WATER FOLLIES

Groundwater Pumping and the Fate of America's Fresh Waters

ROBERT GLENNON

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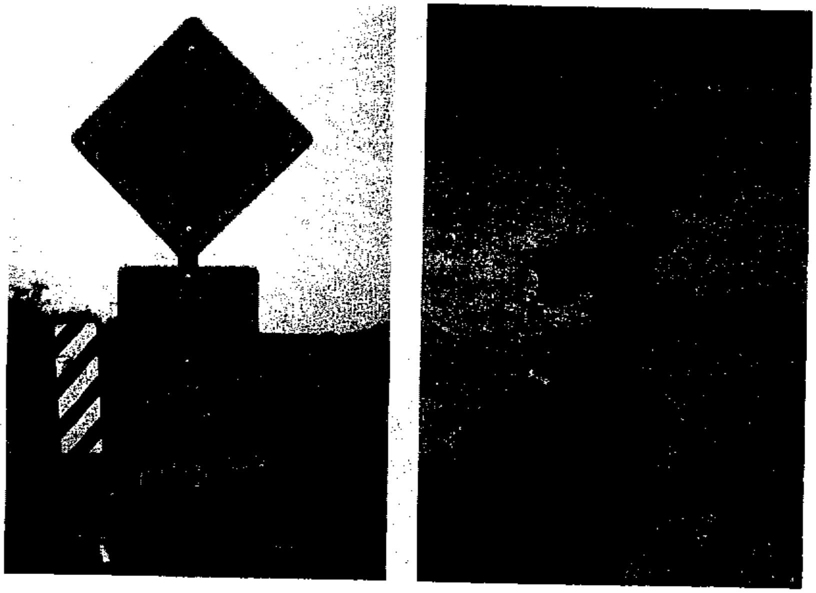

Figure 2.4. Sign warning motorists of subsidence hazard was erected after an earth fissure damaged a road in Pima County, Arizona (left). Earth fissure near Picacho, Arizona (right). Photographs courtesy of the U.S. Geological Survey.

ables, but often, cracks in the earth's surface, called fissures, appear. In southern Arizona, some fissures measure ten feet wide, fifty feet deep, and several miles long.

Subsidence at the surface can damage homes and commercial structures and reduce property values. Underground, this settling process compacts the soil and reduces the storage capacity of the aquifer, impeding natural recharge. Land subsidence is a serious problem in Florida and coastal areas of east Texas, including the cities of Houston and Galveston, where groundwater pumping has caused significant subsidence that increases the risk of flooding and makes coastal areas more vulnerable to destructive tidal surges from hurricanes. Land subsidence caused by groundwater pumping is hardly a new phenomenon. That's what happened to Ubar.

The final consequence of groundwater pumping is its impact on surface water, including lakes, ponds, rivers, creeks, streams, springs, wetlands, and estuaries. These consequences range from minimal to catastrophic. As an example of a catastrophe, consider the Santa Cruz River.

Chapter 3

How Does a River Go Dry?

The Santa Cruz in Tucson

"All streams flow into the sea;
yet the sea is not full.
To the place the streams come from,
there they return again."
—Ecclesiastes 1:7

Driving west from Tucson, Arizona, toward the Tucson Mountains, you reach a bridge and a sign that reads "Santa Cruz River." As you glance at the fifty-yard-wide stream channel below the bridge, you're struck by an incongruous sight. There is no water in the Santa Cruz River. The channel is an expanse of dry sand. When tourists see the dry river, they chortle: "In Arizona, even rivers look like a desert!" However, the Santa Cruz through Tucson was not always a dry wash. Not too long ago, it had perennial flow in some sections and intermittent flow in others. In the uplands, adjacent to the river, stood enormous stands of mesquite trees and, along the banks, cottonwood and willow trees formed a lush riparian corridor that shaded the river and provided wonderful habitat for birds, small game, and even deer, coyote, bobcats, and an occasional mountain lion. But groundwater pumping has lowered the water table, drained the river of its flow, killed the cottonwood, willow, and mesquite trees, and driven much of the wildlife elsewhere. Today, the river flows only during spring snowmelt, during heavy rains such as the summer monsoon, or because of the release of effluent from the city's treatment plant. The Santa Cruz in Tucson is a dry river, an oxymoron.

Located in the Sonoran Desert, Tucson is approximately 2,500 feet above sea level and receives twelve inches of rain in a typical year (compared, for instance, to the state of Michigan, which receives thirty-five inches). Although the rainfall may seem modest, some southwestern deserts receive an average of three inches of rain per year. As a result, the habitat includes large numbers of mesquite and palo verde trees, shrubs, wildflowers, and animals, making the Sonoran the most diverse of North America's deserts.

Tucson sits in an alluvial valley rimmed by five mountain ranges that provide beautiful vistas, forests of pine and aspen trees, cool retreats from the summer heat, and even a ski resort. The higher mountains, particularly the Santa Catalinas, the Rincons, and the Santa Ritas, receive an average of thirty to forty inches of rain per year. During spring snowmelt, mountain creeks fill with water that tumbles down to the valley below, filling the Santa Cruz River that runs north through Tucson. The headwaters of the Santa Cruz River are in the Patagonia Mountains in southern Arizona, and the river first flows south into Mexico; it then loops back and reenters the United States. It continues north up a valley between the Sierrita Mountains to the west and the Santa Rita Mountains to the east. It passes through the San Xavier Indian Reservation, a division of the Tohono O'odham Nation, past an eighteenth-century mission, San Xavier del Bac, and then through the city of Tucson. North of Tucson, the river veers west and eventually flows into the Gila River near Phoenix.

The Santa Cruz River provided the impetus for original settlements in Tucson, first by Native Americans, then by Hispanic missionaries and settlers. Indeed, the word "Tucson" derives from a Tohono O'odham word, *stook-zone*, meaning "water at the foot of black mountain." The Santa Cruz River's perennial flows fostered self-sufficient agricultural communities whose principal crops included corn, beans, squash, and cotton. Recent archaeological discoveries have determined that Tucson was populated during the Late Archaic period—8,000 B.C. to 150 A.D.—by skilled farmers, not just hunters and gatherers. These prehistoric farmers were followed by the Hohokam, whose civilization thrived until about 1450 A.D. Their descendants, the Tohono O'odham, continued to live in the Santa Cruz valley, where they developed a quite clever farming technique known as *ak chin*. Immediately after the spring floods began to subside, Tohono

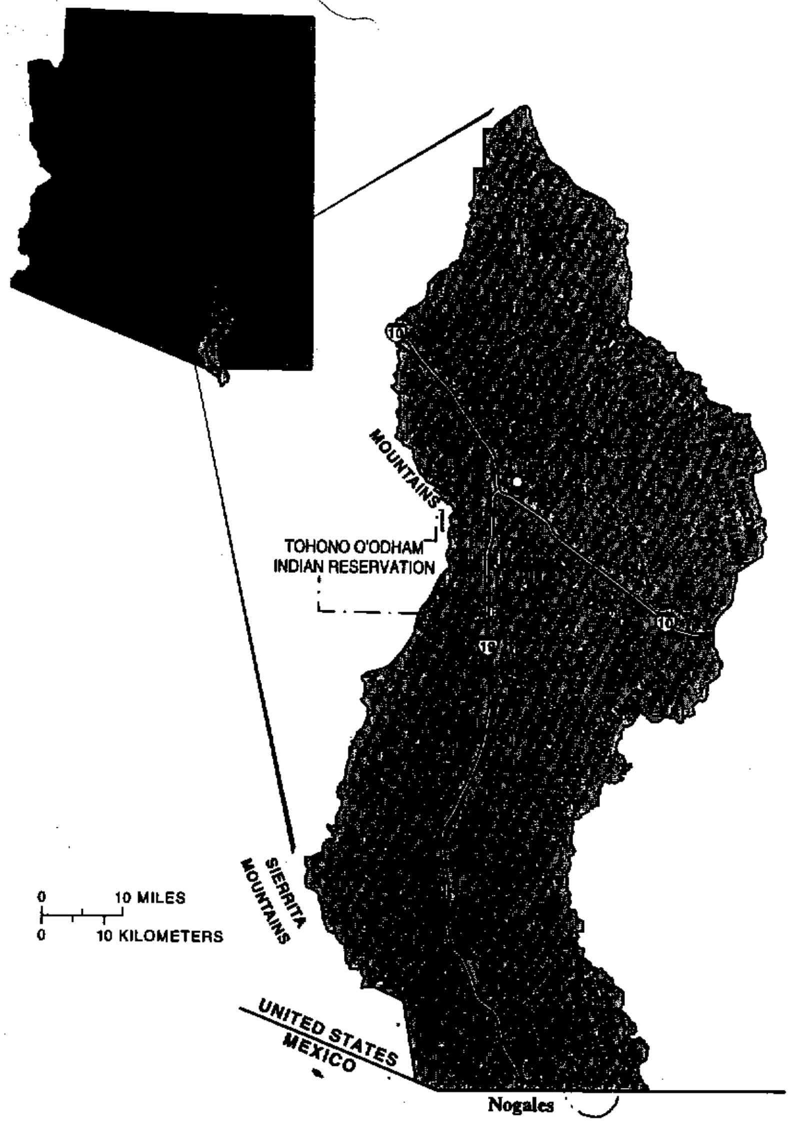

FIGURE 3.1. The upper Santa Cruz River basin in southern Arizona.

O'odham farmers would rush into the fertile floodplain and plant seeds of beans, squash, melon, and cat's claw (a vine used for weaving baskets).

In the late seventeenth century, the first Spanish settlers arrived, led by a Jesuit missionary, Father Eusebio Francisco Kino, who founded the mission at San Xavier del Bac. Father Kino introduced livestock grazing to the Santa Cruz valley, as well as new crops, including wheat, barley, oats, carrots, onions, and fruit trees. Unfortunately, the Europeans also brought with them diseases to which the Native Americans were vulnerable. The Indian population in the valley decreased by 95 percent between 1700 and 1800.

With the discovery of gold in California, the Old Pueblo, as Tucson came to be known, became a trading center and a stopping point for travelers heading west as well as north. Travelers entering Arizona from the east preferred this route, known as the southern route or the Gila Trail, because travel across northern Arizona meant confronting the Grand Canyon, while travelers across central Arizona encountered the rugged White Mountains and Mogollon Rim, areas controlled by Apaches, with whom there were increasing feuds. With the arrival of stagecoaches in the 1850s, the end of war with the Apaches in the 1870s, and finally, the completion of the Southern Pacific railroad system in the 1880s, most pioneers eventually opted to select one of the more northern routes. Tucson's era as a trading center had faded.

In the nineteenth century, giant cottonwood trees, smaller willow trees, and shrubs grew along the banks of the Santa Cruz River, creating a rich riparian environment that attracted myriad bird species and abundant wildlife. The diaries of early explorers describe a river full of "fish and tortoises of various kinds." Beaver, muskrat, and waterfowl were common. On the upland areas, mesquite bosques (near-river forests) covered vast areas. Nineteenth-century travelers described a valley covered with poplar, willow, ash, oak, and walnut trees. In the nineteenth century, two dams built across the river created Silver and Warner Lakes. The impounded water powered two gristmills to supply flour and a small stamping mill to process ore from nearby mines. The lakes became popular recreational spots, provided opportunities for waterfowl hunting, and sustained a commercial fishing venture.

Also in the late nineteenth century, new groundwater pump technology opened the way for more intensive use of water for agriculture in the Santa Cruz Valley. Alfalfa for cattle and wheat for human consumption grew well in the valley but demanded large-scale irrigation efforts. So too did pecan and citrus trees. The increased irrigation caused the water table to drop to a depth the technology could not reach. This decline, in turn, prompted farmers to dig crosscut ditches across the river in an attempt to collect more subsurface water. In the 1890s, heavy rains flooded the river and the ditches caused what hydrologists call entrenchment: the degradation of the river channel by a scouring process that lowers the river bottom and leaves steep or vertical banks along the sides. As the soil dries out, the banks collapse and the river channel becomes wider and deeper.

The European settlers contributed to the further degradation of the river when they cut trees to clear fields, build homes, fuel fires, and operate groundwater pumps. The removal of trees from a riparian zone severely impacts the river. Trees, shrubs, and grasses along rivers and creeks, as well as adjoining wetlands, slow the flow of water, which is particularly important during high flows or floods. Put simply, without trees, shrubs, grasses, and wetlands, rainwater enters the river channel more quickly and produces a more intense flood. The flooding process itself further abrades the river bottom, thus exacerbating the entrenchment process. Even though these human activities degraded the Santa Cruz River, the river remained relatively healthy and supported perennial flows until the 1940s; there were cottonwood-willow forests adjacent to the river and huge mesquite bosques on the upland areas. The Tohono O'odham still grew beans and corn in the fertile floodplain.

Today, the Santa Cruz River is but a sad mirage of a real river. The cottonwood and willow trees that once lined the river have died, as have the stands of mesquite, poplar, and oak. The birds and wildlife have gone away. The river has died. What happened? To answer this question and to understand the stories that follow, we must understand how water moves.

As the author of Ecclesiastes understood, water goes through a succession of different phases, called the hydrologic cycle. Fueled by the energy of the sun and the force of gravity, the hydrologic cycle continually moves water from the oceans to the land and back again. Oceans cover more than 70 percent of the earth's surface and absorb most of the sun's radiant energy. The sun's energy evaporates seawater, leaves behind the salts, and circulates the water into the atmosphere. Wind currents eventually carry the moisture-laden air over land, which sharply increases the relative humidity. As the relative humidity increases, the water vapor eventually

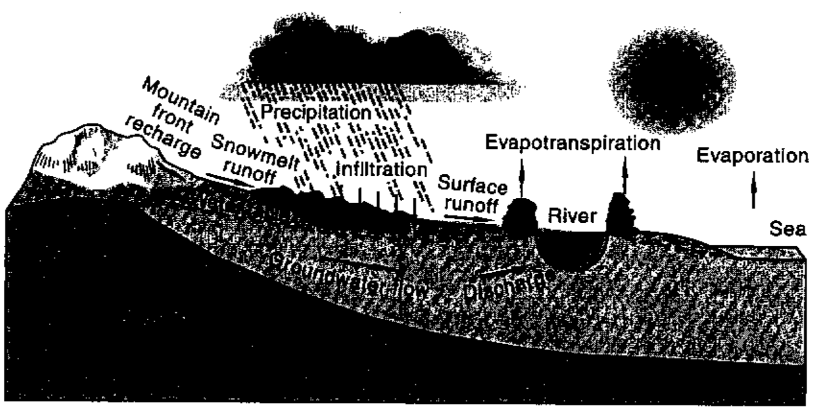

FIGURE 3.2. The hydrologic cycle.

condenses and becomes precipitation, in the form of rain, snow, or hail. As precipitation reaches land, the process of evaporation begins again and 50 percent of the precipitation returns directly to the atmosphere.

Three things happen to the other 50 percent. First, plants and trees absorb water from the soil through their roots but release water back into the atmosphere through their leaves, in a process known as transpiration. Second, the snowmelt or rain moves over the surface of the earth as gravity inevitably causes water to seek the lowest level. This surface runoff flows into creeks, streams, and rivers; eventually some water reaches the ocean, and the hydrologic cycle begins again. Third, and most importantly for our purposes, water percolates or infiltrates into the ground, in a process called recharge, where the water may remain for years, centuries, or even millennia. A portion of the groundwater near rivers and streams eventually emerges from the ground, in a process called discharge, to augment the surface flows of rivers or streams.

Less than 1 percent of the water in the hydrologic cycle is potable (drinkable). The oceans hold about 96.5 percent of the earth's water, though ocean water is clearly not potable because of its salinity. Of the remaining 3.5 percent, 1.7 percent is tied up in polar ice. Another 1 percent of freshwater is less saline than ocean water but still too salty to be drinkable. That leaves only 0.8 percent in lakes, marshes, and rivers, in the ground, and in the atmosphere. Equally surprising, most of this freshwater is not found in lakes, marshes, rivers, other surface water, or the atmosphere. It is groundwater! There is thirty times more potable water in the ground than there is in all the rivers and lakes on earth.

How does groundwater get into the ground? The movement of groundwater depends not only on gravity, but also on the particular geologic characteristics of what geologists call aquifers, subsurface geologic formations saturated with water. Most aquifers are composed of layers of fine sand and silt, larger gravel particles, fractured rock, and clay. In any particular geological setting, sediments or fractures produce interconnected voids that allow the transmission of water through the ground. Over the passage of millennia, water collects in aquifers—lots of water during wetter times such as the ice ages and less at other times. But aquifers are not static in their accumulation of water; their ability to accumulate water depends on recharge and discharge processes. Most recharge occurs when water from snowmelt and rainfall infiltrates the ground and percolates down to the aquifer. Over millions of years, recharge gradually added to the amount of water stored in aquifers. As the amount of water increased, some groundwater flowed from the aquifers toward rivers, creeks, or the ocean, where it discharged from the ground and joined the surface water. In the Santa Cruz River, water discharging from the aquifer sustained the river's perennial flow.

The character of an aquifer depends on the geologic history of the region. In the Santa Cruz River valley, a set of mountain ranges consisting of hard rock, such as granite, surrounds an alluvial valley. Beneath the valley floor is a hard rock formation called, reasonably enough, bedrock, which is impermeable to water flow. The alluvium—loose sediments hundreds of feet thick deposited on top of the bedrock—consists of sand and gravel eroded from the surrounding mountain ranges by wind and water. In the northern part of the United States, deposits associated with continental glaciers formed aquifers. With crushing force, glaciers moved south from the colder regions, grinding the bedrock over which they moved into sand, gravel, and even large boulders, only to leave this material in massive deposits called glacial till as the glaciers retreated in warmer millennia. In Texas, the Edwards Aquifer in the San Antonio region is an example of a large limestone aquifer. Water flowing through small limestone cracks over eons dissolved the limestone, and the cracks became fissures and even grew into caverns. Even harder rocks, such as granite and basalt (lava), can form aquifers if they are fractured.

An easy way to understand recharge and discharge from aquifers is to conduct an experiment with your bathtub. First, plug the bottom of the tub, then dump a couple of hundred pounds of sand into it. Your spouse may think that you have lost your mind but will come around once you announce that you are conducting an experiment in hydrology. If you haven't been committed to an institution by now, turn the water on and let it run for ten to fifteen minutes. This is the recharge. Now, let it alone for a day or so, telling your spouse to shower at the gym, and you will find that the sand at the top of the tub is virtually dry. Under the force of gravity, the molecules of water moved down through the sand and pooled up at the bottom, filling in all the spaces around the granules of sand. Every child who has ever played in beach sand as the tide receded knows that if you dig into moist or dry sand deep enough, you will "discover" water. If you take a kitchen spoon and dig into the sand in your tub, the level at which you hit water is the water table. Below the water table, the sand is completely saturated with water; above the water table, the sand contains air spaces or pockets. Water percolates through the sand in your bathtub in the same way that rain or snowmelt recharges an aquifer. Similarly, the water that drains from your tub resembles how an aquifer discharges water to a river. The bottom of the tub slopes gradually down toward the drain hole. If you remove the drain plug, the water will slowly move down the slope of the tub and out through the drain. The same thing happens when an aquifer discharges water. Where does that naturally discharged water go? To surface watercourses, such as the Santa Cruz River.

Groundwater and surface water are not separate categories of water any more than liquid water and ice are truly separate. The designations "groundwater" and "surface water" merely describe the *physical* location of the water in the hydrologic cycle. Indeed, ground- and surface water form a continuum. Groundwater may become surface water in some portions of a stream, and surface water may become groundwater in other portions. In most regions of the country, virtually all groundwater was once stream flow that seeped into the ground. The converse is also true but not obvious. Consider the following puzzle: where might water in a river come from if it has not rained in a while? No longer a puzzle to you: the water comes from groundwater that has seeped from the aquifer into the river, in what's known as baseflow.

Whether water flows from an aquifer to a stream or the other way around depends on the level of the water table adjacent to the stream. If the level of a stream is lower than the water table in the surrounding aquifer, water will flow from the aquifer into the stream. A stream that receives discharge from an aquifer is called a gaining stream. Conversely, if the level of a stream is higher than the water table in the surrounding aquifer, then water will flow from the stream toward the aquifer. A stream that recharges an aquifer is called a losing stream(figure 3.3).

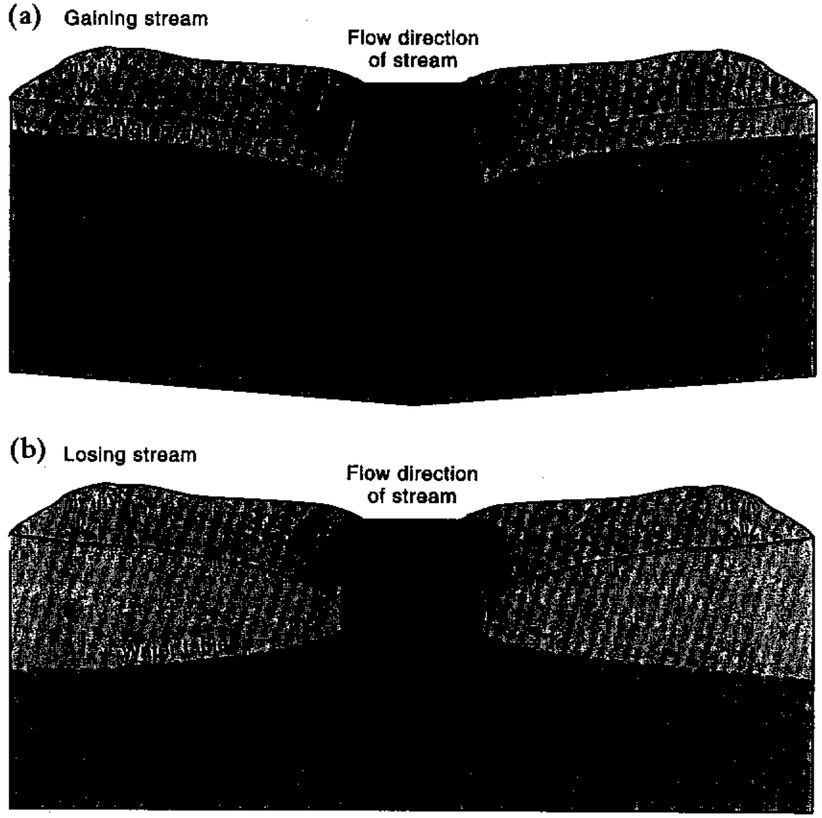

FIGURE 3.3. In a gaining stream (a), water discharges from the surrounding soil into the stream, but in a losing stream (b), water infiltrates the ground. Figures courtesy of the U.S. Geological Survey.

To understand baseflow and gaining and losing streams, consider those times when the basement of your house has flooded. After a very heavy rainstorm, your lawn turned into a small pond. Then water began to pour into the basement window wells through casement window frames, or the trap door, and down the walls, where it formed another pond at the foot of your basement stairs. At this point, you had two choices. You could immediately begin to mop up the mess. Or you could turn on the TV and hope that the waters would recede. Sometimes, quite remarkably, they did. Where did they go? Because your basement pond was the equivalent of a losing river, water seeped from the basement through cracks in the foundation into the aquifer—well, actually just the ground below and adjacent to your home. It was possible for water to drain from your house because the water table was below the basement floor.

But now recall a time when you went to retrieve your tennis racquet from the basement, only to find a small puddle in the corner by the workbench. You were surprised because it had not rained recently. Yet the nearby wall was wet and, on closer inspection, water slowly seeped through a crack in the wall. You were very annoyed, so much so that the lesson in hydrology completely escaped you. Your basement was the equivalent of a gaining river with water discharging from the aquifer into the river (the basement). This process is continually occurring in almost every river, but we can't see it because it usually occurs below the surface of the water in the river. Water can discharge into your basement if the groundwater table is above the bottom of your foundation. Under the force of gravity, water flowed to the lowest spot, which, alas, was through a crack in your wall. It is no surprise that houses with such seepage problems are more likely to be found in Houston—a low-elevation region with abundant rainfall—than in Denver—a high-elevation arid region. Even in your neighborhood, your next-door neighbor will have a more severe basement flooding problem if he or she lives downhill closer to a wetland.

The hydrologic cycle teaches us that water exists in different phases and locations. It migrates through a continuous cycle of existence as ocean water, evaporation, condensation, precipitation, infiltration, recharge, discharge, and evaporation again, as the cycle begins anew. For humans, the inherent problem with the hydrologic cycle comes from the physical distribution of the amount of water in each stage, such as rivers, lakes, and aquifers. Water is often not where we want it when we want it. Sometimes it flows seemingly inexplicably where we don't want it, like our basements. More often, we can't get enough of it when we need it. Therefore, we spend billions of dollars on dams, canals, and groundwater wells to move water, thereby altering the hydrologic cycle.

As we now know, it takes energy to move water. For centuries, farmers used muscle power or machines to divert surface water into canals or ditches to irrigate their fields. On a larger scale, humans altered surface water flows by building dams, an effort that requires enormous energy. Using energy to pump groundwater and alter the hydrologic cycle eventually dried up the Santa Cruz River.

When a groundwater well begins to pump water, the withdrawal usually exceeds the rate at which groundwater flows into the vicinity of the well. The withdrawal lowers the surrounding water table, which begins to slope toward the well and creates a cone of depression that looks like the vortex in a drain (figure 3.4a). The shape of the cone depends on several factors, especially the rate at which water is pumped and the permeability of the soil. Water flows more quickly through more permeable soil. As a result, the shape of the cone in this soil will be flatter. If the soil is less permeable, water will flow more slowly, and the shape of the cone will be steeper. If this shape seems incongruous, consider that water enters a well not only at the bottom of the well but also through all points in the screened section of the well shaft below the water table. In permeable soil, water quickly flows laterally to replace the water pumped out of the well. As a result, the cone of depression is relatively flat. In less permeable soil, the water level in the well drops because the lateral flow is too slow to replace the pumped water. A sharp drop in the level of water in the wall produces a steep cone of depression that may resemble an ice cream cone. The initial cone of depression is in the immediate area of the well. As the pumping continues, the cone grows and expands until it intersects a source of water to capture, such as a river or a stream. At this point, the cone draws water directly from the river or stream (figure 3.4b). The pumping has lowered the water table so that less water discharges into the river, thus decreasing the river's flow.

What ultimately killed the Santa Cruz River was groundwater pumping. Recharge from rain and snowmelt typically adds 140,000 acre-feet per year (af/yr) to the aquifer. Before groundwater pumping commenced, the aquifer discharged water into the Santa Cruz River. However, between 1940 and 2000, groundwater pumping jumped from approximately 50,000 af/yr to 330,000 af/yr. What prompted the increase in pumping?

Municipal pumping skyrocketed as the city of Tucson water department and private water companies drilled new wells to supply a population that grew from 14,000 in 1912 to 800,000 in 2000. Mining also played a major role because open-pit copper mines pump large quantities of groundwater. The third major user of groundwater in the Santa Cruz val-

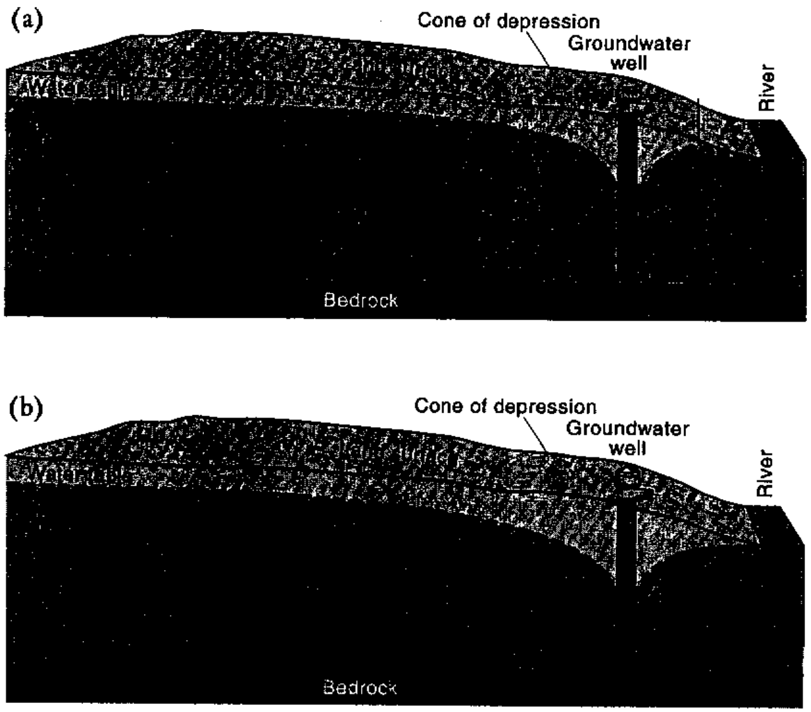

FIGURE 3.4. Under natural conditions, recharge to the water table is equal to discharge to the stream. In (a), the onset of groundwater pumping changes the equilibrium. Now recharge to the aquifer equals discharge to the stream *and* pumping from the well. Note the cone of depression created around the well by groundwater pumping. In (b), groundwater pumping has begun to draw water from the stream. Figures courtesy of the U.S. Geological Survey.

ley, as in every western state, is agriculture. Tucson provides a particularly hospitable climate for growing pecans, alfalfa, wheat, and especially Pima cotton, a soft, strong variety used in fine shirts and towels. As the population grew, the city, the mines, and the farmers collectively began to pump groundwater in an unsustainable fashion. In Arizona, groundwater pumping has dried up or degraded 90 percent of the state's once perennial desert streams, rivers, and riparian habitats.

When the city of Tucson, the mines, and the farmers began to pump groundwater, they introduced a new discharge process. The pumping captured water from the river, first indirectly, then directly. As illustrated in figure 3.4, the pumps intercepted water that had been moving toward the Santa Cruz River and, but for the pumping, would have discharged to the river. The pumping decreased discharge to the stream, increased the rate of recharge to the aquifer (by creating a partial vacuum that atmospheric pressure will refill), and drew on water stored in the aquifer. Note that the stream in figure 3.4a remained a gaining stream because it continued to receive discharge from the aquifer, but it receives less water than before the pumping commenced.

As Tucson's groundwater pumping increased exponentially, the water table plummeted 200 feet, creating significant land subsidence and damage to the foundations of homes and other buildings. As the water table dropped, groundwater pumping changed the relationship between the aquifer and the Santa Cruz River. As in figure 3.4b, groundwater pumping began to withdraw water from beneath and adjacent to the Santa Cruz River which, in turn, caused river water to infiltrate the ground. Once the water table declined below the level of the Santa Cruz River, water began to flow from the river to the aquifer. Groundwater pumping caused the annual flows of the river gradually to diminish and eventually to dry up completely. Groundwater pumping literally sucked the water out of the Santa Cruz River.

Another analogy may highlight the significance of this fact. Suppose you are a rational consumer (the science of economics, remarkably enough, is based on such assumptions). Second, I will assume that your income, on the average, is equal to your expenditures. I know this second assumption is equally unrealistic, as does anyone who knows anything about our national credit card debt. Nonetheless, suppose you crave a vacation on Maui. The vacation on Maui is the equivalent of groundwater pumping. What options do you have for paying for this little jaunt to Hawaii? You have three choices: (1) you can increase your income by moonlighting (increase recharge); (2) you can decrease your expenditures by forgoing fancy restaurants (decrease discharge); or (3) you can withdraw money from your savings account (draw from storage). Paying for the trip to Hawaii must result from some combination of an increase in income, a decrease in expenditures, and a reduction in savings. (I consider flashing plastic as a reduction in savings regardless of the number of frequent flyer miles that you receive.) Similarly, groundwater pumping must increase recharge, decrease discharge, or reduce the amount of water in storage. All three occurred in the Santa Cruz River valley.

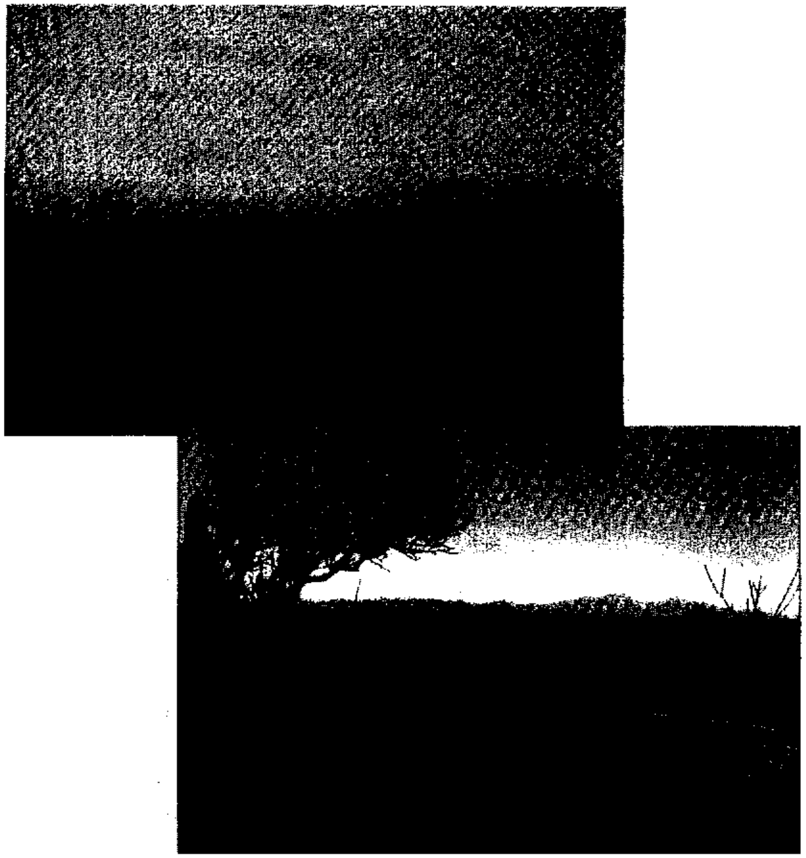

Figure 3.5. Two photographs of the same section of the Santa Cruz River south of Tucson, Arizona, one taken in 1942, the other in 1989. Photographs courtesy of the U.S. Geological Survey.

In addition to drying up the Santa Cruz River, the pumping has had another horrible environmental consequence. The once vast stands of cottonwood, willow, and mesquite trees died as groundwater pumping lowered the water table below the root zone of the trees. A lush riparian zone of tens of thousands of acres became a dismal expanse of sandy soil. Figure 3.5 reproduces photographs of a reach of the Santa Cruz River. The one on the top, taken in 1942, shows a dense stand of mesquite and cottonwood trees. By 1989, when the photograph on the bottom was taken at the same location (notice the rock in the foreground of both photos), the deciduous trees had died of thirst, and the river had become nothing more than a barren bed of sand.

Riparian conditions were made worse by the efforts of the U.S. Army Corps of Engineers to channelize the banks for flood control purposes. Today, the banks of the Santa Cruz River are cement-lined, a process that involves, first, the removal of existing trees and shrubs in and along the sides of the arroyo and, then, application of a mixture of cement and river soil to the banks of the river channel. The soil-cementing process inflicts great harm on our rivers, streams, and arroyos in the name of flood control. Instead of preventing floods, it quite perversely makes them worse. The river channel, more constricted by soil cement, funnels floodwater downstream with greater velocity and force. At whatever point downstream that the soil cement ends is where greater erosion and flood damage will occur. The only winners are land speculators who purchased worthless land in a floodplain now made valuable because a wall of soil cement keeps the river's flood flows at bay.

Soil-cementing the banks sealed the fate of the riparian zones along the Santa Cruz River. Trees and shrubs don't grow through cement. The cement lining has also adversely affected birds and animals. Birds of course are attracted to both trees and water; take away both and you must say goodbye to the birds. In the Southwest, dry washes, called arroyos, serve as wildlife corridors for deer, coyotes, javelinas, mountain lions, bobcats, raccoons, and gray foxes, as well as smaller mammals such as cottontail and jackrabbits and ground squirrels. Think of arroyos as animal freeways: it is easier to move great distances in the washes than through higher land full of mesquite, ironwood, and acacia trees and opuntia and cholla cacti. Soil-cemented banks, because they are almost vertical and are bereft of vegetation, make it more difficult for animals to use arroyos as transportation corridors.

Metropolises of the American Southwest—Los Angeles, San Diego, Las Vegas, Phoenix, Tucson, to name just a few—exist only because we have altered the hydrologic cycle. We have created homes for tens of millions of people in areas with scarce water resources by building dams and canals that divert entire rivers out of their natural courses and by pumping groundwater in an unsustainable fashion.

In contrast, the Tohono O'odham's *ak chin* farming had a simple elegance that depended on the natural hydrologic cycle to maintain a high groundwater table that discharged groundwater to a gaining stream and that kept the floodplain moist after the spring floods receded. The moist soil provided enough water to sustain the beans and other crops until harvest. The Tohono O'odham learned this technique, one in harmony with nature, from their ancestors, the Hohokam, who may have learned it from even earlier inhabitants of the Santa Cruz River valley. The impact of groundwater pumping on the Santa Cruz River has had grievous consequences for the Tohono O'odham. The *ak chin* technique that endured for centuries, or even millennia, has been destroyed in mere decades by groundwater pumping. Recently, a Tohono O'odham elder was asked: "What happened to the Santa Cruz River?" He responded: "The city of Tucson took it."

Chapter 4

A River at Risk

The Upper San Pedro River in Arizona

"The well was dry beside the door,
And so we went with pail and can
Across the fields behind the house
To seek the brook if still it ran. . . ."
—Robert Frost

The headwaters of the San Pedro River rise in Mexico approximately twenty miles south of the Arizona border. The river flows north into Arizona, past the Huachuca Mountains, the cities of Sierra Vista and Benson, and the town of Mammoth, and joins the Gila River near the town of Winkelman. Runoff from the Huachuca Mountains has created streams, fragile oases in a harsh environment, that flow down the mountain canyons into the San Pedro River.

During the past two centuries, substantial geomorphic changes have occurred in the San Pedro River valley as the river washed sand downstream. Cienegas, or marshlands, were common along the San Pedro in the nineteenth century. So were beavers. In 1879, there was so much standing water that the *Arizona Daily Star* described the San Pedro as "the valley of the shadow of death," due to frequent outbreaks of malaria, dengue and yellow fever. Although it would be another two decades before the experience of building the Panama Canal confirmed the link between mosquitoes and malaria, suspicion in the 1880s that swamps caused disease led to