sierra Vista, Bisbee, and Tombstone, and the rural residents. Groundwater is also the essential component among the water sources that sustain the base flow of the San Pedro River and its associated riparian ecosystem,

[1] 321 report dates can be confusing. For example, the 2007 report assesses the hydrologic state of the Subwatershed in calendar year 2006. It was delivered for review in late 2007, and included "2007 Report to Congress" in the title. It was not actually delivered to Congress, however, until late in 2008, and thus 2008 is the citation date: "Department of the Interior, 2008." As a result, each report has 3 years associated with it--the report year (the 2007 321 Report), the data year (the state of the Subwatershed in 2006) and the publication year (Department of the Interior, 2008).

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formally protected through an act of Congress as the San Pedro Riparian National Conservation Area (SPRNCA). Water outflow from the Sierra Vista Subwatershed (Subwatershed), including water withdrawn by pumping, exceeds natural inflow to the regional aquifer within the Subwatershed. As a result, groundwater levels in parts of the Subwatershed are declining and groundwater storage is being depleted. In the absence of more effective management measures, continued water-level declines and associated storage depletion will continue to diminish groundwater flow to the San Pedro River.

The Defense Authorization Act of 2004 (Public Law 108-136, Section 321, hereinafter referred to as Section 321 and included as Appendix B) set goals and an end date of 2011 for achieving, by various means, a sustainable level of groundwater use from the Subwatershed. In addition, the Act formally recognizes the Upper San Pedro Partnership (Partnership) and alters the way the Endangered Species Act applies to Fort Huachuca. The Partnership is specified as the regional cooperative organization for recommending policies and projects to mitigate water-use impacts in the Subwatershed. Section 321 directs the Secretary of the Interior, in consultation with the Secretaries of Agriculture and Defense and in cooperation with the Partnership members, to report on the water-use management measures (management measures) that are being implemented and those needed to restore and maintain the sustainable yield of the regional aquifer by and after September 30, 2011.

The Partnership, formed in 1998, is a consortium of 21 Federal and State agencies, local jurisdictions, and non-governmental organizations whose collective goal is to ensure an adequate supply of water to meet the reasonable needs of the Subwatershed residents and the San Pedro River. Partnership members include owners or managers of land, entities capable of implementing water-management measures, and resource agencies. In pursuit of its goals, the Partnership has initiated and (or) funded studies to better understand the regional hydrologic system, the riparian system, and recharge processes. The Partnership also has invested significant resources into systematically

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identifying, evaluating, and documenting management measures that could be used to attain sustainable yield of the regional aquifer. A complete listing of Partnership members is found in Appendix F, a complete listing of Partnership reports is contained in Appendix C, and additional information about the Partnership is available at: http://www.usppartnership.com.

Because the local groundwater system is complex, the consequences of groundwater use and the effectiveness of alternative water-management strategies will be better understood only through ongoing research and monitoring efforts. The results of monitoring will provide information needed to assess progress toward sustainable use of the regional aquifer and to improve management decisions as part of an adaptive management process. Decisions associated with sustainable yield must be made today in the absence of a perfect knowledge of the consequences of today's actions and tomorrow's conditions, but as new information becomes available, resource decisions can be amended or revised; in other words, management of resources adapts to the new circumstances and (or) knowledge. For this reason, the continued operation of a well-designed monitoring program is important to provide feedback on the status and trends of aquifer conditions and the impact and effectiveness of mitigation measures.

Description of the Upper San Pedro Basin and the Sierra Vista Subwatershed

Physical System

The Upper San Pedro Basin[2] is a groundwater management unit that extends from the United States-Mexico border to a bedrock constriction called The Narrows about 11 miles north of Benson, Arizona (fig. A1). The Subwatershed is a 950 mi^2 area bounded on the west by the Huachuca Mountains and on the east by the Mule Mountains and Tombstone Hills. The southern boundary of the Subwatershed is the United States-Mexico border, and the northern boundary is a watershed divide

[2] The Upper San Pedro Basin is formally defined by statute in the Arizona Groundwater Management Act of 1980. The hydrologic boundaries of the Upper San Pedro Basin (a groundwater unit) and the San Pedro surface water drainage do not coincide although the differences are minor. This report makes no attempt to resolve these differences in terminology.

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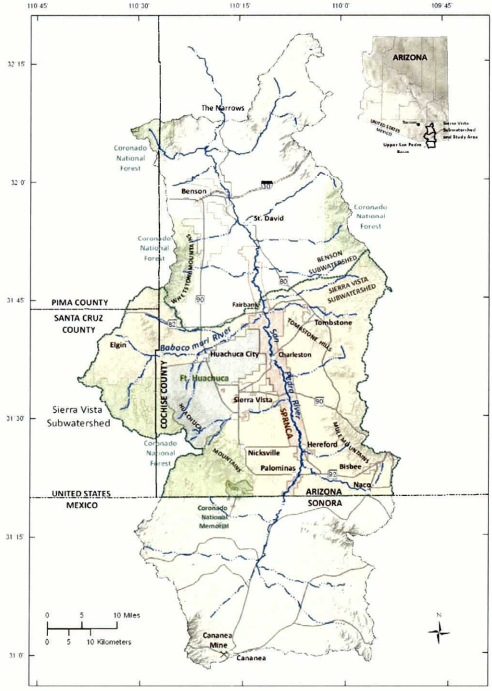

Figure A1. Location of the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona.

across the Upper San Pedro Basin that intersects the river at the gaging station near Tombstone, about 1.5 mi downstream from the ghost town of Fairbank (fig. A2). The area within these bounds is an alluvium-filled valley with surfaces that slope gradually down from the base of the mountains to the San Pedro River, which flows north out of Mexico through the center of the valley. The basin's alluvial sediments constitute the Subwatershed's regional aquifer.

The Subwatershed supports an ecologically diverse riparian system along the San Pedro River. In 1988, Congress designated portions of the river as the San Pedro Riparian National Conservation Area (Public Law 100-696) to be managed by the Bureau of Land Management (BLM). The legislation directed the Secretary of the Interior to conserve, protect, and enhance the natural resources of this riparian system—the first riparian national conservation area in the country. The biological significance of the river stems from the contrast between the riparian ecosystem and most of the surrounding area. The riparian system supports a diverse biota comprising approximately 400 avian species, 81 mammalian species, and 43 species of reptiles/amphibians (Bureau of Land Management, 1989) and is a primary hemispheric corridor for migrating birds. The SPRNCA boundaries define a corridor along the San Pedro River up to 5 mi wide and extending about 35 mi north from the international boundary with Mexico (fig. A1). The climate of the Subwatershed is semiarid. The Agricultural Research Service estimated a Subwatershed area average precipitation of about 8.5 inches for 2009 (Appendix E). About 65 percent of the annual precipitation arrives in summer thunderstorms with most of the remainder resulting from winter storms (Goodrich and others, 2000).

Because precipitation in the Subwatershed is concentrated in the mountains, most recharge to the regional aquifer system occurs at the periphery of the Subwatershed, near the junction of the mountains and basin floor (Pool and Coes, 1999). Some storm flow recharges through ephemeral stream channels (Coes and Pool, 2005), and water also enters the Subwatershed through the subsurface as underflow

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from Mexico. On an annual basis, natural groundwater discharge in the Subwatershed occurs primarily through the use of water by riparian vegetation along the river corridor (evapotranspiration). Groundwater outflow in excess of that used by riparian vegetation discharges to the San Pedro River (base flow). Some water also exits at the downstream boundary of the Subwatershed as groundwater underflow.

In the Subwatershed, flow in the San Pedro River is perennial in some reaches and intermittent in others. The ecologic condition of the riparian forest directly depends on the presence of shallow groundwater within the flood plain, whereas the SPRNCA's aquatic habitats are directly dependent on stretches of perennial streamflow. This hydrologic context depends on consistent groundwater flow from the regional aquifer system to the stream (Pool and Coes, 1999). The location of perennial streamflow is controlled by geology as well as by the amount and location of groundwater recharge and discharge (both natural and anthropogenic). The primary perennial river reach extends from about 7 mi south of Charleston, to one mile north of Charleston. Charleston is a ghost town on Charleston Road at the river, and the location of the USGS streamflow-gaging station San Pedro River at Charleston (station number 09471000; fig. A2).

Socioeconomic setting

The Subwatershed supports a human population of about 82,460 (estimated from Arizona Department of Commerce (ADOC) (2010) data) that is distributed among the unincorporated rural areas and the municipalities of Bisbee, Sierra Vista, Huachuca City, and Tombstone. The population of Sierra Vista, the Subwatershed's largest city, was 46,597 in 2009 (Arizona Department of Commerce, 2010). This includes the permanent residents of the U.S. Army's Fort Huachuca.

Fort Huachuca is the region's largest employer. The direct, indirect, and induced population in the Subwatershed attributable to the Fort may be more than 32,000 (U. S. Fish and Wildlife Service,

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2007). The Fort occupies approximately 78,000 acres in the Subwatershed, much of which remains undeveloped. A recent economic impact analysis of Arizona's military installations estimates Fort Huachuca's $2.38 billion annual impact as the greatest of the nine installations in the State (The Maguire Company, 2008).

Essential Definitions

Sustainable Yield

The Partnership has adopted the definition of "sustainable yield" as "…managing [groundwater] in a way that can be maintained for an indefinite period of time, without causing unacceptable environmental, economic, or social consequences" (Alley and others, 1999). Therefore, a sustainable level of groundwater pumping for the Subwatershed could be an amount between zero and a level that arrests storage depletion, with the understanding that to call an amount of pumping other than zero "sustainable" will entail some consequences at some point in the future. Eight indicators used to assess Partnership progress toward sustainable yield are:

- Regional aquifer levels
- Near-stream alluvial aquifer levels
- Near-stream vertical gradients
- Spring and artesian well discharge
- Streamflow permanence
- Streamflow (summer and winter 7-day low flow or days of no flow)
- Aquifer storage change measured using microgravity techniques
- Annual storage deficit

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The term "safe yield" is not interchangeable with "sustainable yield" in the context of this report. The State of Arizona defines safe yield as "a water management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of ground water withdrawn [by pumping]...and the annual amount of natural and artificial recharge...(A.R.S. § 45-562 (A))." Safe yield does not consider the water required to sustain riparian ecosystems and streamflow and therefore is not used by the Partnership as a management concept.

Overdraft

In this report "overdraft" is defined as groundwater consumption in excess of sustainable yield. This is consistent with the concept that pumping beyond a sustainable level is "over pumping."

Management Measures

"Management measures" are projects and policies that are intended either to reduce water consumption (conservation) or to increase recharge to the aquifer system. Examples include water-conservation ordinances and municipal wastewater reuse and artificial and enhanced recharge. Rain-water harvesting and importation also may be considered management measures. The yields from these measures are "management-measure yields."

Recharge

"Groundwater recharge" is the addition of water to the groundwater system. It can occur either naturally (directly from precipitation or surface flow over pervious surfaces in areas of negative (downward) hydraulic gradients) or artificially (from retention/detention basins or effluent recharge). Recharge occurs when water moves from the land surface through the unsaturated zone to the regional aquifer. Over the long term, recharge is balanced approximately by discharge to surface waters, to

plants, and to flow of groundwater out of an aquifer. This balance can be altered locally, however, as a result of pumping, land use, and (or) climate changes (Delin and Falteisek, 2007).

Recharge is not equivalent to surface infiltration. In the case of natural recharge in arid or semi-arid climates, most of the water that infiltrates never passes the root zone but rather returns to the atmosphere as soil evaporation or plant transpiration. Typically, only a small portion of water that naturally infiltrates becomes recharge (Todd, 1980). In the case of artificial recharge including that found in the Subwatershed, recharge ponds are designed to maximize the amount of infiltrating water that recharges the groundwater system.

Spatial Water Management

"Spatial water management" refers to land-use decisions made on the basis of knowledge that the location from which water is pumped from an aquifer influences where and when streamflow depletions will occur. As a general rule, pumping farther from a stream delays the onset of streamflow depletion (Alley and others, 1999). Spatial water management considers the effect of the distribution of pumping as part of decision making, but does not necessarily regard the total amount of groundwater pumping. It is a strategy that only can be used to delay the effects of pumping further into the future.

Strategy to Attain Sustainability

The Partnership continues to work to put in place a strategy to attain a sustainable yield of groundwater withdrawals in the Subwatershed. To date, this strategy has involved implementation of a variety of specific management measures that are designed to reduce the net impacts on the groundwater system and includes: conservation, reuse, recharge, importation, and spatial water management. Engineered augmentation and redistribution are under consideration as additional management strategies at this time.

The identification and implementation of management measures by the Partnership and its members occur within the context of adaptive management. The underlying premise is that the management process should continue to improve through time, or adapt, as additional information about the success of prior measures becomes available and (or) as the physical context changes within which the measures are applied. As monitoring and project data are evaluated, the Partnership learns what existing measures work and what additional measures may be needed to reach a sustainable level of groundwater withdrawals. An advantage of the adaptive-management process is that measures with a high level of certainty (in yield and funding) can be implemented immediately, and less-certain measures can be evaluated for later implementation.

The ultimate goal of water-use management in the Subwatershed is to attain a sustainable yield of groundwater withdrawals (pumping) from the regional aquifer system. What yield is considered sustainable has yet to be fully quantified, partly because this would depend on a definition of unacceptable consequences shared by all stakeholders. The impacts of sustained drought and climate change also may affect the quantification of sustainable yield. The Partnership has agreed on eight indicators that are used to assess Partnership progress toward sustainable yield in the Subwatershed. Thus, though an explicit quantification of Subwatershed sustainable yield does not exist, the Partnership does agree on the spectrum of Subwatershed conditions that will be used to measure progress toward sustainability.

Various management measures serve different purposes. Conservation measures, for example, improve water-use efficiency, while recharge and reuse of wastewater reduce the net withdrawals from the aquifer. Some techniques, such as spatial water management, do not necessarily reduce water use, but rather serve to buy time by delaying the effects of pumping on streamflow depletion. The Bureau of Reclamation (Reclamation) has been working with the Partnership for a number of years on developing

one such management approach: engineered augmentation of Subwatershed water supplies. In 2007, Reclamation and the Partnership completed an appraisal-level study, which described the need for augmentation to achieve sustainable yield in the Subwatershed. The Appraisal Report analyzed alternatives and screened them to identify viable solutions. Of 14 augmentation alternatives evaluated, the Partnership selected three for further analysis.

A feasibility study, which provides a much more detailed analysis of the technical, legal and institutional issues, is the required next step toward construction of an augmentation project. The Omnibus Public Land Management Act of 2009 (P.L. 111-11) authorized Reclamation to conduct a feasibility study of water augmentation alternatives in the Sierra Vista Subwatershed. The feasibility report will address the significant issues, some of which must be resolved by local stakeholders before an augmentation alternative can be considered for a recommendation for construction.

Specific management measures planned through 2011

The Partnership and its members maintain a roster of deficit reducing water-management measures that either are implemented currently and planned for continuation, or are planned for implementation before 2011 (table A1). The yields from these projects constitute deficit reducing measures currently planned by Partnership members. The projects generally represent conservation, recharge, reuse, or land-management measures that are possible within the resource limitations of the members. In keeping with the adaptive management process, some future planned yields (2010–11) have been modified from prior Section 321 reports to reflect improved knowledge and potential new projects (table A1). , Using only the current suite of management measures the projected aquifer storage deficit will not reach zero by 2011 (fig. 1). The Partnership is currently investigating additional management measures such as engineered augmentation.

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Guided by its science agencies, the Partnership has always strived to incorporate the best available science into its estimates of each component of the groundwater budget. As a result, several individual component values have been revised since the beginning of 321 reporting. The current and future deficits depicted in figure 1, therefore, cannot be compared directly to similar results in Section 321 reports prior to the 2010 report because the earlier reports relied on different estimates of a number of items in the water budget (table 2a). For example, the current, 2010 321 Report uses the new base flow discharge estimate of Kennedy and Gungle (2010), and previous 321 Reports used the lower estimate of ADWR (2005a). Since the first 321 Report, other water budget revisions have been made to urban-enhanced recharge, riparian plant evapotranspiration, and the estimate of rural exempt well pumping. As a result, the current estimate of the deficit is about 1,800 acre-ft larger than what would have been calculated had only the original groundwater inflows and outflows from the 2002 estimate been used. This is discussed further in the final section of this appendix, "Storage Deficit in 2009."

The Partnership also recognizes the importance of spatial water management in forestalling impacts to the base flows of the San Pedro River. For example, in March 2006 the Cochise County Board of Supervisors adopted a resolution to prohibit increased residential densities within 2 mi of the SPRNCA boundary. Assuming a given total rate of pumping, this effort will restrict the most intense pumping from new developments to greater distances from the river, thereby increasing the time before streamflow is reduced and giving additional time for planning. Partnership-initiated science (for example, Leake and others, 2008) has begun to quantitatively define the relation between the location of a management action and the timing of its effect on streamflow. Guided by this work, the Partnership is considering locating future recharge projects at those points along the river where benefits to streamflow can be realized most rapidly.

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Table A1. Planned annual yields for 2010 through 2011 of Partnership member management measures to reduce aquifer overdraft.

[Yields are in acre-ft/yr; Conservation yields in each year are relative to a zero yield in the baseline year of 2002; Recharge yields are total values and are relative to a baseline of zero acre-ft; projections provided by respective jurisdictions]

		2010 Yield	2011 Yield
Description	Measure type	Planned	Planned
Fort Huachuca[1]			
Conservation measures[2]	Conservation	800	800
Effluent recharge	Recharge	200	200
Stormwater detention basins	Recharge	50	50
Cochise County			
Conservation measures[3]	Conservation	120	120
Stormwater detention basins	Recharge	30	30
Sierra Vista			
Conservation measures[2]	Conservation	1,750	1,800
Improved golf course efficiency	Conservation	15	15
Effluent recharge[4]	Recharge	3,000	3,000
Stormwater detention basins	Recharge	300	300
Bisbee			
Conservation measures[1]	Conservation	50	60
Reduced groundwater pumping through effluent reuse	Conservation	485	485
Effluent recharge[5]	Recharge	5	15
Huachuca City			
Conservation measures[1,6]	Conservation	50	50
Tombstone			
Conservation measures[1]	Conservation	10	20
Effluent recharge[5]	Recharge	100	100
Bureau of Land Management			
Mesquite and tamarisk reduction[7]	Conservation	640	660
Urban enhanced ephemeral-stream channel stormwater recharge			
Increase in stormwater recharge in ephemeral channels by urbanization[8]	Recharge	2,300	2,300
Incidental Yields			
Retirement of agricultural pumping	Conservation	2,070	2,070
Total yields			
Total yield[9]		11,200	11,300

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[1]Fort Huachuca is wholly contained within the boundaries of the City of Sierra Vista, and Fort Huachuca's anticipated conservation yields are also included in the Sierra Vista yields shown in table A1. The Total yield found at the bottom of this table does not include the values from the Fort Huachuca Conservation Measures line. Fort Huachuca's yields were double counted in previous 321 reports.

[2]Yield relative to 2002 baseline of zero. Conservation efforts started earlier than 2002 that continue to provide yields do not display a yield in the table because they are already incorporated in actual water-use figures. Yields for 2010–11 are projected yields based on additional planned measures. Actual water use will vary annually owing to effectiveness of conservation, weather, and other factors.

[3] Conservation yield attributable to Cochise County cannot be quantitatively projected owing to the large number of small unmetered wells. The reported yield is attributable to toilet-replacement rebates and assumed savings from code changes. Cochise County has enacted various code changes that should yield future water savings that will increase in proportion to population. Conservation measures enacted include: hot water on demand, gray water plumbing, high-efficiency commercial laundry facilities, humidity sensors on outdoor irrigation, new turf restrictions, limits on evaporative coolers, and a ban on artificial water features (lakes, ponds, or fountains).

[4]The City of Sierra Vista has known for some time that several hundred additional acre-ft of incidental recharge have been infiltrating through the bottoms of the EOP wetlands ponds, although the amount of that additional recharge has not been known. A recent consultant's study of the city's recharge facility concluded 350 acre-ft/yr of incidental recharge from the wetlands should be included in the 2009 recharge total. Previously unreported recharge from 2003 – 2007 is estimated to be about 700 acre-ft/yr, and for 2008 about 800 acre-ft (written commun., Mike Hemesath, Director, Department of Public Works, City of Sierra Vista, April 9, 2010; Hemesath, 2010).

[5]Ninety-five percent of total effluent discharged is assumed to recharge the groundwater system. Bisbee effluent is released to and recharged in Greenbush Draw; Tombstone effluent is released to and recharged in Walnut Gulch.

[6]Huachuca City's waste water will be treated at Fort Huachuca's waste-water treatment plant and the effluent recharged on Fort Huachuca beginning in 2010. The Huachuca City planned effluent recharge yield is included as part of Ft. Huachuca's planned effluent yield beginning in 2010.

[7]Water-use savings through management of invasive mesquite and tamarisk using various treatments. Mesquite and tamarisk reduction reduces water use by replacing these trees with more shallowly rooted plants. Yield from mesquite and tamarisk reduction estimated using an Agricultural Research Service model of riparian evapotranspiration in the San Pedro Riparian National Conservation Area. Water conservation is greatest initially following treatment and decreases over time.

[8]Urbanization in semiarid climates can increase recharge by concentrating rainfall runoff in ephemeral-stream channels. Initial estimates provided by the Agricultural Research Service of natural recharge enhanced beyond predevelopment levels by urbanization—credit not claimed by any particular Partnership member. These preliminary estimates will be refined through ongoing research and monitoring programs. Increased water use due to urbanization likely exceeds increased recharge. All urban-enhanced recharge estimates represent quantities expected in an average year—no current monitoring can provide year-specific values. Projections for 2010–11 are based on 2001 land-cover data and do not account for increases that likely will occur as impervious-surface area increases.

[9]Total yields rounded to nearest 100 acre-ft. Yields based on the best current data and assumptions. Yield values differ from the prior Section 321 reports owing both to changes in implemented and planned projects and to the use of improved methods to reanalyze yields.

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Strategy to Assess Sustainability

The language of Section 321 specifies that reports shall be prepared annually through 2011 that discuss "the water use management and conservation measures that have been implemented and are needed to restore and maintain the sustainable yield of the regional aquifer by and after September 30, 2011." Although Section 321 does require that overdrafts from the aquifer be reduced, the language in the bill leaves "sustainable yield" largely undefined. The Partnership therefore adopted the definition of sustainable yield stated previously: "…managing [groundwater] in a way that can be maintained for an indefinite period of time, without causing unacceptable environmental, economic, or social consequences."

To make the adopted definition meaningful in the context of management decisions, indicator trends (for example, declining groundwater levels in a near-stream well) and potential consequences for the system (for example, a loss of riparian diversity) must be evaluated. Indicators are easily measured aspects of the system that are clearly related to a potential consequence and thus provide useful information about the system as a whole. Defining specific indicators helps to evaluate system status and trends (Farrell and Hart, 1998). An indicator can be evaluated relative to a threshold value (or metric) that has been determined to indicate system health, or in the case of the Subwatershed, to indicate sustainable yield. Indicators also can be evaluated relative to overall progress toward sustainable yield without necessarily defining specific numerical thresholds.

The first Section 321 report (Department of the Interior, 2005) and the annual reports prior to the 2009 report considered a single quantifiable indicator—annual aquifer storage deficit calculated from the water budget. The calculated value of aquifer deficit in each year represents the numeric value of the indicator. The threshold for sustainable yield was defined as an annual aquifer storage balance of zero; a

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zero or positive balance (accumulating aquifer storage) was defined as sustainable and a negative annual storage balance (an aquifer storage deficit) was considered unsustainable.

The intent of the Partnership from the beginning of the Section 321 reporting process has been to define and report on a suite of sustainability indicators, including the aquifer storage deficit. In 2009 the Partnership agreed upon seven additional indicators that will be evaluated annually to assess progress toward system health and sustainable groundwater use in the Subwatershed. These indicators are introduced below. The indicators will be used in this appendix to assess overall progress toward sustainable yield; the assessment is based on data collected from monitoring sites throughout the Subwatershed (fig. A2).

Groundwater indicators

There are four groundwater indicators. They are based on a combination of data from completed scientific projects and the established and active monitoring program. The groundwater indicators are: regional aquifer water levels, aquifer storage change, water levels in the San Pedro River stream alluvium, and near-stream vertical hydraulic gradients.

Regional aquifer water levels

The most immediate and direct effect of groundwater pumping is a decline in aquifer water levels. Declines in water levels beneath long-term pumping centers in the Subwatershed have been measured over decades and indicate a general trend of loss in aquifer storage (Arizona Department of Water Resources, 2005a; Schmerge and others, 2009). As a direct measure of pumping effects, monitoring of both water levels and aquifer storage change using microgravity techniques (discussed below) will serve a primary role in ascertaining the success of Partnership efforts to achieve a sustainable level of groundwater pumping in the Subwatershed.

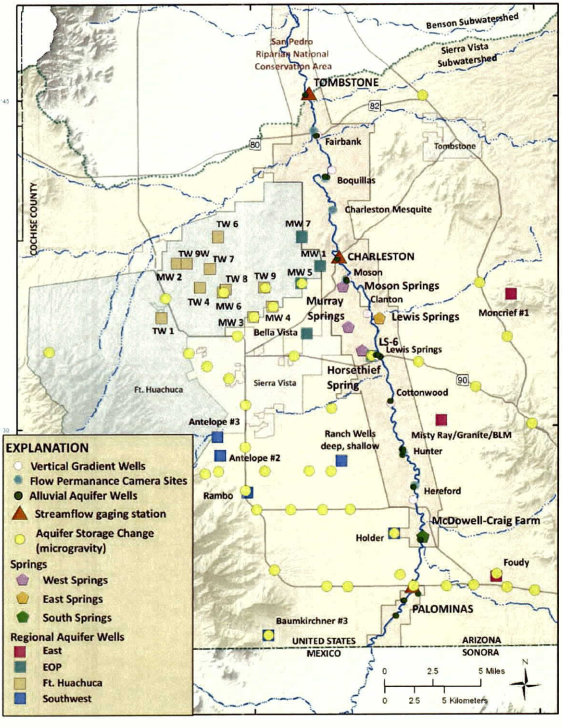

Figure A2. Monitoring locations in the Sierra Vista Subwatershed, Upper San Pedro basin, southeastern Arizona. The indicators of Subwatershed sustainability are evaluated annually to assess progress toward system health and sustainable groundwater use in the Subwatershed using the data collected at these locations.

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Water levels are measured to provide a sense of storage change; water-level decline (drawdown) indicates storage loss and water-level recovery indicates storage increase. Changes in water levels, however, typically cannot be used to accurately quantify storage change because the storage coefficient (capacity of the aquifer system to hold water) is generally not well known. Although water-level measurements do not directly measure storage change, they are important for several reasons:

- They provide a direct indication of changes in the direction of groundwater flow and in the strength of hydraulic gradients driving this flow;
- Water levels have been measured at many locations in the Subwatershed and at some locations for long periods of time, and therefore provide a historical context within which to interpret changes;
- They are easily measured and measurements can be made with millimeter precision.

A regional aquifer network of about 30 wells (figs. A3a and A3b) has been monitored since about 2000, although records are longer or shorter depending on the well. Water levels in fifteen of these wells have been monitored by the USGS through periodic (quarterly) manual measurements and continuous automated measurements using data loggers. The remaining 15 wells are on Fort Huachuca and until 2009 were monitored bimonthly by the Fort, USGS, or Arizona Department of Water Resources (ADWR) personnel. The distribution of these wells is concentrated in areas most likely to be influenced by pumping in the Sierra Vista/Fort Huachuca area, but the distribution of the monitoring wells spans from the mountain front to near the river. ADWR also measures water levels periodically (about every 5 years) in a large numbers of wells, including pumping wells, throughout the Subwatershed (Schmerge and others, 2009). The future of this state program is currently uncertain.

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Groundwater storage change—direct measurement

Since about 2005, direct measurements of groundwater storage change have been made using microgravity methods at 36 stations across the Subwatershed (figs. A4a and A4b). Gravity methods quantify changes in groundwater storage by measuring changes in total mass beneath a point on the Earth's surface. A reasonable assumption can be made that, at a site that remains undisturbed, the only change in mass through time is due to the removal or addition of underlying water (Pool and Eychaner, 1995). Because this method directly measures changes in mass (water), estimates of storage change are not limited by uncertainties in hydraulic properties such as the storage coefficient. Another advantage is that microgravity measurements integrate mass change within a radius up to about 1 km, depending on the depth to water, whereas water levels reflect conditions only in the immediate vicinity of a well. Microgravity measurements can be less precise than water-level measurements, however, and in general cannot be made continuously, as can water-level measurements made in a well equipped with a pressure transducer and a data logger.

Near-stream alluvial aquifer water levels

Much of the riparian vegetation along the San Pedro River can thrive only with direct access to shallow groundwater in the stream alluvium near the river, and thus the effect on vegetation of declines in the stream-alluvium water levels is relatively rapid. For this reason, near-stream alluvial water levels are among the most important indicators of riparian system health adopted by the Partnership. A Partnership-initiated investigation determined the relation between riparian vegetation variables and hydrologic conditions (Leenhouts and others, 2006). One outcome of the study was a map that assigned a riparian condition class (dry, intermediate, or wet) to each of 14 reaches. The condition class assignments were based on various measurements of riparian vegetation and were then related to groundwater depth and streamflow permanence (the percentage of time in a year a stream flows). This

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provided information about the hydrologic conditions that support particular riparian conditions. Thirty wells are monitored by the USGS and BLM in the alluvial aquifer, and these wells are evaluated relative to the condition class in which they are found, either intermediate or wet. [The dry condition class is only found north of the Subwatershed (figs. A5)].[3]

Vertical hydraulic gradients

Generally, water flows from areas of higher hydraulic head to areas of lower hydraulic head (or more precisely, from areas of higher potential energy to areas of lower potential energy). The difference in heads divided by the distance between the points where the heads are measured is a hydraulic gradient. In an aquifer, differences in heads, or groundwater levels, can occur across both vertical and horizontal distances. Measurements of the changes in water levels provide a sensitive measure of changes in the force that moves water from one place to another. Some locations, such as gaining reaches of the San Pedro River, have vertical hydraulic gradients that drive water upward from deeper parts of the aquifer into the stream system. Vertical hydraulic gradients have been measured continuously at the Lewis Springs monitoring station near the junction of highway 90 and the San Pedro River for 15 years, and at various other locations along the river for 9 years or less. Seven well pairs are monitored by the USGS for vertical gradient data. Similar to the alluvial aquifer water levels, the vertical gradient wells are evaluated relative to the riparian condition class within which they are found (fig. A6).

Streamflow

Like the groundwater indicators, the two streamflow indicators are based on a combination of data from completed scientific projects and the established and active monitoring program. The

[3] Because of problems with obtaining the complete alluvial aquifer data set, many locations only include data through 2008.

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streamflow indicators are related to winter and summer low flow or annual number of days of no flow, and streamflow permanence.

Low flow and days of no flow

The USGS operates nine streamflow-gaging stations and one stage recorder in the Subwatershed; three of the gaging stations plus the stage recorder are on the main stem of the San Pedro River (figs. A7a and A7b). Data applicable for evaluating changes in the hydrologic system and progress toward sustainability are collected at the gaging stations. The periods of record for the main stem gaging stations vary from more than 100 years at the streamflow-gaging station at Charleston (station number 09471000; continuous in time and location since 1935) to 54 total years at the stream-flow gaging station at Palominas (station number 09470500; includes three major data gaps since 1930) to 32 total years at the streamflow-gaging station at Tombstone (station number 09471550; includes one ten-year data gap since 1967). These data provide a spatially distributed measure of temporal streamflow variations. Stations located downstream of groundwater discharge locations provide information on changes in outflows from the regional aquifer system.

Two specific indicators of sustainability adopted by the Partnership are the 7-day winter and 7-day summer low flows of the San Pedro River at Charleston. A 7-day low flow is the lowest value from a series of 7-day moving averages through a period of interest, and provides a sense of how much groundwater is discharging to the stream. The winter 7-day low flow at Charleston is calculated from data collected between January 15 and March 15 and the summer low flow is calculated using June data.[4]

[4] In some years the lowest flow occurs after June 30. The purpose of 321 monitoring and reporting is to assess progress made toward achieving sustainable use of groundwater in the Subwatershed from one year to the next. Therefore, the use of a temporally consistent period (e.g. the month of June) is used to compare the conditions in the system from one year to the next. If 0 cfs flow were to occur at the gaging station in July or August of a given year, this would be an interesting fact but would be indicative more about the quantity of summer precipitation than it would the state of the regional aquifer in that year as compared to previous years.

Because there are often periods of no flow at both Palominas and Tombstone, 7-day low flow values are not useful indicators of progress toward sustainability at those locations. Instead, total days of annual no-flow have been calculated as a proxy for low flow—as less groundwater discharges to the stream and (or) as more surface water discharges from the stream into the ground, the number of no-flow days each year will generally increase. As with most proxies, this one is not perfect. The number of days of flood flows each year can increase or decrease the number of days of no-flow.

Annual no-flow data can also be inverted to provide additional streamflow permanence data points (discussed next) along the San Pedro River.

Streamflow Permanence

Leenhouts and others (2006) reported on the relation of streamflow permanence to the three riparian condition classes (wet, intermediate, and dry) (fig. A8). Average flow permanences of 48, 78, and 100 percent for dry, intermediate, and wet classes, respectively were reported for water year 2002, and 17, 63, and 98 percent for water year 2003. Subsequently, the Agricultural Research Service installed automatic digital cameras at eight sites along the San Pedro River (six within the Subwatershed reach). BLM has since taken over the camera data collection, and has categorized the photos of the river into dry (no water visible) and wet (water visible, ponded or moving) from which they calculate annual streamflow permanence at each of the sites. Streamflow-gaging stations at Palominas, Charleston, and Tombstone, and a stage recorder near Lewis Springs provide additional streamflow permanence data for a total of 10 streamflow permanence sites in the Subwatershed reach of the river (fig. A8).

Springflow

In addition to stream base flow, springs represent another path through which water leaves the groundwater system and as such can indicate how natural and human-induced changes to the hydrologic

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system affect the aquifer. Infrequent measurements of spring flow were collected between 1988, when the SPRNCA was established, and 2003. Additional measurements were begun in 2003, and a systematic network of quarterly discharge measurements at four springs was initiated in response to Section 321 needs in early 2005 (Murray, Horsethief, and Lewis Springs, and McDowell-Craig Flowing Well). A fifth spring (Moson Springs) was added to the monitoring network in 2007 (fig. A9).

Water Budget

In previous Section 321 reports covering years prior to 2007 (Department of the Interior, 2005, 2006, 2007), a water-budget approach was used to define an initial goal for attaining a sustainable yield of groundwater use. The goal was defined relative to a calculated annual aquifer-storage deficit of about 9,900 acre-ft/yr for 2002. In the initial, 2004 321 Report (reporting on data year 2002) (Department of the Interior, 2005) this goal was specifically stated: "The Partnership plans to offset net groundwater use [by an amount] in excess of 10,000 acre-ft/yr." This goal was based on the rationale that continued storage depletion would contribute to the cumulative storage deficit and increase the long-term risk of continued reduction in base flow in the San Pedro River. Beginning to accrete storage initiates the process of reducing the cumulative deficit.

The water-budget approach has some advantages. A water budget can be calculated relatively quickly using mostly existing information. A water budget is similar in some ways to a fiscal budget, and is easily expressed and understood by people with a variety of experience. Water budgets, however, also include significant limitations because they summarize a complex, time-varying, three-dimensional flow system of large areal extent in a few numbers. As a result, a traditional water budget cannot be used to evaluate many aspects of sustainability.

For example, evaluation of the effects of spatial water management is not possible via a water budget analysis alone. It may be possible to pump groundwater in a deficit condition in a particular area

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of the regional aquifer without changing base flow in sensitive reaches of the riparian system, whereas pumping relatively small quantities of water near the river and upstream from sensitive reaches may have significant impacts over long reaches of stream. A water budget is unable to forecast time-varying consequences to outflows caused by pumping, although removing water from an aquifer without replenishing it has the eventual effect of reducing outflows through the natural discharge locations. A water budget also does not provide any measure of how pumping is changing water levels in the aquifer. Differences in water levels throughout an aquifer are the driving force that moves water through the system. Changing those levels modifies how groundwater moves. An additional problem with a water budget approach alone is that the annual groundwater storage deficit could reach zero, but long after groundwater elevations have dropped below the riparian root zone—clearly an unsustainable condition for the SPRNCA.

The Partnership has included the aquifer storage deficit calculated from the water budget as an indicator of sustainability, and further agreed to a sustainable yield threshold of zero acre-ft per year. An annual loss from storage, therefore, is not sustainable, and a zero change or gain is considered sustainable.

As noted above and discussed further at the end of this appendix ("Storage Deficit in 2009"), because of improved estimates for a number of elements in the water budget, the best estimate of the 2002 Subwatershed annual deficit has increased by about 1,800 acre-ft, from 9,900 to 11,700 acre-ft, since the publication of the first report. The most recent in this series of improvements occurs this year. Kennedy and Gungle (2010) have completed an analysis of the amount of groundwater that exits the Subwatershed as base flow in the river and have provided the Partnership with an improved estimation of this value—an increase of more than 1,600 acre-ft per year. This value will be included in the Subwatershed water budget of the current 321 Report for the first time.

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Progress toward Sustainability

The 2004, 2005, and 2006 321 Reports—reporting on years 2002, 2004, and 2005, respectively (Department of the Interior 2005, 2006, 2007) focused primarily on year-to-year changes in the aquifer-storage deficit calculated using a water-budget approach. The 2007 321 Report that reported on year 2006 (Department of the Interior, 2008) was the first to include a general discussion of some indicators. In the 2009 report, progress toward achieving a sustainable yield of groundwater use in the Subwatershed was assessed using six of the eight indicators described in the previous section. A matrix that now includes all eight indicators and an evaluation of the Partnership's progress toward sustainable yield based on changes in each indicator is shown in table 5 of this report.

All eight indicators are affected by climate in addition to human-induced changes, although some are more sensitive than others. In addition to reporting on the annual changes of indicators, therefore, it is also important to consider multi-annual (short-term) and multi-decadal (long-term) trends when assessing hydrologic trends in the Subwatershed. Indicators in the matrix are thus assessed with regard to (1) annual change, (2) short-term trends (2002 – 2009), and, (3) the longest term trends available (table 5). In addition, a statistical analysis run on the short-term and long-term data assessed the persistence of any trends over the period of interest. In figures (for example figs. 3a, 3b) where a trend is considered significant ($p \leq 0.05$). a trend line is provided, and an arrow is included to indicate if the data trend is improving (green, up arrow) or degrading (red, down arrow) with time; where no trend is discernible, no trend line nor arrow is provided.[5] Regardless of whether or not trends are discernable, both annual change and short-term trends in the Subwatershed are typically driven by natural variability in the system including intermittent recharge events and intervening dry years as well as decadal-scale

[5] A table of statistical trend test results (R^2 and p-values) can be found in Appendix G of this report.

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wet periods and droughts. Thus, short-term trends may not be indicative of longer term movement toward or away from sustainable groundwater use in the Subwatershed.

Owing to both human causes and natural conditions, data trends in different parts of the Subwatershed may be different. For example, we might anticipate indicators to respond differently in the vicinity of the City of Sierra Vista's Environmental Operations Park treated effluent recharge facility (EOP) than in the urbanized areas of Fort Huachuca and Sierra Vista, or on the more rural east side of the river. For this reason, where appropriate, the indicators are analyzed by subregion.

Groundwater Indicators

Regional aquifer water levels

An analysis of historical water-level trends is provided in Pool and Coes (1999), and in the ADWR's Active Management Area review report (Arizona Department of Water Resources, 2005b). In the regional aquifer system, a general and widely distributed decline of 0.3–0.5 ft/yr occurred from the 1940s through the 1970s followed by a period of no decline or slight recovery. Pool and Coes (1999) suggest that this regional pattern of decline followed by cessation of decline or recovery resulted from shifting precipitation patterns. Rates of water-level declines have been larger in the Sierra Vista-Fort Huachuca area. Long-term records along the San Pedro River near Palominas show only a few feet of decline resulting from historic near-stream agricultural pumping, but that has been sufficient to convert a stream reach that was perennial as recently as the early 1960's to intermittent. The southwest subregion includes wells with very long records, with low points in the record around 1970 followed by some recovery.

As the historical analysis above implies, water-level trends in different parts of the Subwatershed are different because of differences in hydrogeology and human impacts. Therefore, evaluation of the

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regional aquifer water-level indicator is separated into four subregions: East, EOP, Fort Huachuca, and Southwest. The East subregion includes all regional aquifer wells monitored east of the San Pedro River (three wells). The EOP subregion includes all wells that reasonably could be influenced by Sierra Vista's EOP. This includes three wells along the northeastern boundary of Fort Huachuca (five wells total). The Fort Huachuca subregion includes all other monitoring wells on Fort Huachuca, found primarily on the Fort's east range (eleven wells). The Southwest subregion includes wells found south of Fort Huachuca and west of the San Pedro River (seven wells).

With the exception of the Southwest subregion, regional water levels trended downward across the Subwatershed from 2008 to 2009, with all declines being less than 1 ft (fig. A3a). Over the short term East and EOP subregions that showed some recovery through 2007 or 2008 have since declined. The Southwest wells, close to the Huachuca mountain front, show the greatest variability including a large increase in the mean subregion water level from 2007 to 2009 primarily due to the rise in the Antelope #3 well in Garden Canyon Wash which responded to a major recharge event in the summer of 2008. The Fort Huachuca wells returned to the steady, near-linear decline of previous years after showing little decline in 2008.

Water levels in the EOP subregion show two distinct short-term trends. Bella Vista and LS-6 increased steadily from 2002 to 2007 and have since declined, while the monitor wells at the east end of Fort Huachuca decreased from 2002 to 2005, showed little variability through 2008, and in 2009 showed some recovery. This may be a function of their proximity to EOP recharge, local natural recharge events, and (or) the geology of the well locations (fig. A3a).

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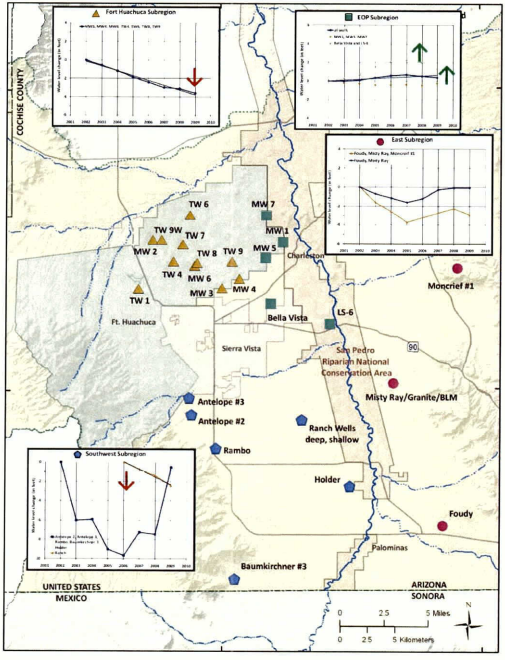

Figure A3a. Short-term trends of median annual water levels for regional aquifer wells, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Water level trends in EOP subregion show two distinct trends and are both included in addition to the mean trend of all EOP wells. East subregion well Moncrief #1 is missing 2 years of data but trend is similar to other East subregion wells; plots with and without Moncrief #1 are provided. Record for Ranch wells in Southwest subregion is just 4 years and is plotted separately. Green upward arrow indicates statistically significant increasing trend; red downward arrow indicates statistically significant decreasing trend; no arrow indicates no statistically significant trend observed.

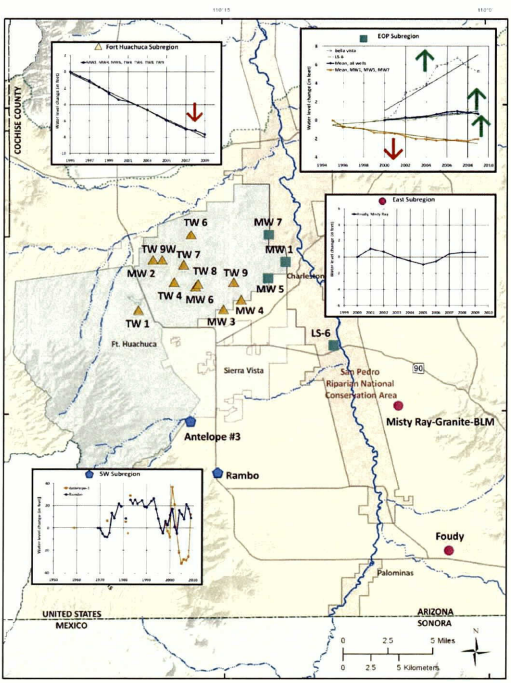

Figure A3b. Long-term trends of average annual water levels for regional aquifer wells, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Wells missing from subregion plots are missing significant portions of the early data record. Note that scale of vertical axis on Southwest Subregion plot is significantly greater than other three plots (80 feet versus 12 feet). Green upward arrow indicates statistically significant increasing trend; red downward arrow indicates statistically significant decreasing trend; no arrow indicates no statistically significant trend observed.

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Groundwater storage change—direct measurement

Direct measurements of groundwater storage change are made in the Subwatershed using microgravity techniques. These measurements have been made at a broad network of stations in the Subwatershed (figs. A4a and A4b) and can be applied at locations with or without existing wells. Measured changes of 1 μGal equal a little less than a 1-inch change in the free-standing water level (Pool and Eychaner, 1995). Gravity measurements in the Subwatershed began in about 2000. In 2005 the network of gravity stations was reconfigured and the data reported here are from 2005 to 2009. In 2008, gravity measurements commenced at 5 additional sites on the East Range of Fort Huachuca using a portable absolute gravimeter.

From 2008 to 2009, microgravity measurements at 23 stations in the Subwatershed show little aquifer storage change. These sites are generally away from populated areas. Microgravity measurements at 15 stations, mostly concentrated in more populated areas, show a decrease in aquifer storage. Four sites in the northern part of the Subwatershed show an increase in aquifer storage. This pattern and magnitude of change is largely similar to observations for the period November 2007 to November 2008. Summer rainfall during this earlier period, however, was much greater than that observed during the 2008 to 2009 period (see Appendix E). This similar gravity response under differing precipitation regimes suggests that when calculated on an annual basis, storage change may be dominated by pumping rather than climate, and reinforces earlier work that suggests basin-floor recharge (away from mountains and stream channels) is minimal (Walvoord and Scanlon, 2004, Coes and Pool, 2005).

Cumulative microgravity change from August 2005 to November 2009 shows that the greatest decline in aquifer storage is in the vicinity of Ramsey Road and Hereford Road. The area within the City of Sierra Vista is generally stable. One explanation for this pattern of storage change, where the

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decline is greater in a less-densely populated area, is that the more evenly distributed wells in the more rural area cause a uniform decline in aquifer storage, whereas wells in the more urban area are fewer but larger, and are not adequately sampled by the gravity monitoring network. Arizona Department of Water Resources well measurement sweeps from 2001 and 2006 show a pattern similar to that of the gravity data, with greater declines in water levels occurring in the more rural areas south of Sierra Vista than within the city itself (Schmerge and others, 2009).

Near-stream alluvial aquifer water levels

Near-stream alluvial aquifer water levels are found in the pre- and post-entrenchment alluvium (the old and new river flood plains). As previously noted, Leenhouts and others (2006) divide the SPRNCA into 14 reaches and classify each into dry, intermediate, or wet riparian ecological condition class. Four of the reaches, including the only dry reach, occur north of the Sierra Vista Subwatershed. The condition classes are based upon vegetation traits that are sensitive to streamflow permanence and (or) groundwater levels in the alluvial aquifer, and thus have specific hydrologic conditions associated with them. Combining adjacent reaches of like condition classes creates 5 subregions for analysis: Palominas (intermediate), Hereford (wet), Hunter (intermediate), Central (wet), and North (intermediate) (fig A5).

Because only a small subset of alluvial aquifer wells has a record that goes back before 2001, the long term record is just one year longer than the short term record, or it is represented by a small subset of the subregion's available wells. Little information is gained by contrasting data sets with a single data year of difference, and so just a single set of alluvial aquifer plots is provided for review and analysis of this indicator. Where earlier data are available, however (Central and Hereford subregions), an additional long-term plot has been added to the graph.

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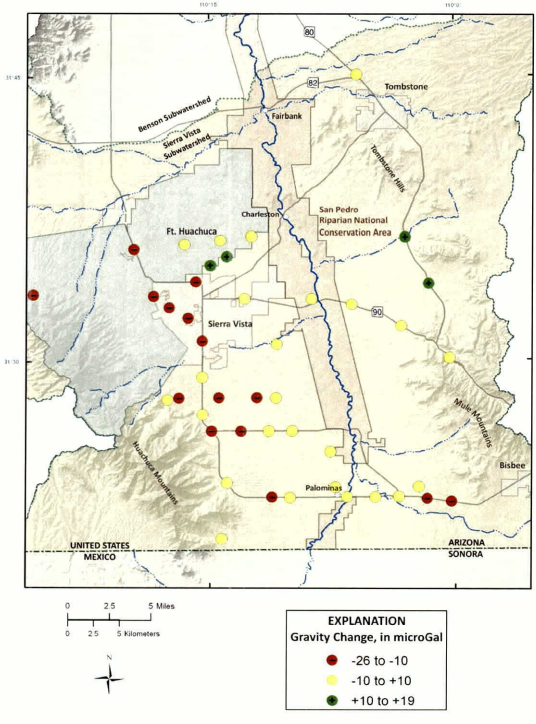

Figure A4a. Aquifer storage change 2008–09 as measured using microgravity techniques, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. In general, a change of 1 µGal equals a little less than a 1-in change in free-standing water level.

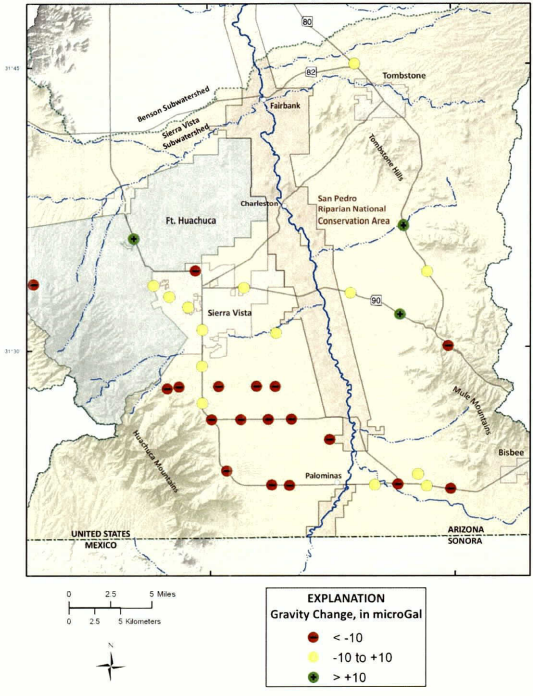

Figure A4b. Aquifer storage change 2005–09 as measured using microgravity techniques, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. In general, a change of 1 µGal equals a little less than a 1-in change in free standing water level.

Since 2001, the alluvial aquifer levels have increased in both the Palominas and Central subregions. This may be a response to the cessation of agriculture irrigation pumping in the Palominas area and to the recharge of treated effluent at the EOP near the center of the Central subregion. Water levels have also been increasing over the short term in the Hunter subregion, to the north of Hereford. There is a significant downward trend in the Hereford subregion over the longer term (beginning in 2000), although water levels have been rising there since 2005.

Vertical hydraulic gradients

Changes in the vertical hydraulic gradient measured in wells near the San Pedro River indicate changes in the tendency for water to flow between the stream and the groundwater system. A positive vertical gradient near the river indicates that the water is flowing from the regional aquifer into the stream while a negative vertical gradient indicates that the stream is losing water to the aquifer. As with the alluvial aquifer water-levels indicator, the SPRNCA is divided into five subregions based on the wet and intermediate riparian condition classes (fig. A6): Palominas (one well pair, south of Arizona Route 92 at Palominas), Hereford (one well pair, just north of Hereford Road and south of the perennial reach,) Hunter (no well pairs), Central (three well pairs along the principal perennial reach, from about a mile south of Arizona route 90 to just north of Charleston), and North (two well pairs, north of the principal perennial river reach which ends just north of Charleston). Note that the Hunter subregion has no well pairs suitable for vertical gradient analysis leaving four subregions for analysis.

Similar to the case with near-stream alluvial aquifer water levels, the majority of the vertical gradient well pair records extend to just 2001 and so a single set of plots is provided covering data years 2001–09. Three of the four subregions show positive vertical gradients (right axis on plots fig. A6), indicating that water throughout much of the Subwatershed is moving toward and discharging to the river. In some areas such as Palominas, however, a clay layer may reduce the

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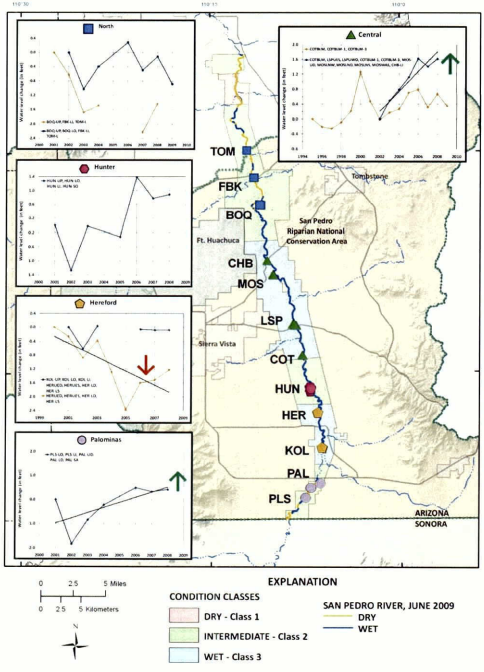

Figure A5. Trends of average annual water levels for alluvial aquifer wells, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Hereford and Central subregions include wells with longer term records and these are plotted separately. Water level records that begin with 2001 data are plotted once and evaluated as a short term trend. Green upward arrow indicates statistically significant increasing trend; red downward arrow indicates statistically significant decreasing trend; no arrow indicates no statistically significant trend observed.

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efficiency with which regional aquifer groundwater is able to discharge to the alluvial aquifer and the river despite a strong vertical gradient. Hereford is the one location where the vertical gradient is negative, indicating that water from the river and the alluvial aquifer discharges to the regional aquifer in this area. In the Hunter area downstream from Hereford, the San Pedro can be dry in sections during the fore-summer drought, although this was not the case in 2009 (fig. A6).

The Palominas region shows the greatest variability but no trend since 2001, while Hereford shows little variability but a significant downward trend over the same period. The vertical gradient in the Central subregion has been increasing since 2004, but over the full nine year interval the trend is not statistically significant. Lewis Springs is the one well pair with a fairly long record, beginning in 1995. With the exception of a minor dip in 2004, the vertical gradient there has remained relatively stable over the 15 year period.

Streamflow

Low flow and days of no flow

The USGS operates three streamflow-gaging stations along the San Pedro River in the Subwatershed that collect data applicable for evaluating changes in the hydrologic system and progress toward sustainability: Palominas, Charleston, and Tombstone (figs. A7a and A7b). These data provide a spatially distributed measure of temporal streamflow variation. Annual variability in groundwater discharge to the river can be tracked through seasonal low-flow observations at Charleston and through the number of total no-flow days at Palominas and Tombstone. Although the streamflow-gaging station located on the Lower Babocomari may be of equal importance to these three in assessing hydrologic conditions (Pool and Coes, 1999), at this time the Partnership has not included streamflow measured at the Lower Babocomari streamflow-gaging station as an indicator of sustainability.

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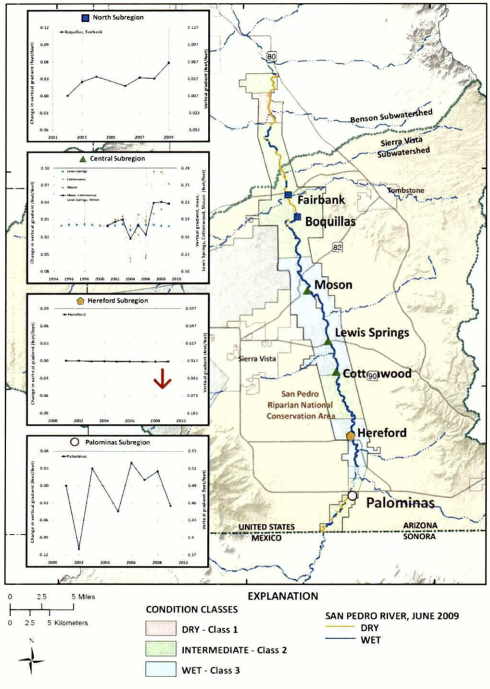

Figure A6. Trends of average annual vertical gradients for deep and shallow near-stream wells, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Central subregion includes well pairs with longer term records and these are plotted separately. Vertical gradient records that begin with 2001 data are plotted once and evaluated as a short term trend. Red downward arrow indicates statistically significant decreasing trend; no arrow indicates no statistically significant trend observed.

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Base flow at the Charleston gaging station varies seasonally, typically with a higher base flow during the winter months, and the lowest flow in June or early July (fig. A7b). These seasonal variations are primarily related to changing rates of near-stream withdrawals by riparian vegetation. Pool and Coes (1999) observed that short-term trends in both summer and winter base flow are closely related to wet-season runoff. Longer-term trends are the result of one or more natural and (or) human caused factors in addition to precipitation trends. For 321 reporting, 7-day summer (June) and winter (January 15 through March 15) low flows of the San Pedro River at Charleston are used as a base-flow proxy to evaluate trends, and thus serve as indicators of sustainability[6].

In 2009 the June 7-day low flow at Charleston was 1.64 cfs. This is the highest June 7-day low flow value since 321 reporting began in 2002, and just the second time since 321 reporting began that the June 7-day low flow has exceeded 1.0 cfs (1.11 cfs in 2004 is the other; fig. A7a). The last time that the June 7-day low flow was at least this high was in 2001 (2.94 cfs). The 10-year average 7-day June low flow (2000–09) declined slightly from 1.12 cfs in 2008 to 1.10 cfs in 2009. The 10 year average includes some years likely affected by storm runoff. Despite this year's increase in June low-flow, the long-term trend in June 7-day low flow remains statistically significant (fig. A7b).

The decreasing trend in June low flow has been discussed previously in Pool and Coes (1999) and Thomas and Pool (2006)[7] as well as in previous 321 reports. A significant decreasing trend in June low flows remains after accounting for precipitation trends, and may result from one or more factors including increases in riparian and (or) upland vegetation, changes in stream-channel morphology, near-stream and regional-aquifer pumping, construction of surface-water detention basins and tanks, urbanization, and livestock grazing (Thomas and Pool, 2006).

[6] See footnote (4), p. A21
[7] Thomas and Pool (2006) used a three-day low flow period in their analysis

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The winter 7-day low flow for 2009 was 11.7 cfs, a decrease of 0.7 cfs from 2008 (fig. A7b). The 9-year average winter 7-day low flow is 10.5 cfs (2000–09; winter 2001 is removed from the 10-year average because of the anomalous effect of a series of large storm-related flows in October of 2000), which is a 0.7 cfs increase from 2008 (9.8 cfs in 2008). Since the beginning of 321 reporting in 2002, 7-day winter low flows have ranged from 7.1 cfs in 2004 to 13.9 cfs in 2002 and 2007 (fig. A7a). Over the entire record, 7-day winter low flow discharge has ranged from 5.3 cfs in 1999 to 51.4 cfs in 1985. Thomas and Pool (2006) report that there is no statistically significant short-term nor long-term trend in winter low flow at Charleston based on all years of data through 2002, and this appears to remain the case through 2009. Low flow values above about 20 cfs are generally assumed to be affected by storm runoff, however, and when such flows are removed from the record, a significant downward trend is evident (fig. A7b).

For gaging stations such as Palominas and Tombstone that stop flowing during the driest times of the year, an analysis of annual no-flow days is used as the surrogate for base flow trends. As previously noted, the number of days of storm flow influences the number of days of no-flow (more storm flows, fewer no-flow days) and thus there is more inter-annual variability in this value than in 7-day low flow values. This is evident when evaluating the long-term trends.

The number of no-flow days per year at Palominas is zero in the early part of the record, but once agricultural pumping commenced in earnest in the area in the 1940's (Pool and Coes, 1999) the river ceased to flow in some years for tens of days separated by years with zero or near-zero days of no flow (fig. A7b). In 1969, the river did not flow at Palominas for 159 days, but by 1975 that number had declined again to just 2. The short-term trend at Palominas reflects this variability—the third highest

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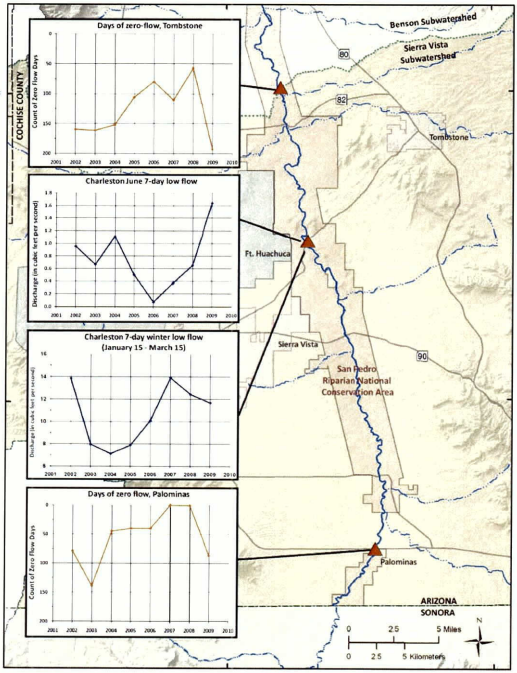

Figure A7a. Short-term trends of 7-day June and 7-day Winter (January 15–March 15) low flow at Charleston gaging station, and of total days of no flow at Tombstone and Palominas streamflow-gaging stations, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Scale of vertical axes varies among plots.

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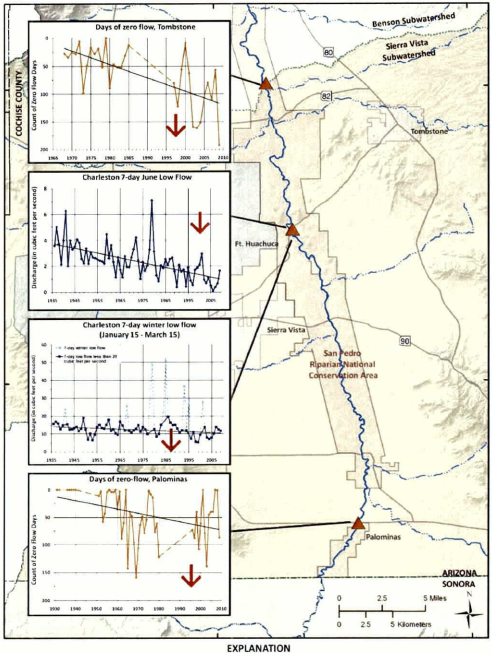

Figure A7b. Long-term trends of 7-day June and 7-day Winter (January 15–March 15) low flow at Charleston gaging station, and of total days of no flow at Tombstone and Palominas streamflow-gaging stations, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Years when Charleston winter low flows do not drop below 20 cubic feet per second are influenced by storm runoff and not reflective of base flow conditions. Such years have been removed from winter low flow analysis. Scale of vertical axes varies among plots. Red downward arrow indicates statistically significant decreasing trend.

number of no-flow days in the record is in 2003 (139) and by 2007 and 2008 the number of no-flow days dropped to zero and one, respectively (fig. A7a). In 2009 this number increased once again to 87 days without flow. Despite the variability in the long-term record, there is a significant increasing trend in the number of days without flow at Palominas.

The Tombstone record is much shorter, beginning in 1968. The number of no-flow days per year varies between near-zero and 100 through 1985, and averages about 37 days without flow per year for the period, after which there is a 10 year gap in the station record. Following the data gap the number of no-flow days per year increases, varying between 50 and 160 from 1997 through 2008, with the exception of the wet year of 2000 (fig. A7b). In 2009, following the latest start ever to winter base flow at the Tombstone gaging station, the number of days of no flow at Tombstone reached 193, the most on record. The average annual days of no flow for the latter period (including 2000) is 104, an increase in the annual average of 67 days from the earlier period of record. Given the marked increase in no-flow days per year after 1997, the lack of Tombstone streamflow data during 1986–96 is particularly problematic, as the timing and thus potential cause of this change is obscured. Since 2002, the short-term trend had been toward fewer no-flow days per year, from about 160 days in 2002 and 2003 to less than 60 days in 2008. The 193 days without flow in 2009 reverses this apparent trend (fig. A7a).

Streamflow Permanence

In spring 2006, ARS installed and began operating eight automatic recording digital cameras at sites along the San Pedro River in order to monitor streamflow permanence. The BLM currently operates these sites. Six of the sites are in the Subwatershed (fig. A8). Streamflow-gaging stations provide similar data to evaluate streamflow permanence, and the Palominas, Charleston, and Tombstone gaging stations, and the stage recorder near Lewis Springs are included in this analysis. Of the 10 streamflow permanence sites in the Subwatershed, 4 (Hereford, Lewis Springs, Moson, and Charleston)

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are located in the "wet" riparian condition class identified by Stromberg and others (2006), and the other 6 sites are in the "intermediate" class (fig. A8). Leenhouts and others (2006) found average streamflow permanence for the wet condition class in water years 2002 and 2003 ranged from 98 to 100 percent and average stream flow permanence for the intermediate condition class ranged from 63 to 78 percent.

Because the automatic cameras have only been in operation for three years, multi-annual data trends are not yet evident, annual climate variability is the principal driver. In 2007 and 2008, nine and ten of the sites, respectively, were within or above the average streamflow permanence ranges established by Leenhouts and others (2006). In 2009 there was an exceptionally dry summer monsoon, and permanence values for the three sites in the northern intermediate condition class (Charleston Mesquite, Fairbank, and Tombstone) were below the intermediate streamflow permanence range. Streamflow permanence at five of the other seven monitoring sites were within the established ranges, including all four sites in the wet condition class (all at 100 percent).

Springflow

Springs provide another pathway for groundwater to discharge to the surface. The five Subwatershed spring sites currently monitored are separated into three subregions—West (Murray Springs, Horsethief Spring, Moson Spring), East (Lewis Springs), and South (McDowell-Craig Farm flowing well) (fig. A9). All sites are relatively close to the San Pedro River, and the West subregion springs are down gradient from the EOP recharge facility.

From 2008 to 2009, total flow measured at all West subregion springs increased by about 9 gallons per minute (4percent), ranging from a decrease of about 3 gallons per minute (13percent) at Moson Spring to an increase of 13 gallons per minute (6.5percent) at Murray Springs. Of the total discharge from the West subregion springs, more than 88 percent was from Murray Springs in 2009

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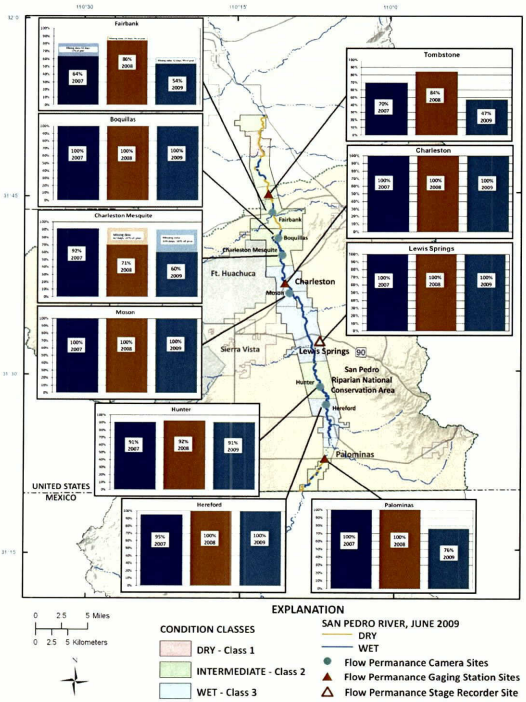

Figure A8. Streamflow permanence, in percent of year for 2007, 2008, and 2009, at selected sites, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Fairbank and Charleston Mesquite sites include some years with small portions of missing data, represented by that percentage of bar graph in pastel color.

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(median of 213 gallons per minute (0.47 cfs) of 241 gallons per minute (0.54 cfs) median discharge from all West subregion springs combined). From 2008 to 2009 spring discharge measured from Lewis Springs, across the river east of the West subregion, decreased 15 percent and discharge measured at the flowing McDowell-Craig Farm well in the South subregion decreased 44 percent (fig. A9).

Discharge measurements at Murray Springs began in 2003, and at Moson Springs in 2007. Measurements at the other three sites began in 2005. For the West subregion springs Murray Springs show an increasing trend since 321 monitoring began. No clear trend is evident in other subregion springs during this period (fig. A9). Discharge from Murray Springs, located within Curry Draw and down gradient from the Sierra Vista EOP, has increased from a median annual value of 3.8 gallons per minute (0.0085 cfs) in March 2003, when monitoring began, to 213 gallons per minute (0.47 cfs) in 2009 or about 340 acre-ft of discharge for the year. In addition, the source of emanation has expanded from the original Murray Springs location to farther upstream in Curry Draw.

The spring is about 1.5 mi down gradient from the center of the Sierra Vista Water Reclamation Facility, and about 0.9 mi down gradient from the nearest EOP recharge ponds. Incidental recharge from the EOP constructed wetlands was determined for the first time in 2009. In addition, the estimated incidental losses for previous years have been calculated. Taking these new data into account, the City of Sierra Vista has averaged about 2,480 acre-ft/yr of total treated effluent recharge since 2002, with about 2,240 acre-ft of total recharge occurring in 2009 (95 acre-ft less than the actual amount of total recharge occurring in 2008, but 700 acre-ft more than the value reported for 2008, before the incidental losses had been quantified). The increasing trend in discharge at Murray Springs since 2002 likely is related to the ongoing recharge of treated effluent at the EOP over the same period.

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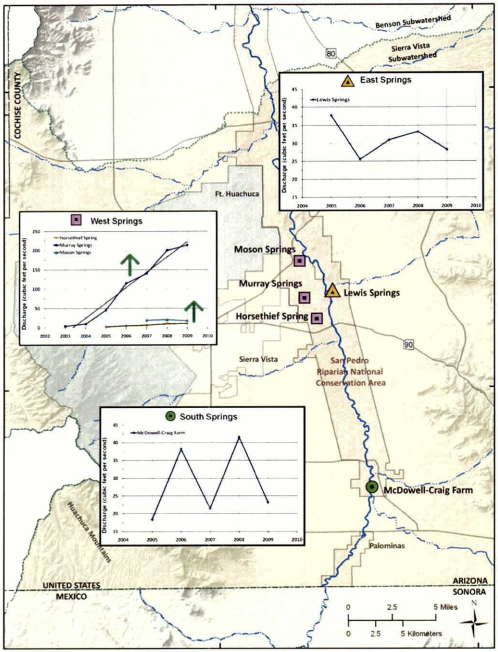

Figure A9. Short-term trends in spring discharge, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona. Green upward arrow indicates statistically significant increasing trend; no arrow indicates no statistically significant trend observed.

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Water Budget

The initial 2004 Section 321 Report (Department of the Interior, 2005) outlined a set of management measures to be implemented in each calendar year through 2011 in order to attain a sustainable yield of groundwater from the regional aquifer of the Subwatershed. These measures can be characterized broadly as conservation and recharge. More specifically, conservation includes effluent reuse, code changes, and reductions in irrigated agriculture, recharge includes the effluent and storm-water recharge projects that return or introduce additional sources of water to the aquifer.

Conservation yields are determined specifically for each Partnership member owing to differences in data availability. In rural Cochise County, for example, much of the groundwater is pumped by unmetered private wells and the amount of pumping is estimated from the number of wells and an assumed per-well use. Because actual pumped volumes are unavailable for individual wells, conservation was estimated for specific projects and summed to create grouped yields. Only yields from projects actually implemented since 2002 were counted. The estimated conservation yields were then assumed to represent actual water savings. For Sierra Vista, Fort Huachuca, and Huachuca City, sufficient data were available to calculate a per capita pumpage value for 2002 (the baseline year) and for 2009. Conservation was then calculated as the difference between actual pumping in 2009 and the pumping that would have occurred in 2009 had the population used water at the 2002 per capita rate. The per capita pumping in Huachuca City, for example, decreased from 136 gallons per capita per day (gpcd) in 2002 to 111 gpcd in 2009, a reduction in use of about 55 acre-ft per year for the jurisdiction. Although Subwatershed per capita pumping has declined, population has increased. This results in a net decrease in pumping since 2002 that is much smaller (1,300 acre-ft) than the total conservation yields (4,000 acre-ft), because the conservation yields represent the reduction in *projected* pumping were no

management measures employed, while the net decrease since 2002 is the reduction in *actual* pumping.[8] Because the Partnership is continually striving to develop improved estimates of recharge and conservation yields, some yields reported here and in table A1 and table 4 differ from same-category yields reported in prior Section 321 reports.

Planned and Actual Management Measure Yields

The effect of conservation and recharge, once estimated, may be combined to calculate a total yield of management measures — this combined yield describes the reduction in net groundwater use in the Subwatershed compared with the use that would have occurred in the absence of management measures.

The following discussion and table 4 compare previously planned management-measure yields with estimates of the actual yields obtained for calendar year 2009. Last year's Section 321 Report (2009, reporting on calendar year 2008) projected a combined deficit-reducing yield of about 10,700 acre-ft for 2009. The actual yield calculated for 2009 is 10,400 acre-ft (table 4). This is a 700 acre-ft increase from the yield calculated for 2008 (9,700 acre-ft). Sierra Vista's reported effluent recharge value increased from 2008 to 2009 by about 700 acre-ft in part due to the inclusion, for the first time, of an estimate of the water losses (assumed recharge) in the wetlands treatment process. In 2009 this additional incidental treated effluent recharge was estimated to be about 350 acre-ft (M. Hemesath, City of Sierra Vista Director of Public Works, written commun., April 9, 2010). The conservation yield reported for Sierra Vista (including Fort Huachuca) also increased by 100 acre-ft from 2008 to 2009. Effluent recharge and detention basin recharge on Ft. Huachuca decreased by about 120 acre-ft combined in 2009, due in large part to an extremely dry summer (Appendix E).

[8] In 2005 the method of estimating rural exempt-well population was revised, resulting in a reduction of 640 acre-ft in estimated rural groundwater pumping. Total pumping reported in 2002 (18,500 acre-ft) was thus over-reported by the same amount (640 acre-ft) and was actually closer to 17,800 acre-ft. Therefore, the 2009 total pumping figure actually represents about 1,300 acre-ft less pumping than in 2002.

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The overall yield includes active Partnership member projects, a decrease in agricultural pumping caused by the sale and retirement of agricultural property, and yields from increased recharge caused by urbanization. Urbanization in arid climates can increase recharge by directing additional storm water runoff to ephemeral stream channels where the ratio of infiltration to evaporation is increased (Kennedy, 2007; Lohse and others, 2010). The Partnership does not suggest that urbanization increases recharge more than urbanization increases pumping, but rather that the increased recharge offsets some of the increased pumping. See the 2004 Section 321 Report (Department of the Interior, 2005) for additional details.

Measures without quantified yields

In some cases, such as for rural areas of Cochise County where pumping is not metered, conservation management measures have been enacted that do not have a yield reported owing to the difficulty in quantifying the yield. In addition, methods such as Transfer of Development Rights have been made available to the development community as part of the strategy of spatial water management. In 2006 Cochise County enacted a conservation management plan that requires developers to limit water use in a planned higher density zoned development to that amount projected for use under the former, lower density zoning. In 2006 the County also established a zoning overlay district within the Subwatershed that requires a number of water-conservation provisions for new-house construction and amends the zoning regulations to allow for formal Transfer of Development Rights away from hydrologically more sensitive areas to areas of lesser impact on streamflow. In addition, future subdivisions within the unincorporated areas of the Subwatershed are now required to be served by a water company or water district rather than unregulated individual wells.

In 2007, the BLM established a similarly preventative policy with regard to land disposals within the Upper San Pedro Groundwater Basin which includes the Sierra Vista Subwatershed. The

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BLM will defer approval of land use authorizations unless the request demonstrates that the intended uses of those lands will not require groundwater from the Groundwater Basin (Nathan Dieterich, Bureau of Land Management Hydrologist, written commun., 2008).

Various conservation efforts of Sierra Vista and Fort Huachuca are not included in table 4 (nor table A1) owing to the timing of their implementation. The Section 321 reports use a 2002 baseline year for calculations. Any conservation efforts initiated prior to that year are intrinsically included in the baseline value and cannot be separately counted. Water usage would currently be higher in the absence of those measures.

Revisions to the base water budget

As part of its effort to review and improve all values found in the Subwatershed water budget, in 2009 the Partnership charged the USGS with conducting a thorough analysis of base flow discharge at the Tombstone gaging station. The results of this work have now been published (Kennedy and Gungle, 2010) and the net result is an increase in the estimate of average annual base flow at the Tombstone gaging station of 1,640 acre-ft. Because base flow is groundwater discharged to the river, this represents a similar increase in the annual groundwater budget deficit. The previous average annual base flow value of 3,250 acre-ft/yr used in 321 Reports from 2002 through 2009 was calculated by ADWR (2005a, 2005b) based on 1997–2004 data. Kennedy and Gungle's (2010) revised value of 4,890 acre-ft/yr is based on the entire period of record (1968–86 and 1997–2009; the gaging station was not in operation between the two sub-periods).

If this revised base flow value represented an increase from 2002 in the long-term average amount of water flowing past the Tombstone gaging station, it would indicate progress toward sustainability—more water is available from the regional aquifer to enter the river and thus more water is exiting the Subwatershed as base flow. This is not the case, however. Rather, this revised estimate is

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an improved estimate of the true state of the average annual base flow at Tombstone, and thus the increased outflow number means that the annual deficit is somewhat larger than previously thought.

In addition to the current revision to the Tombstone base-flow discharge value, a number of other significant changes have been made to the Subwatershed groundwater budget since the 2004 321 Report (Department of the Interior, 2005) when the 2002 annual groundwater deficit was estimated to be 9,900 acre-ft (table 2a). In the 2005 report (reporting on 2004; Department of the Interior, 2006), urban enhanced recharge (2,300 acre-ft/yr) was added to the water budget. In the 2007 321 Report (reporting on 2006; Department of the Interior, 2008), a revision to the calculation of the rural population using exempt wells resulted in a reduction in the 2006 annual deficit of 640 acre-ft/yr, and an analysis of average annual riparian ET led to an increase of 3,100 acre-ft in the estimated annual average volume of water discharged by plants and evaporation (Scott, 2006). As discussed in the previous paragraph, the average base flow discharge value is revised in this year's report, increasing that amount by 1,640 acre-ft. Adding up the four major changes to the annual water budget means that the estimated annual deficit of 6,100 acre-ft in 2009 is about 1,800 acre-ft larger than what it would have been had none of these additions to, or revisions of, the 2002 Subwatershed groundwater budget occurred (table 2b).

Storage Deficit in 2009

A groundwater storage deficit of about 6,100 acre-ft in the Subwatershed was estimated for 2009 by combining estimated total pumping with management-measure yields in a Subwatershed water budget (table 1). The greatest changes from the water budget published in the 2008 321 report were in the estimate of average annual base flow discharged from the subwatershed as measured at the Tombstone gaging station (an increase in the estimate of more than 1,600 acre-ft), in groundwater pumping (an increase of about 500 acre-ft), and in effluent recharge from the jurisdictions of Sierra

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Vista, Ft. Huachuca, Bisbee, and Tombstone (an increase of more than 500 acre-ft). In 2009, groundwater pumping increased in every pumping category, and showed an overall increase for the first time since 2004. This may have been in part due to an exceptionally dry summer in 2009, which also accounts for the decrease in detention basin recharge (Appendix E). Total pumping in the 2009 water budget was the estimated sum of uses by private water companies, municipalities, Fort Huachuca, golf courses, rural residents using exempt wells, agriculture, and industry. The effectiveness of conservation measures is intrinsically included in values for total pumping and is not part of the deficit calculation in table 1. Estimates for conservation yields, however, are included in table 4 and figure 1 to indicate how much water likely was saved compared to a condition where no conservation measures were implemented. An exception is conservation through reduction of mesquite near the San Pedro River; it is independent of groundwater pumping and therefore tabulated separately. In 2009, the total conservation yield relative to the 2002 baseline (estimated from table 4) was about 4,000 acre-ft, an increase of 100 acre-ft from 2008. Rural conservation measures (the combined benefits of mesquite reduction and retirement of agricultural pumping; see table 4) amounted to about 2,700 acre-ft in 2009, a value unchanged from 2008.

It is important to recognize the progress that has been made in reducing the annual deficit in aquifer storage in the Sierra Vista Subwatershed. Since 2002, when 321 reporting began, groundwater pumping in the Subwatershed has decreased by about 1,300 acre-ft[9]. Active management measures throughout the Subwatershed have yielded an additional 4,100 acre-ft of water that either enters the aquifer as additional recharge or that is no longer being withdrawn from the aquifer by invasive mesquites. In total in 2009 there is about 5,400 acre-ft less water being lost from the regional aquifer than in 2002. Further active management measures will need to be instituted in the Subwatershed,

[9] See footnote (8), p. A49

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however, if the Partnership is to further reduce the annual aquifer storage deficit and some day begin to accrete storage.

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Glossary

Base flow
The sustained flow in a stream that comes from groundwater discharge or seepage.

Consumptive use
The portion of groundwater pumped that is not returned to the aquifer as recharge.

Deficit
Synonymous with aquifer storage loss.

Management target
A quantified goal to reduce net groundwater consumption as part of reaching sustainable yield. The Partnership has chosen, as a management target, to eliminate aquifer storage depletion and begin accreting storage.

Net groundwater consumption
Groundwater removed from the regional aquifer that is not returned through incidental or artificial recharge or replaced through enhanced recharge.

Overdraft
Net groundwater consumption from the regional aquifer in excess of sustainable yield.

Partnership
An abbreviation of the Upper San Pedro Partnership which is a collaboration of public agencies and organizations that own or control land, or water use, in the Sierra Vista Subwatershed portion of the Upper San Pedro River Basin, and that have the authority and resources to identify reasonable, feasible, cost-effective projects and policies, and the ability to actually implement them. Federal, State, and local governmental and nongovernmental entities whose mission is to create a water-management plan that meets the needs both of Sierra Vista Subwatershed residents and of the San Pedro Riparian National Conservation Area .

Recharge, artificial
Groundwater recharge of municipal effluent in specifically engineered recharge facilities.

Recharge, enhanced
The increase in naturally occurring groundwater recharge through ephemeral channels due to urbanization.

Recharge, incidental
Groundwater recharge from sources not specifically engineered to generate recharge such as septic tanks, golf courses, and agricultural operations.

Regional aquifer
The regional aquifer is defined as the aquifer underlying the Sierra Vista Subwatershed.

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Riparian
Vegetation, habitat, or ecosystems that depend on surface and (or) subsurface water flow.

Storage change
The change in the volume of water stored in an aquifer through time. Storage change results from a difference between inflows and outflows. It is often expressed as an annual volume.

Storage depletion
A decrease in aquifer storage.

Sustainable yield
The level of groundwater use that can be maintained for an indefinite period of time without causing unacceptable environmental, economic, or social consequences.

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