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Understanding and Managing the Effects of Groundwater Pumping on Streamflow

Groundwater is a critical resource in the United States because it provides drinking water, irrigates crops, supports industry, and is a source of water for rivers, streams, lakes, and springs. Wells that pump water out of aquifers can reduce the amount of groundwater that flows into rivers and streams, which can have detrimental impacts on aquatic ecosystems and the availability of surface water. Estimation of rates, locations, and timing of streamflow depletion due to groundwater pumping is needed for water-resource managers and users throughout the United States, but the complexity of groundwater and surface-water systems and their interactions presents a major challenge. The understanding of streamflow depletion and evaluation of water-management practices have improved during recent years through the use of computer models that simulate aquifer conditions and the effects of pumping groundwater on streams.

The Lower Colorado River and adjacent farmland near Yuma, Arizona. Court rulings on use of water in the river have recognized that water can be withdrawn from the Colorado River by "underground pumping." (Photograph courtesy of Andy Pernick, Bureau of Reclamation)

Introduction

Groundwater is an important source of water for many human needs, including drinking water, agriculture, and industry. Groundwater and surface-water systems are connected, and groundwater discharge is often the primary source of streamflow, particularly during periods with no rainfall or snowmelt (fig. 1*A*). Pumping from wells reduces the amount of groundwater that flows to streams and, in some cases, can draw streamflow into the underlying aquifer. Streamflow reduction caused by pumping, also referred to as "depletion" or "capture," has become an important water-resource management issue because of the negative effects that reduced flows can have on aquatic ecosystems, the availability of surface water, and the aesthetic value of streams and rivers.

Managing the effects of streamflow depletion by wells is one of the most common and often one of the most challenging aspects of conjunctively managing groundwater and surface-water systems. Scientific research and practical applications of this research to real-world settings over the past seven decades have improved the understanding of the capture process by hydrologists, providing valuable insights to water administrators for improving groundwater and surface-water management. This Fact Sheet summarizes some of the basic information about how groundwater pumping affects streams, misconceptions that have developed around the process of streamflow depletion, and methods for understanding and managing streamflow depletion by wells. A more detailed description of these and other issues related to the effects of pumping on streams is provided in U.S. Geological Survey Circular 1376.

A Vermilion Flycatcher in the riparian corridor of the San Pedro River, Arizona. (Photograph courtesy of Bob Herrmann, copyright 2011.)

Sources of Water to a Well

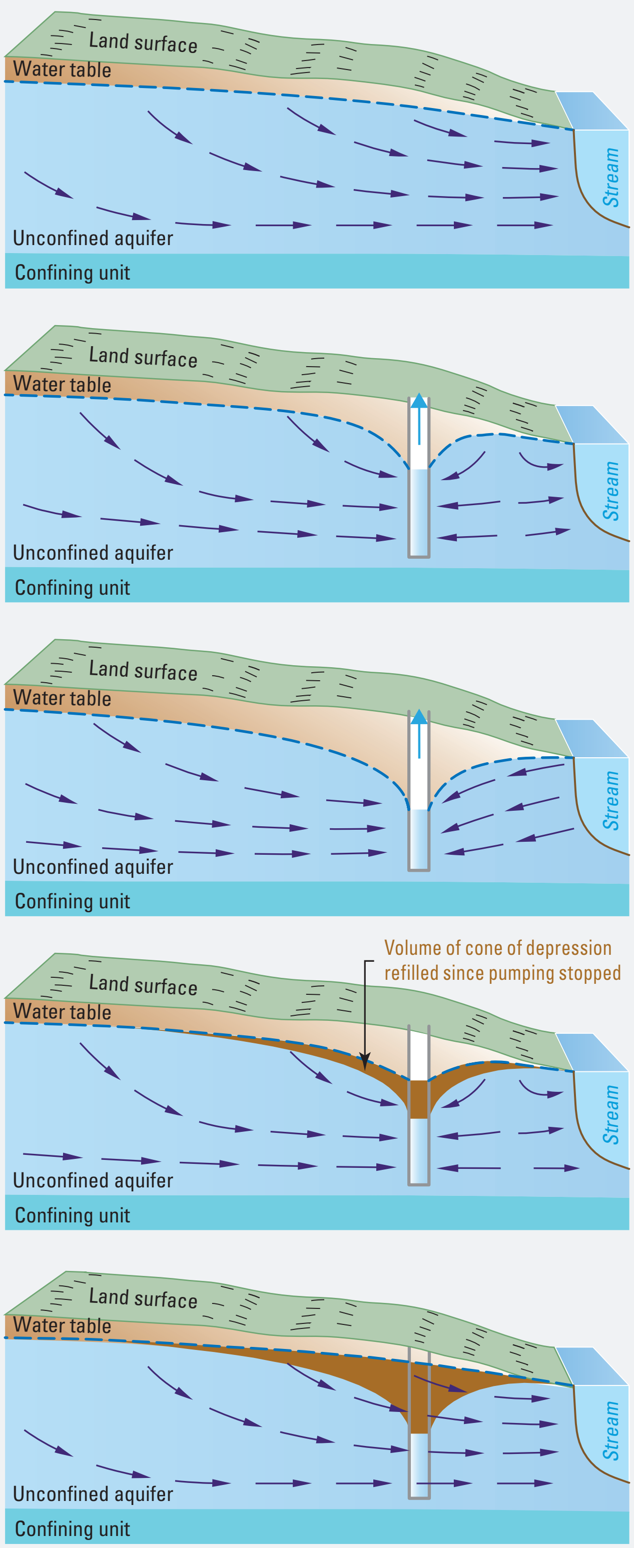
When a well begins to pump water from an aquifer, it first pulls water closest to the well from storage within the aquifer, forming a "cone of depression" in the water table around the well (fig. 1*B*). These water-level declines are largest at the well and decrease with distance from the well. Over time, the cone of depression deepens and expands outward from the well.

The release of water from aquifer storage continues to be the only source of water to the well until the cone of depression reaches one or more locations from which water can be captured—commonly streams that are hydraulically connected to the aquifer.

Captured streamflow consists of two possible components: groundwater that would otherwise have discharged to a stream or river ("captured groundwater discharge") and streamflow that is drawn into an aquifer because of pumping ("induced infiltration" of streamflow; fig. 1*C*). Streamflow depletion, therefore, is the sum of captured groundwater discharge and induced infiltration. Captured groundwater discharge is often the primary component of streamflow depletion, but if pumping rates are relatively large or the locations of withdrawal are relatively close to a stream, then induced infiltration may become an important component of depletion.

Other hydrologic features also can be affected by pumping wells. Groundwater withdrawals can decrease groundwater discharge rates to lakes and springs and reduce the amount of water that would otherwise be available to groundwater-dependent plants in riparian areas.

Figure 1. Progressive changes to groundwater flow and streamflow before, during, and after pumping at a hypothetical well site.



A. Under natural conditions, recharge at the water table is equal to discharge at the stream.

B. Pumping from a well removes water from storage in a cone of depression and reduces discharge to the stream.

C. In some circumstances, the pumping rate of the well may be large enough to cause water to flow from the stream to the aquifer, a process called induced infiltration of streamflow.

D. After pumping stops, groundwater levels begin to recover, and water flows into aquifer storage to refill the cone of depression created by the previous pumping stress.

E. Eventually, the system may return to its prepumping condition with no additional changes in aquifer storage or streamflow depletion.

Time Response of Streamflow Depletion

The timing of streamflow depletion from pumping at a particular well is affected by many factors, including the geologic structure, dimensions, and hydraulic properties of the groundwater system and streambeds, and—importantly—the distance from the pumping location to the streams connected to the aquifer. Substantial streamflow depletion by a well that is tens of feet from a stream may occur in a matter of days, whereas depletion from a well that is tens of miles from the nearest stream may occur over decades or even centuries.

An example of the transition from aquifer storage to streamflow depletion as a source of pumped water is illustrated in figure 2. At any given time, the sum of aquifer storage change and streamflow depletion account for 100 percent of the pumping rate of the well, with a trend toward the condition in which all of the pumping rate is from depletion. The pumping time at which 50 percent of the pumping rate is from depletion is referred to as the "time to depletion-dominated supply."

Common Misconceptions Regarding Streamflow Depletion by Wells

Despite the many advances that have been made in our understanding of the processes that affect streamflow depletion by wells, several misconceptions related to the effects of pumping on streamflow have developed over the years. These include the following:

Misconception 1: Total development of groundwater resources from an aquifer is "sustainable" or "safe" when the overall rate of groundwater extraction does not exceed the long-term average rate of recharge to the aquifer. In many aquifers, however, the level of groundwater development may be limited by the amount of reduced streamflow that a community or regulatory authority is willing to accept.

Misconception 2: Streamflow depletion is dependent on the rate and direction of water movement in an aquifer. Actually, for all but the most extreme pumping conditions, the rates, locations, and timing of streamflow depletion caused by pumping are independent of the prepumping rates and directions of flow within an aquifer—including the recharge rates to an aquifer. Moreover, depletion is unlikely to be affected by transient events such as changes in aquifer recharge rates or variations in river stage from flood flows in streams.

Misconception 3: Depletion stops immediately after pumping ceases. Streamflow depletion continues after pumping stops because it takes time for groundwater levels in the cone of depression to recover from the previous pumping stress and for the aquifer to be refilled (fig. 1*D*). During the time that the aquifer is being replenished, groundwater that otherwise would have flowed to streams instead goes into aquifer storage; thus, streamflow depletion is ongoing, even though pumping has ceased. In many cases, the time of maximum streamflow depletion actually occurs after pumping has stopped. Eventually, the aquifer and stream may return to their prepumping conditions (fig. 1*E*), but the time required for full recovery may be quite long, possibly much longer than the total time that the well was pumped. Over the time interval from when pumping starts until the system fully recovers to its prepumping levels, the volume of streamflow depletion will equal the volume of water pumped.

Misconception 4: Pumping groundwater exclusively below a clay layer or other confining layer will eliminate the possibility of depletion of surface water connected to the overlying groundwater system. Even though clay or other confining layers can slow the progression of depletion in comparison to equivalent aquifer systems without confining layers, it is not reasonable to expect that pumping beneath an extensive confining layer will entirely eliminate depletion. Furthermore, pumping below discontinuous confining beds may actually increase the speed of the depletion process relative to a condition in which the beds are absent.

Managing Streamflow Depletion by Wells

Managing streamflow depletion by wells is challenging because of the natural complexity of groundwater systems, the often-difficult task of identifying streamflow depletion from data collected at gaging stations, and the time delays that may occur between the onset of pumping until significant (that is, measurable) effects occur in nearby streams. Therefore, effective management of streamflow depletion requires both a long-term planning perspective and a basinwide understanding of how streamflow depletion responds to pumping each well individually and at all wells simultaneously. Many groundwater basins have hundreds or thousands of pumped wells. Individually, these wells may have little effect on streamflow depletion, but small effects of many wells within a basin can combine to produce substantial effects on streamflow and aquatic habitats. Moreover, basinwide groundwater development typically occurs over a period of several decades, and the resulting cumulative effects on streamflow depletion may not be fully realized for many years.

Although monitoring of streamflow depletion at gaging stations can be effective for determining both short-term and long-term changes in streamflow in response to groundwater pumping, the most robust approach for determining the rates, locations, and timing of streamflow depletion is numerical modeling.

Numerical models have been used across the United States to better understand and improve water-management options and practices because they can account for the effects of complex aquifer settings, stream geometries, and pumping histories from large numbers of wells on all types of hydrologic features, including streams. (See case study on the next page.)

Further Information

A fuller exposition of the effects of groundwater pumping on streamflow can be found in:

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. (Available at http://pubs.usgs.gov/circ/1376/.)

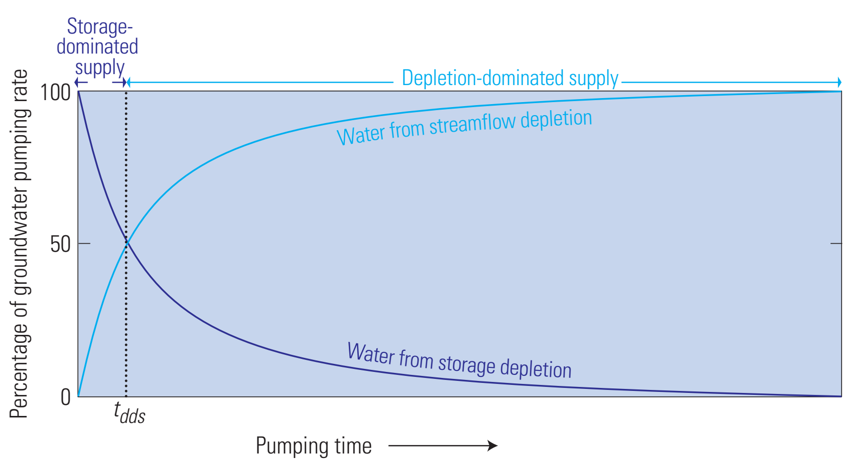
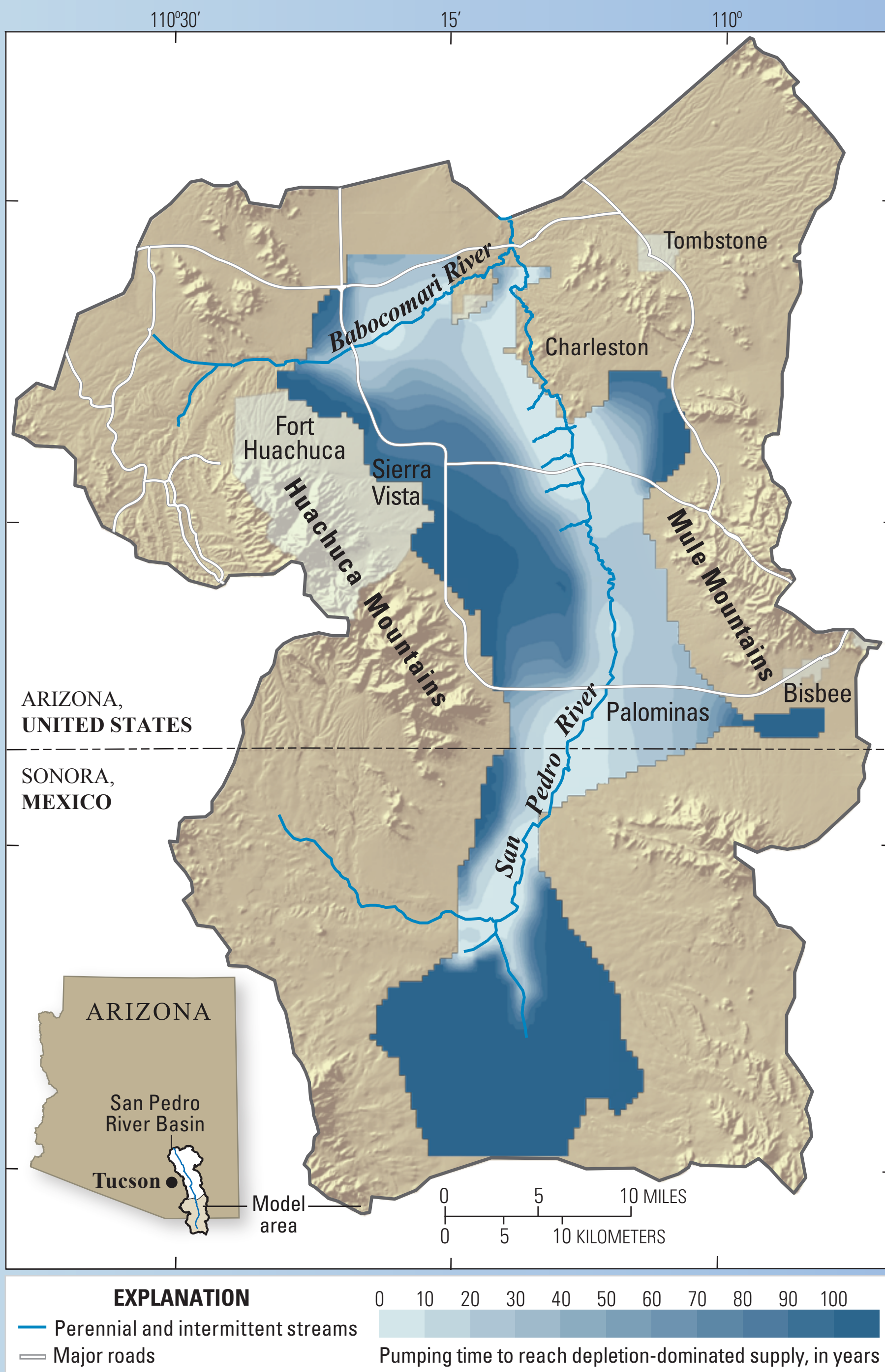


Figure 2. Relation of storage change and streamflow depletion as sources of pumped groundwater through time for a hypothetical well. The variable t_{dds} is the time to reach the condition of depletion-dominated supply for a particular pumping location. In some settings, the transition from storage-dominated to depletion-dominated supply can occur in a matter of days to months, whereas for others depletion-dominated supply may not occur for decades.

Case Study: Use of Numerical Modeling for Analysis of Streamflow Depletion in the Upper San Pedro River Basin

The upper San Pedro River Basin spans the international boundary between the United States and Mexico, covering an area of about 1,700 square miles. Groundwater discharge sustains perennial reaches in the San Pedro River and its tributaries, as well as the adjacent riparian area. The riparian area provides year-round habitat for wildlife species and is an important corridor for birds migrating between Mexico and the United States.

A numerical groundwater model was used by USGS hydrologists to study the timing of depletion from pumping in the aquifer of the upper San Pedro River Basin. Model runs were completed for about 1,500 hypothetical well locations throughout the aquifer. The pumping time required to reach depletion-dominated supply was determined for each of the potential well locations and the results plotted on a map. Maps such as these—which have been referred to as "capture maps"—provide a visual tool for scientists and water-resource managers to better understand the effects of pumping at individual locations within a larger set of possible pumping locations within the aquifer. In the resulting map, the lightest color, generally adjacent to connected rivers, indicates that depletion-dominated supply would occur within 10 years of pumping. In contrast, the darkest color indicates that depletion-dominated supply would not be reached within 100 years.



Pumping time required to reach depletion-dominated supply as a function of well location in the primary aquifer underlying the upper San Pedro River Basin.

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