ECOLOGY AND CONSERVATION OF THE SAN PEDRO RIVER

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Introduction

Though primarily a desert environment, some of the mountain blocks in the Basin and Range Physiographic Province of the southwestern United States have risen to elevations sufficient to capture annual precipitation in excess of 500 mm and support perennial streams in the mountain canyons. Streamflow from these higher mountain blocks, and groundwater seeping from the mountain blocks into the sediment-filled valleys, also supports perennial and intermittent flow in the streams that course down the valleys between the mountain blocks. The groundwater discharge to the stream is a small but important component of the annual streamflow, and is called baseflow.

In this chapter we explore the hydrologic infrastructure supporting the riparian ecosystem of one such stream, the San Pedro. We discuss some basic aspects of groundwater hydraulics and the interaction of the groundwater and surface water system in the riparian corridor in the present time and the foreseeable future. We use the extensively studied Sierra Vista subwatershed of the upper San Pedro basin as our specific example. The Benson subwatershed is similar to the Sierra Vista subwatershed, although that more northerly portion of the upper San Pedro basin does not contain as much

high-elevation terrain. The lower San Pedro basin also differs in being less than half as wide between the mountain blocks as the upper basin.

Groundwater Overview

AQUIFERS

There are two types of aquifers in the San Pedro basin. One type is found in the mountains where water moves through fractures in the bedrock. The second type is found in the basins and is composed of unconsolidated sediments (clay, silt, sands, and gravels). There are two primary unconsolidated aquifers in the San Pedro basin—the regional aquifer and the floodplain (or stream) alluvial aquifer.

Regional aquifer. The regional aquifer extends throughout much of the basin and is comprised of materials eroded from the adjacent mountains as they rose in the geologic past. This material was transported by the canyon streams to the mountain front and deposited in coalescing fan-shaped deposits. The deposits tended to be coarsest, and thinnest, near the mountain front and finer and thicker (to 300 m and more) near the center of the basin. The mountains arose by a series of movements along the faults that separate the mountain blocks from the valley. These sporadic uplifts disrupted the earlier deposits of sediment and produced new depositional material. Geologists divide the regional aquifer into several distinct units based on their depositional relationships, while hydrologists usually treat them as a single unit, or as two units, with the lower unit being less permeable due to partial cementation and compaction of the sediments. In this chapter we treat the multiple horizons of varying sediment compositions and abilities to transmit water as a single aquifer.

The mountains rose over millions of years, and for most of that time there was no through-flowing stream. Because of this, lakes or playas formed, and deposits of clay and silt that do not transmit water readily were deposited near the basin centers. Eventually, the basin filled, and a through-flowing stream (the ancestral San Pedro River) became established, which transported sediment derived from upstream locales. So, while the regional aquifer contains rocks derived from the adjacent mountains, the floodplain aquifer deposited by the ancestral San Pedro contains rocks from Mexico as well as from local areas. Figure 15.1 shows the relationships of the various hydrogeologic units in the Sierra Vista subbasin.

Floodplain aquifer. The floodplain aquifer is a long, thin body of sediments of varying width and thickness. Both the San Pedro River and its tributaries have influenced the configuration of the floodplain aquifer. Historic fluctuations in climate have caused the river's behavior to alternate between ero-

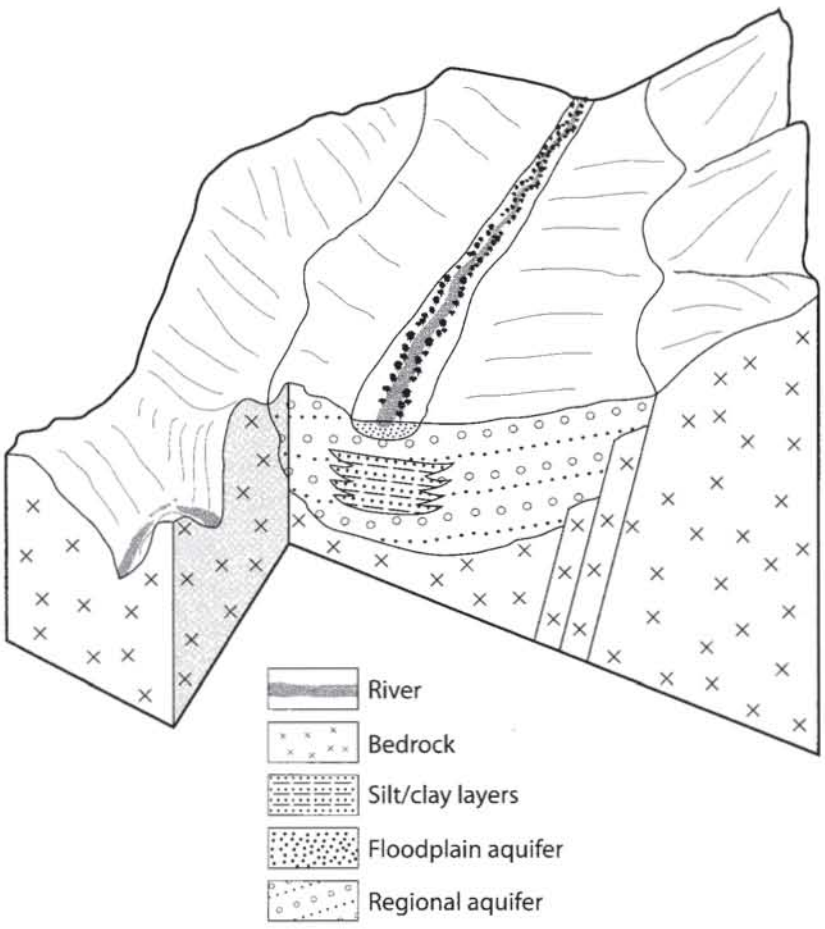


Fig. 15.1. Schematic block diagram showing the relationships and distribution of the hydrogeologic units in the Sierra Vista subbasin of the upper San Pedro River basin.

sional, where the river incises its channel more deeply, to depositional, where the channel fills with sediment and the river spreads out over the floodplain, depositing sediments and building up the floodplain. Local tributaries randomly contribute large sediment loads during the sometimes-spectacular summer thunderstorm season. These monsoon events may affect only one or two tributaries at a time, but their flood flows carry large sediment loads to the San Pedro and create temporary dams that cause aggradation upstream. The end result is a floodplain aquifer that thickens and thins (ranging from a meter or two to perhaps over ten meters in places) as well as widens and narrows in its course down the valley.

GROUNDWATER SOURCE AND FLOW RATES

Source of groundwater. Groundwater in the San Pedro basin, like all groundwater, is derived from rainfall. When rain falls on the ground, three things can happen to the water. It may percolate into the soil, with some used by plants and some reaching (and recharging) the water table (the surface below which all voids and interstices in the earth materials are fully saturated). It

can concentrate into rivulets and run off on the land surface to the nearest stream channel. It can evaporate back into the atmosphere; in this desert environment, this is the fate of most of the precipitation.

Most groundwater recharge occurs at or near the mountain fronts, where precipitation is greatest. The recharge process is poorly understood, but there appear to be three main mechanisms. In the first mechanism, mountain precipitation percolates into the bedrock fractures and then discharges into the regional aquifer at the mountain front. While the bedrock aquifers in the mountains adjacent to the San Pedro are not thought to be highly productive, little is known of their hydraulic properties. A second mechanism includes overland flow off the mountainsides onto the basin soils in between the canyons, and direct precipitation onto these surfaces; if the field capacity of soils is exceeded, water will percolate through the unsaturated zone to the water table of the regional aquifer. However, during the growing season the root systems of shrubs and grasses are likely able to capture all percolating waters. And, such recharge to the regional aquifer may not occur in interstream areas lying more than a couple kilometers from the mountain front where sediments become finer (R. Scott et al. 2000b). The third mechanism is the infiltration of storm runoff from the mountain streams as they debouch from their canyons and flow in their gravel-lined channels over (and into) the regional aquifer. Up to 20 percent of the recharge to the regional aquifer is estimated to be by this mechanism (Coes and Pool 2005). The actual amount of groundwater recharge cannot be directly measured, so it historically has been estimated as a water budget residual, discussed later in this chapter.

Groundwater flow rates. Surface water flows in well-defined channels as streams and rivers, while groundwater flows in myriad tiny threads through the pores and interstices in the sediments or rock fractures. The rate at which groundwater flows in an aquifer is important to know, as it influences the design of groundwater-management systems. It depends on two factors. The first is the ability of the aquifer to transmit water, largely influenced by the size of the openings in fractures (for bedrock aquifers) and the size of the intergranular spaces (for unconsolidated aquifers). The second is the gradient (i.e., the difference in water levels at two points, divided by the distance between them), with higher (steeper) gradients causing water to flow faster. In unconsolidated aquifers, water flows more readily in coarse sands and gravels than in fine sands, silts, and sediments containing clay.

The flow of groundwater is very slow, with flow rates measured in units ranging from meters per day to millimeters per day. Considering the current estimates of 18.5 million m^3 annual recharge to the Sierra Vista subwater-

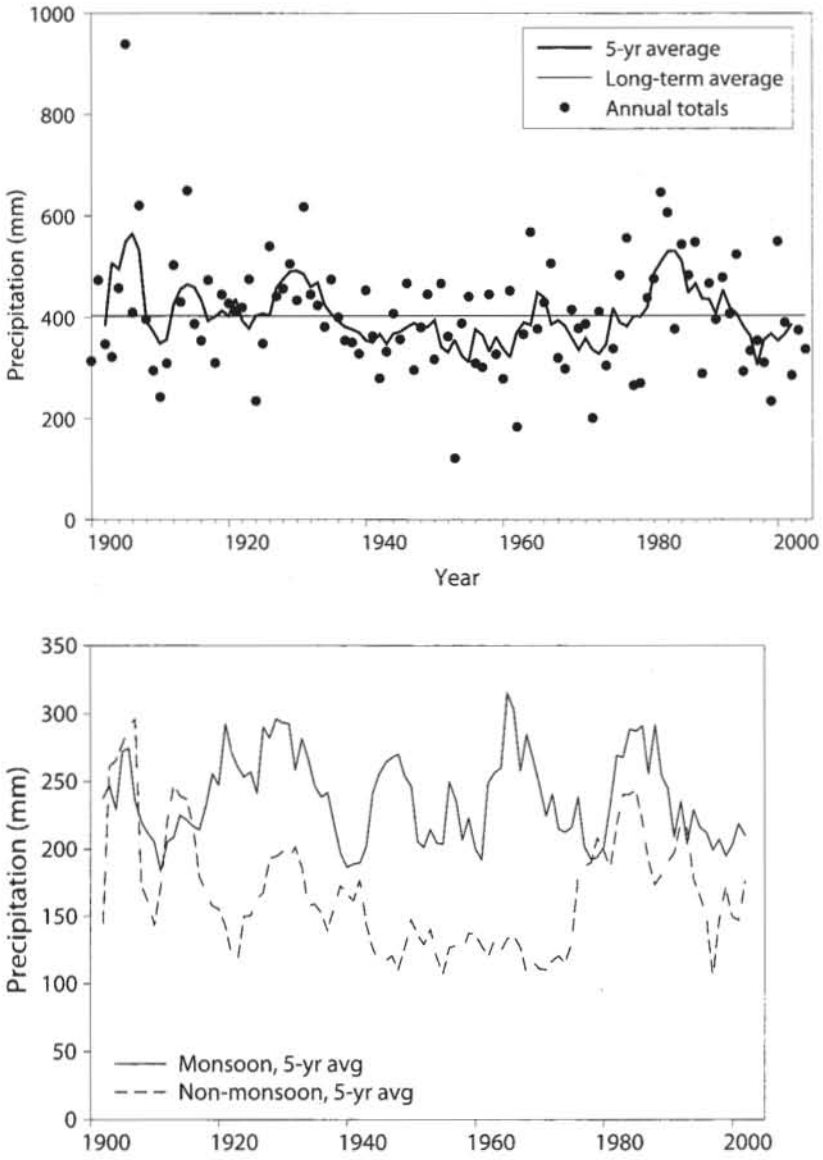


Fig. 15.2. (top; 15.2a): Annual precipitation at Fort Huachuca with a five-year moving average of the point data. (bottom; 15.2b): Monsoon and non-monsoon precipitation at Fort Huachuca, with annual point data smoothed with a five-year moving average.

shed (USDI 2005), and an estimated total volume of 20 km^3 (about half of the 38.24 km^3 of water in the regional aquifer of the upper San Pedro basin above St. David; ADWR 1991), the average time it takes a molecule of water to move from the recharge areas to the stream is about 1,100 years. Water moves streamward in the upper part of the regional aquifer more rapidly, perhaps in as little as 50 years, while water that circulates deeply in the partially consolidated lower units may take 10,000 years.

While there have been wet and dry periods over the past century, no long-term trend is apparent in the annual rainfall record at Fort Huachuca, which dates back to 1900 (fig. 15.2). (A small decline in annual rainfall is evident

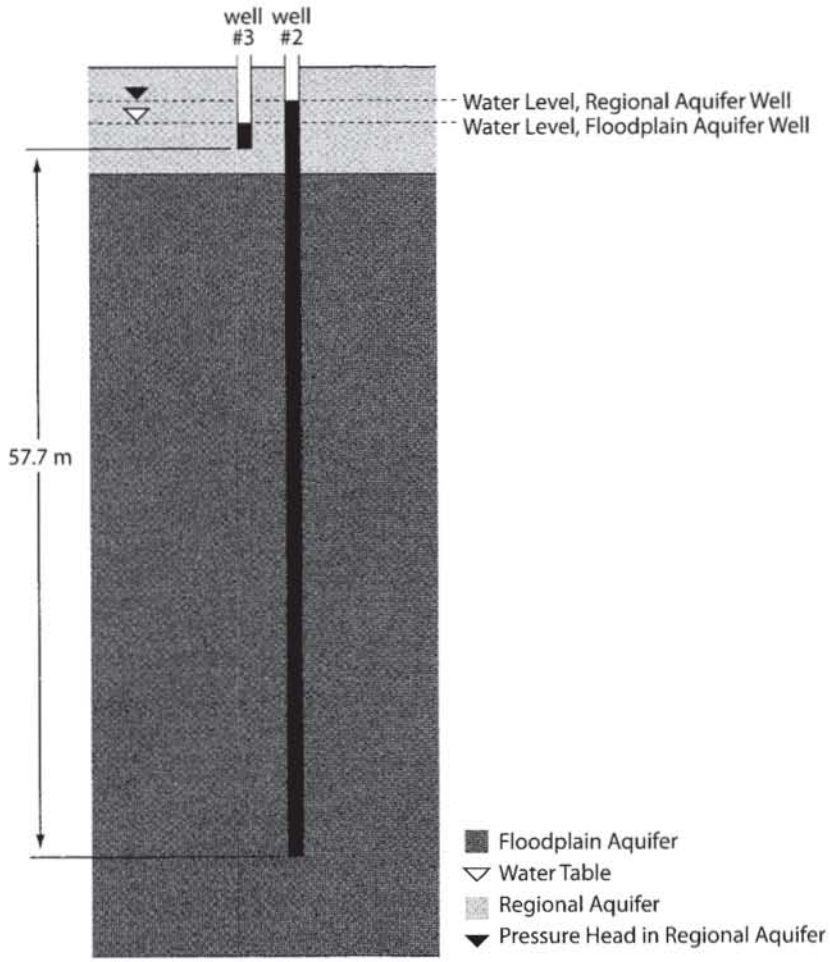
at Tombstone, which dates bask to the 1910s [B. Thomas and Pool 2006] although this decline may be an artifact of temporal changes in the location of this precipitation gaging station within the topographically diverse vicinity of Tombstone.) Near the mountain fronts, where most recharge seems to occur and where water tables are highest, these dry and wet periods can have significant effects on the elevation of the water table, with changes of 10 m or more possible (Pool and Coes 1999). These dramatic fluctuations in water levels become muted as water moves away from the recharge area, with water levels staying more constant during dry and wet periods, unless such periods extend for more than a decade. Thus, the amount of water reaching the stream or the floodplain aquifer from the regional aquifer is reasonably constant over time. In the lower San Pedro basin, the shorter distances from the recharge areas to the stream may reduce the dampening effects of distance described above.

GROUNDWATER FLOW PATHS

Like surface water, groundwater flows from higher elevations toward lower elevations due to the force of gravity. So, by ascertaining the slope or gradient of the water table, one can determine the direction of groundwater flow. This is accomplished by finding the elevation of the water table in a number of places, and then constructing a map with contours that show points of equal elevation of the water table.

Regional aquifer flow paths. Although the layers of clay present in some parts of the regional aquifer cause the water to follow a convoluted path, water in the regional aquifer flows toward, and ultimately reaches, the riparian corridor. This flow has both lateral and vertical components. Figure 15.3 shows the water levels in a pair of wells about 46 m west of the San Pedro River channel in the riparian corridor at Lewis Springs, east of Sierra Vista. Well #2, which penetrates to a depth of about 70 m in the regional aquifer, has a higher water level than well #3, which penetrates to about 7.3 m and taps the floodplain aquifer. Artesian pressure in the regional aquifer causes water in well #2 to rise above the levels of the water table in the floodplain aquifer. The difference in elevation of the two water levels divided by the 57.7 m that separate the opening of each well to the aquifer is the vertical gradient moving water upward from the regional aquifer into the floodplain aquifer.

Floodplain aquifer flow paths. Water in the floodplain aquifer predominantly flows in a downstream flow direction. Superimposed on this downstream gradient or slope on the water table are smaller gradients toward or away from the stream. The direction of these smaller lateral gradients changes with the carrying capacity of the floodplain aquifer. Where the floodplain aquifer is



In May 1998, the average difference in water levels in the two wells was 1.88 m
The average vertically upward gradient was 0.033 m/m

Fig. 15.3. Well pair at Lewis Springs site demonstrating the vertical gradient moving water from the regional aquifer to the overlying floodplain aquifer.

wide and/or thick, it can transport all the groundwater discharged from the regional aquifer, but where the aquifer narrows, or thins, it can't transport all this water, and so the stream transports what the aquifer cannot.

When the stream enters a reach where the floodplain aquifer widens or thickens, water moves into the aquifer from the stream; water-level contours show that water is moving laterally away from the stream as well as in a downstream direction (fig. 15.4). Such reaches are described as losing reaches as streamflow diminishes downstream. In reaches where the floodplain aquifer is getting thinner and/or narrower, water moves back toward the stream, as well as downstream. In these gaining reaches, streamflow increases downstream. In such reaches, the consistent presence of baseflow supports the designation of a perennial reach (see fig. 0.4 in Introduction). The presence of losing reaches creates complexities in trying to estimate the relative importance of various water sources for both the stream and the floodplain aquifer. The

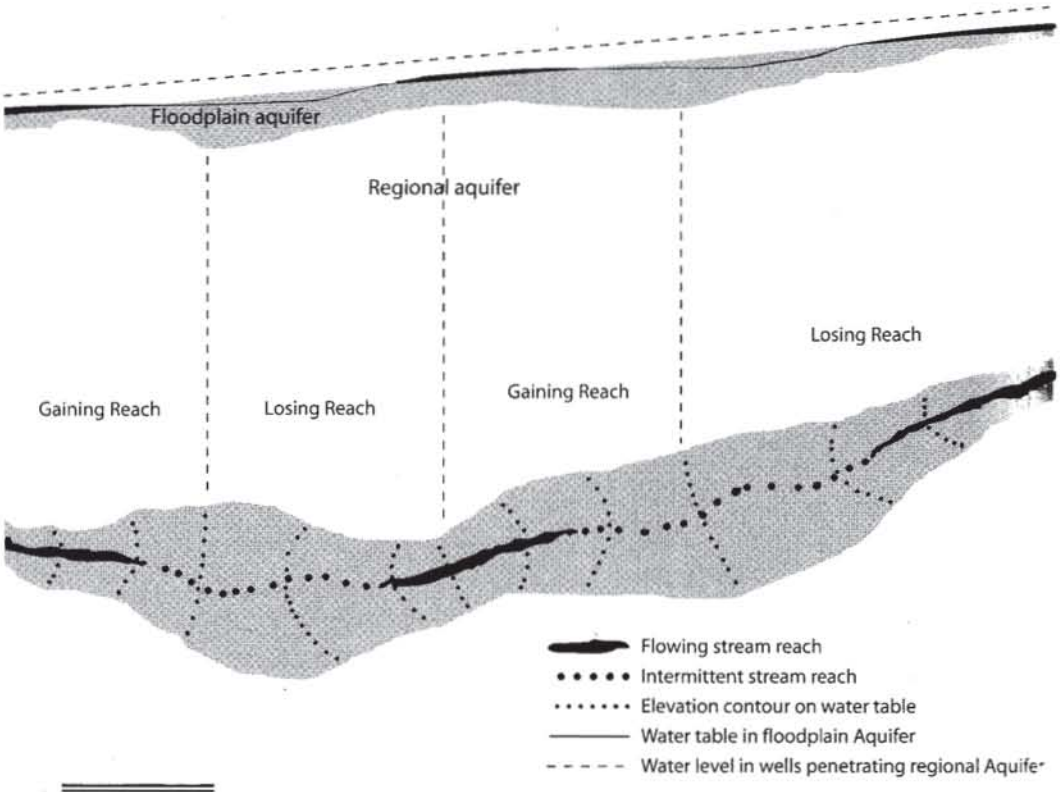


Fig. 15.4. Cross-sectional and plan views of the floodplain aquifer in gaining and losing reaches. Contours that are convex in a downstream direction show water is moving away from the stream. Contours that are concave in the downstream direction show that water is moving toward the stream.

complexities stem from the injection of storm runoff and baseflow contributions from an upstream gaining reach into the floodplain aquifer in losing reaches.

GROUNDWATER-SURFACE WATER INTERACTIONS IN THE FLOODPLAIN AQUIFER

When storm runoff arrives at a stream, the elevation of the stream surface is raised because of the additional flow. In the main channel, if the streamflow produced by this runoff exceeds a predefined threshold, it is considered a peak-above-base (flood peak) even if the flow stays confined within the channel banks. In a gaining reach, this increase in elevation of the stream surface serves to reverse the gradient of the water table, causing groundwater to cease discharging to the stream. The groundwater a little farther away that was still moving toward the stream suddenly can no longer move toward the stream, and so the water levels rise in the floodplain aquifer. This increase is described as bank storage or streamflow that has entered the aquifer. In gaining reaches, the amount of streamflow entering the aquifer is very small, with almost all the increase in water levels in the floodplain aquifer due to the backwater effect of the rising stream surface on the groundwater discharge. In contrast to this, in losing reaches, virtually all of any increase in water levels in the floodplain aquifer is due to stream water entering the aquifer.

As the length of perennial reaches in the San Pedro River has diminished since development of the basin's water resource began, the losing reaches have expanded, providing more aquifer space to capture surface waters during runoff events. In some losing reaches this may currently be the primary support of the riparian ecosystem. These recharged floodwaters also may be contributing to baseflow in a gaining reach downstream.

Effects of Wells Pumping Groundwater

CONES OF DEPRESSION

When a well is pumped, water moves into the well bore from the surrounding aquifer to replace the volume that was pumped out. A cone-shaped gradient or slope, called a cone of depression, is created as the water surface in the well is drawn down by the pumpage (Chow 1964) (fig. 15.5). The cone of depression continues to expand until the amount of water entering the cone balances the amount of water being pumped. Water can enter the cone of depression from various sources: laterally from the surrounding aquifer or stream channel; vertically downward from a usually dry, but sometimes wet, stream channel; or through human structures including leach fields, downspouts on buildings, and recharge basins. When there are multiple wells pumping water from the same aquifer, as in the Sierra Vista subbasin, the cones of depression of each well coalesce in such a way that the decline in the water level at a point is the sum of the incremental declines caused by each well affecting that point.

Although early data on water levels in the basin are sparse, contour maps of the groundwater table have been assembled depicting the water table configuration before significant pumping began (Goode and Maddock 2000). Prior to the development of the deep well turbine pump in the 1940s, the only large-capacity pumps were centrifugal pumps. So while they could pump large quantities of water, their suction lift was limited to about 5 m. Because the depth to water exceeded 5 m in most areas of the basin, even in much of the San Pedro riparian corridor, the water table was too deep for large-capacity pumps. Because wells pumping large amounts of water were non-existent prior to the 1940s, the water table that existed at that time is considered to be the natural or pre-development condition of the water table (also described as the steady-state condition). In some parts of the basin, development of water supplies from wells did not occur until the 1960s, and in these areas, 1960-era water levels are considered to be representative of steady-state conditions.

A recent (1997) map demonstrates the changes that more than 50 years of groundwater pumping have caused in the water table (Goode and Maddock 2000). When the differences in water table elevation from the steady state (1940) to 1997 are plotted, it is evident that the areas of the greatest pumping

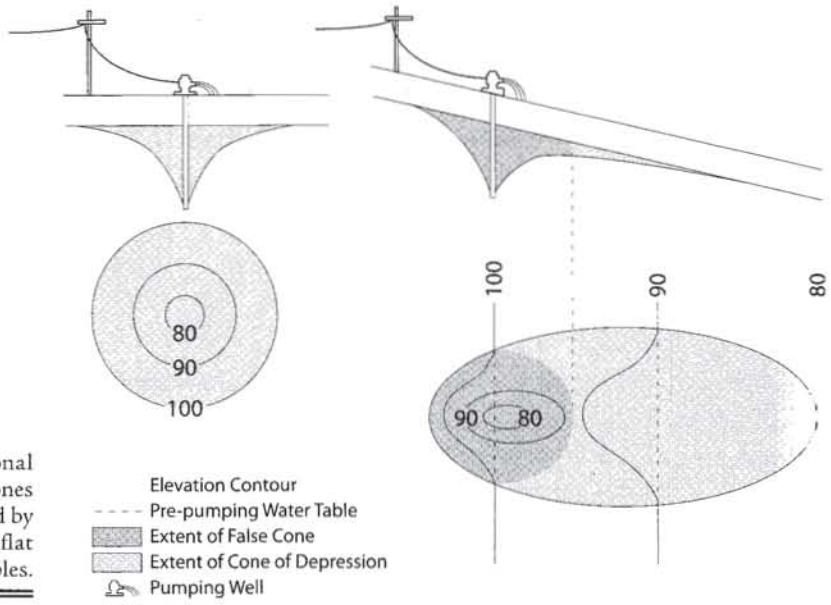


Fig. 15.5. Cross-sectional and plan views of cones of depression formed by pumping wells on flat and sloping water tables.

show the greatest declines (fig. 15.6). While discussions of cones of depression generally address major pumping centers, the composite cone of depression is literally basin wide in the regional aquifer. This map can also be used to estimate the reduction of the volume of water in the aquifer (also called groundwater mining) caused by pumping.

GROUNDWATER BUDGETS

Since 1974, groundwater models have been constructed to evaluate the groundwater resource and its management opportunities in the upper San Pedro basin, and in the Sierra Vista subwatershed in particular (Arizona Water Commission 1974, Freethey 1982, Villnow 1986, Putman et al. 1988, Rovey 1989, Vionnet and Maddock 1992, Corell et al. 1996, Goode and Maddock 2000). All groundwater models require the development of a conceptual water budget to test and evaluate. Mathematical models simulate the movement of water through a hydrologic system, and the modeler adjusts assumptions made for model values that could not be measured to achieve a best fit with values that could be measured, such as baseflow and water levels in wells.

Water budgets have several components, only some of which can be measured directly. The amount of groundwater discharged to the stream as baseflow, and the amount of groundwater pumped by water companies, municipalities, and military installations, are among those that can be measured directly. Some components—such as domestic well pumpage, riparian evapotranspiration (see chap. 2), and ephemeral stream recharge—can be inferred or estimated from partial measurement and extrapolation. The largest unmeasurable budget component is the groundwater recharge that occurs mainly at or near the mountain front. Coes and Pool (2005) estimated

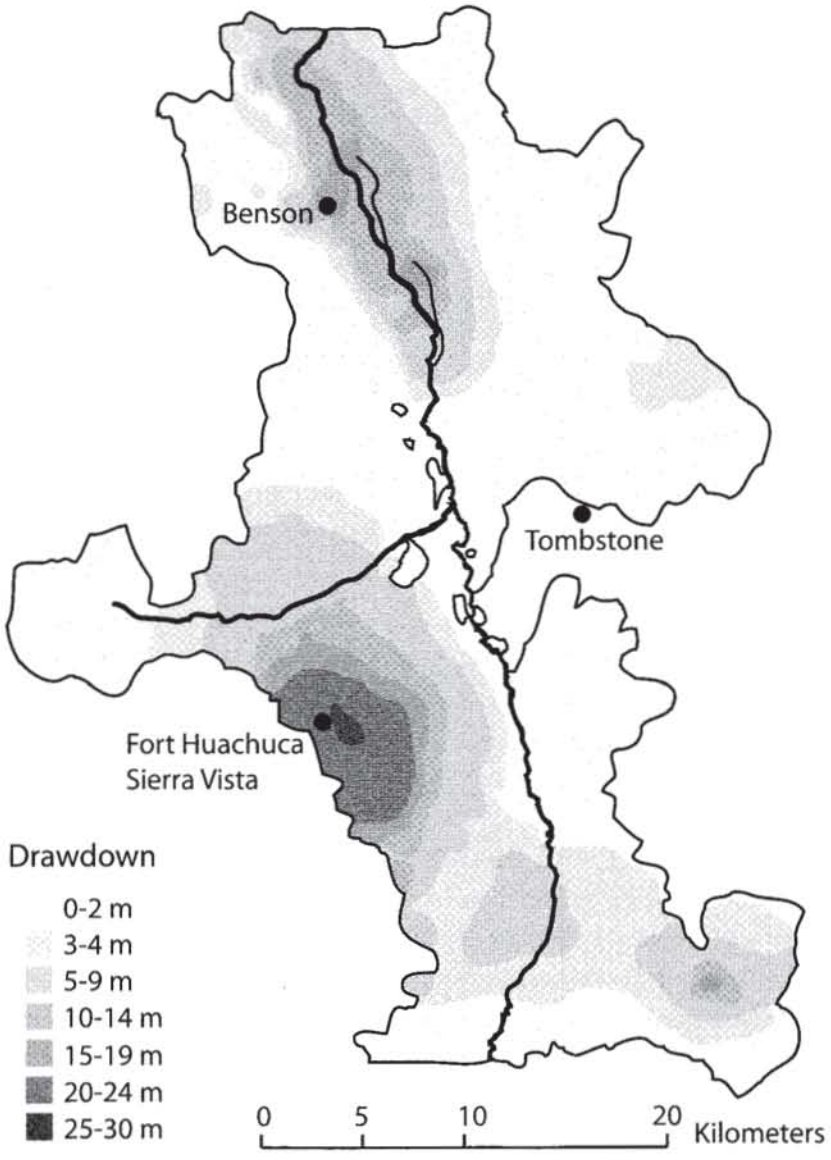


Fig. 15.6. Drawdown from 1940 to 1997 in the regional aquifer in the upper San Pedro basin (after Goode and Maddock 2000).

the relative volumes of recharge occurring under ephemeral stream channels crossing the regional aquifer, and in the future, isotopic and chemical signatures may help to further describe recharge distribution by source throughout the aquifer systems. Two smaller budget values that cannot be directly measured are inflows to, and outflows from, the basin as groundwater from adjacent basins upstream and downstream.

Measured and estimated budget values for the Sierra Vista subbasin are shown in table 15.1. It is important to note different authors use different methods and assumptions to prepare such water budgets, and even single authors may use different techniques when preparing multi-year budgets depending on the availability of data. Thus, great significance should not be placed on changes over time in budget values that are not directly measurable. Several

TABLE 15.1. Water budget values for the Sierra Vista subbasin.

Budget item	Vionnet and Maddock (1992)[1]	Corell et al. (1996)[2]	USDI (2006)[3]
Mountain front recharge	15,480,000m^3	19,360,000m^3	18,500,000m^3
Underflow from Mexico	4,600,000m^3	3,700,000m^3	3,700,000m^3
Riparian ET	9,740,000m^3	8,730,000m^3	9,500,000m^3
Baseflow out	3,080,850m^3	7,955,958m^3	4,000,000m^3
Underflow out	1,150,000m^3	543,000m^3	543,000m^3
Pumpage	16,874,030m^3	13,760,720m^3	20,350,000m^3
Groundwater "mined"*	7,929,672m^3	10,764,880m^3	12,193,000m^3

[1]Data estimates for 1988.

[2]Data estimates for 1991.

[3]Data estimates for 2002.

*Groundwater "mined" is a measure of the deficit between water entering the groundwater system and leaving it in that year.

budget values that are measurable (pumpage and baseflow) have changed considerably over time. In figure 15.7, the shaded area between total inflow and total outflow represents the extent of groundwater mining, or the groundwater budget deficit. It is noteworthy that the groundwater deficit is increasing on an annual basis.

EFFECTS OF THE COMPOSITE CONE OF DEPRESSION ON BASEFLOW

Even though the large pumping centers are several kilometers from the river, the near-basin-wide extent of the composite cone of depression is a powerful argument that groundwater pumping is creating the groundwater deficit and contributing to the declining baseflow of the upper San Pedro River. Temporally, the groundwater deficit tracks the amount of groundwater pumpage, and both are inversely related to the amount of baseflow (fig. 15.7). Patterns in a series of flow duration curves, which show the percentage of time, by decade, that streamflow equaled or exceeded a particular value, also are consistent with the idea that groundwater pumping is affecting San Pedro streamflow (see fig. 16.2). The stream is at or near baseflow about 40 percent of the time, and the portions of the curves to the right of the 60 percent gridline thus show the pattern of depletion. The first decade (1936–1945) represents pre-development flow conditions. Agricultural pumping for irrigation close to the stream in the Palominas–Hereford area is generally agreed to be primarily responsible for reducing baseflow prior to 1956 (Corell et al. 1996), and the 1946–1955 decade curve shows the effects of that near-stream pumpage. Depletion continued in subsequent decades but did not accelerate until the last two decades, when the effects of distant pumping as well as expanding domestic pumping throughout the subwatershed started impacting the stream. While the flow duration curves portray streamflow

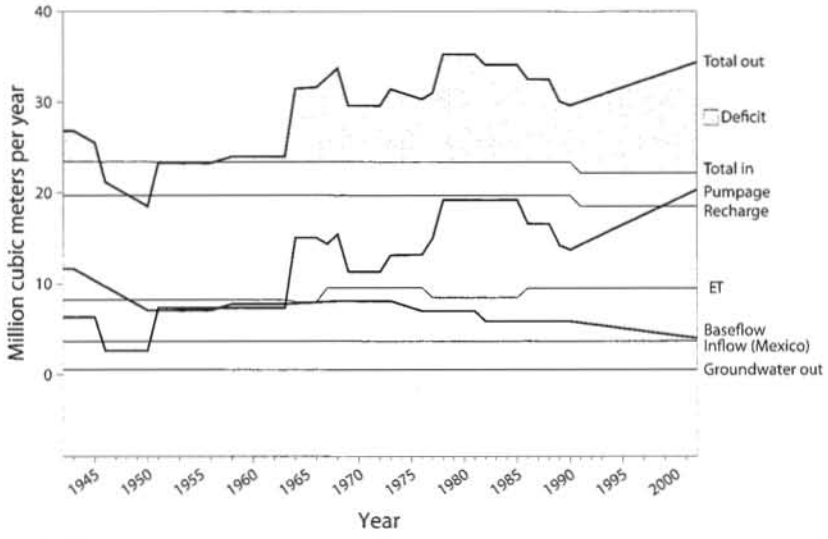


Fig. 15.7. Groundwater budget for the Sierra Vista subwatershed. The shaded area shows the deficit between supply and demand. Data from 1942 to 1990 from Corell et al. (1996); 2002 data from USDI (2006).

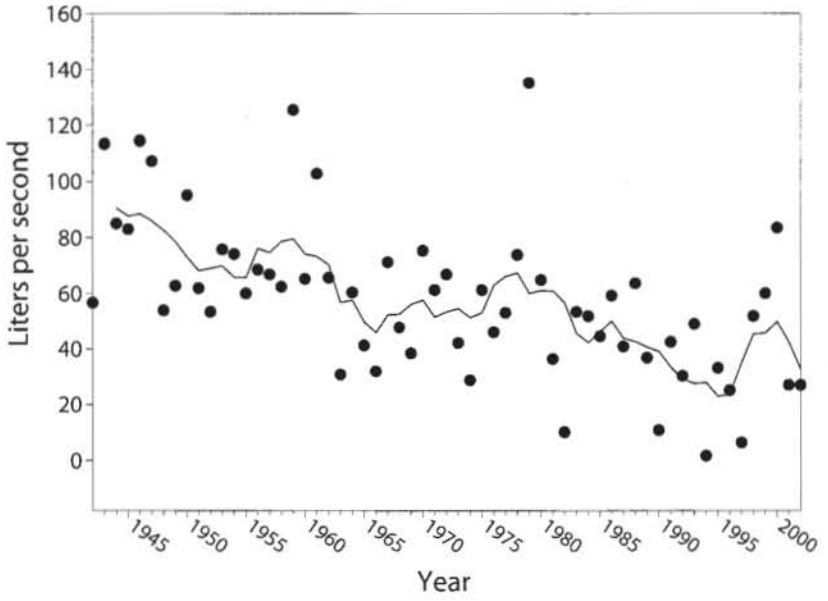


Fig. 15.8. Changes in baseflows in the upper San Pedro River. Annual seven-day low flows for the San Pedro River at Charleston, with a five-year moving average of the annual data to show trends. The seven-day low flow typically occurs in June, before the onset of the summer monsoon season.

depletion, the nature of the plot makes it difficult to decipher what is happening at the very lowest levels of streamflow. By using the average flow in the seven consecutive days of lowest flow each year (annual seven-day low flow) as an index of baseflow discharge, one sees that the baseflow has declined to about one-third of its amount in the early 1940s (fig. 15.8).

Empirical data from groundwater wells also support our contention that groundwater pumpage is a key cause of baseflow decline. Recent data from Lewis Springs, where there are two pairs of wells penetrating the floodplain and regional aquifers, show that since 1997, there has been a 15 to 20 percent reduction in the amount of water moving from the regional aquifer to the floodplain aquifer and thence to the stream (fig. 15.9). This figure demonstrates that the Lewis Springs area is being affected by the expanding cone

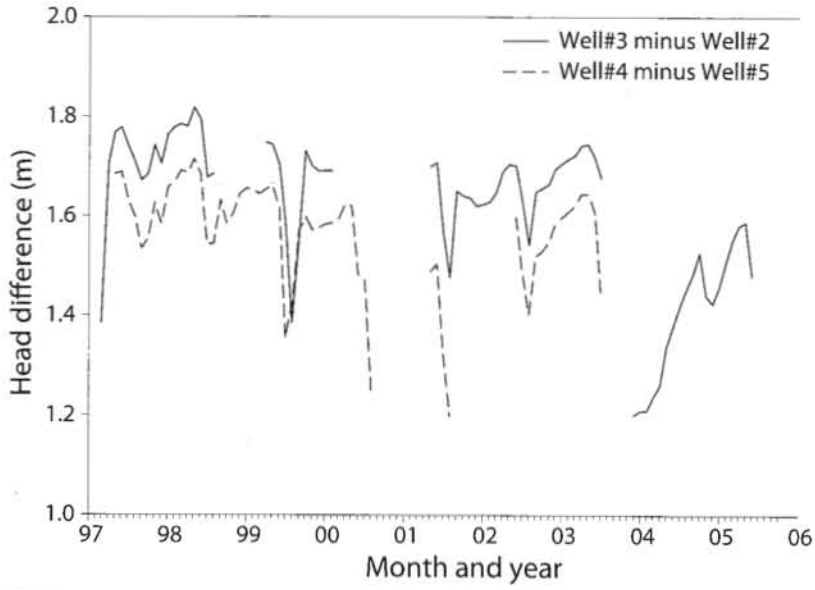


Fig. 15.9. Vertical head differences between the regional and floodplain aquifers in two well pairs at Lewis Springs: well #5 (~61 m deep) and well #4 (~7.3 m deep), and wells #2 and #3 (see fig. 15.3), from March 1997 through June 2005. Both well pairs show similar reductions in the upward vertical gradient from the deeper well. Wells #4 and #5 are within 10 m of the San Pedro river channel (on the west bank) and about 40 m east of wells #2 and #3.

of depression centered on Sierra Vista/Fort Huachuca, which is reducing the hydraulic gradient that moves water toward the river. As figure 15.5 shows. the cone of depression of a pumping well on a sloping water table may extend quite a distance in the down-gradient direction. (Sharma et al. 1997) noted that over the period 1985–1997, baseflow near Lewis Springs showed a slight increase attributed to a substantial reduction in agricultural pumping upstream, while farther downstream there was a reduction in baseflow, presumably due to groundwater pumping.

Some have hypothesized other causes for baseflow decline, including climatic and/or riparian vegetative changes (Thomas and Pool 2006). There have been significant declines in summer precipitation during recent decades. and such climatic changes may be influencing the stream baseflows, though no mechanism explaining such an effect has been postulated. Expansion of the riparian forest following historic channel entrenchment (see chap. 12) also may be a contributing factor, but the extent of this effect has not been definitively determined.

RECENT STREAMFLOW DECLINES

Starting on July 9, 2005, and continuing until the summer monsoon rains began on July 16, the U.S. Geological Survey stream gage at Charleston recorded zero flow for the first time since the gage was established at that site in 1942. A recent analysis by R. Koehler (written communication, 2005)

based on the period of record for the Charleston gage from 1935 concludes that winter baseflows may reach a zero flow level at Charleston as early as 2010. As noted earlier in this chapter, there may be increased contribution to baseflow from floodwater infiltrating the floodplain aquifer in losing reaches. Though that mechanism provides a new source of water to sustain baseflow, it has not been sufficient to compensate for the diminishment of baseflow from groundwater discharge.

Should the present annual deficits continue their current trend (fig. 15.7), the composite cone of depression will continue to expand and deepen, and consequently, less and less water will reach the riparian corridor, baseflows will cease, and flow in the river will be driven entirely by occasional flood pulses. If tomorrow there were a catastrophic failure of the Western power grid and all groundwater pumping in the basin ceased, the cone of depression would continue to expand, even as it started to recover in the deepest parts of the cone, and, in the absence of effective mitigation, would create the same scenario for the river. If the power grid was never fixed, the hydrologic system would slowly recover to something approximating the conditions in 1940, but as a study of a groundwater mining operation planned in the Safford Valley demonstrates (USBLM 2003), this recovery process may take centuries.

Summary

The riparian ecosystem of the San Pedro basin, and the baseflows in the stream itself, are dependent on the discharge of groundwater from the regional aquifer, which in turn depends on rainfall. Though annual rainfall has fluctuated with decade-long wet and dry periods, the long-term average annual rainfall displays no obvious trend, and the great distance between the recharge areas near the mountains and the stream serves to modulate these short-term fluctuations; thus, the discharge from the regional aquifer to the riparian corridor under natural conditions would be nearly constant. Groundwater pumping in the basin has increased significantly over the last half century, and in the Sierra Vista subwatershed, groundwater pumpage now exceeds the rate of natural recharge. As most of the groundwater pumping is located between the recharge areas and the river, the pumps are intercepting water that otherwise would reach the riparian corridor. While the full impact of this pumping has not yet been felt at the river, the baseflow discharge of the river has diminished by 66 percent since 1942. As the full effects reach the river, baseflow will cease, as it did briefly in 2005 for the first time in the history of the Charleston stream gage. To preserve the river's flow, mitigation must involve elements designed to block the expansion of the basin-wide cone of depression in the riparian corridor.