CAST® Issue Paper
Number 63
February 2019

Aquifer Depletion and Potential Impacts on Long-term Irrigated Agricultural Productivity

When developing policies that regulate groundwater systems that are being depleted, the potential consequences of groundwater depletion need to be fully assessed to determine the trade-offs that exist between the undesired impacts of groundwater depletion and whether these impacts outweigh the benefits associated with groundwater use. (Photo from Ed Hennigan/Shutterstock.)

ABSTRACT

Groundwater is the Earth's most extracted raw material, with almost 1,000 cubic kilometers per year (800 million acre-feet per year) of groundwater pumped from aquifers around the world. Approximately 70% of groundwater withdrawals worldwide are used to support agricultural production systems, and within the United States, about 71% of groundwater withdrawals are used for irrigating croplands. This percentage of groundwater used to support agriculture is even higher in arid and semi-arid areas, where the only consistent source of irrigation water is groundwater. In these regions, however, the use of groundwater typically far exceeds the rate at which it is naturally replenished, indicating that these critical groundwater resources are being slowly depleted. Within the United States, groundwater depletion has occurred in many important agricultural production regions, including the Great Plains Region (Nebraska, Colorado, Oklahoma, New Mexico, and northern Texas), the Central Valley of California, the Mississippi Embayment Aquifer (Mississippi River lowlands bordering Arkansas and Mississippi), aquifers in southern Arizona, and smaller aquifers in many western states.

The groundwater resource with the greatest long-term depletion is the High Plains (Ogallala) aquifer in the Great Plains Region of the United States, where groundwater levels have declined by more than 50 meters (150 feet) in some areas. The Central Valley of California, however, is experiencing the highest groundwater depletion intensity

CAST Issue Paper 63 Task Force Members

Authors

John Tracy, Chair, Texas A&M AgriLife Research—Texas Water Resources Institute and Department of Civil Engineering, Texas A&M University, College Station

Jennifer Johnson, River and Reservoir Operations, Bureau of Reclamation, Boise, Idaho

Leonard Konikow, U.S. Geological Survey, Reston, Virginia (retired)

Gretchen Miller, Department of Civil Engineering, Texas A&M University, College Station

Dana Osborne Porter, Department of Biological and Agricultural Engineering, Texas A&M University, Lubbock

Zhuping Sheng, Texas A&M AgriLife Research Center at El Paso and Department of Biological and Agricultural Engineering, Texas A&M University, El Paso

Steve Sibray, Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln

Reviewers

Michael Campana, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis

Jay Lund, Department of Civil and Environmental Engineering, University of California–Davis

C. G. Olson, U.S. Geological Survey, Reston, Virginia (Emeritus Scientist)

CAST Liaison

David Baltensperger, Department of Soil and Crop Sciences, Texas A&M University, College Station

because of increased use over the last several decades. The most obvious consequences of depleting groundwater resources are the loss of a long-term water supply and the increased costs of pumping groundwater as the water table declines further below the ground surface. There are many other consequences associated with groundwater depletion, however, including the loss of the productivity of groundwater production wells (possibly requiring the construction of new wells); the depletion of the flow of water in rivers, creeks, and lakes when they are hydrologically connected to underlying aquifers; the shifting and subsidence of land surfaces that can occur when groundwater is extracted from aquifers; and the intrusion of high saline, or poor quality, water from other subsurface formations.

The most effective approaches for addressing groundwater depletion focus on reducing or eliminating the imbalance between the inflow and outflow of water to an aquifer. Methods that focus on increasing the inflow to groundwater resources include the development of managed aquifer recharge systems and altering land-use practices to increase the infiltration of water below the land surface. Methods that focus on decreasing groundwater use include the implementation of more efficient irrigation systems, the development of agricultural crops that require less water, and the creation of economic incentives to encourage water conservation. All of these methods should be considered when developing plans to address the long-term consequences of groundwater depletion. In addition, when developing policies that regulate groundwater systems that are being depleted, the potential consequences of groundwater depletion need to be fully assessed to determine the trade-offs that exist between the undesired impacts of groundwater depletion and whether these impacts outweigh the benefits associated with groundwater use.

INTRODUCTION

Groundwater is the Earth's most extracted raw material, with almost 1,000 cubic kilometers per year (km^3/yr) (800 million acre-feet per year) of groundwater used to support agricultural, municipal, commercial, industrial, and energy production (Margat and van der Gun 2013). Approximately 70% of groundwater withdrawals are used for irrigated agriculture (71% in the United States) (Margat and van der Gun 2013). The annual groundwater use is only a small fraction of total economically available groundwater, estimated to be 0.00041%/yr (Gleeson et al. 2016). Although this appears to indicate that groundwater use could be sustained at its current levels for centuries to come, it does not reflect the spatial distribution of groundwater extraction and availability and that much extraction is from geologic formations without significant recharge since meaningful groundwater pumpage to support agricultural production has occurred (i.e., within the last 60 years). In addition, in many areas of the world, including the United States, groundwater extraction is concentrated in semi-arid to arid regions, where the age of groundwater can range from hundreds to thousands of years, suggesting that this groundwater is not being replenished at the rate that it is being extracted and that these groundwater resources are being depleted. Consequences of the long-term depletion of groundwater resources include the direct impacts of depleting the resource, which can reduce water availability for local and regional societies, economies, and ecosystems, and global impacts of groundwater being released to the atmosphere and oceans once it is brought above ground, contributing approximately 0.3 to 0.4 millimeters (mm)/yr of sea level rise since 2000 (Döll et al. 2014; Konikow 2011).

This issue paper reviews the causes and consequences of *groundwater depletion*[1], with a focus on impacts to agriculture as the largest sector of groundwater use. This understanding can aid in developing effective policies and practices for

---

[1] Italicized terms (except genus/species names and published material titles) are defined in the Glossary.

groundwater development, use, and management. Before groundwater depletion can be addressed, however, a basic understanding of the principles of groundwater occurrence and behavior is necessary.

Basic Principles of Groundwater Occurrence and Behavior in Aquifers

Understanding Groundwater

Groundwater occurs almost everywhere, and it is generally defined as the occurrence of water in the soil, sediment, and rock at pressures at or greater than atmospheric pressure. Practically speaking, when a well is being drilled, groundwater is encountered when water starts filling the well from surrounding soil and rock. The depth at which this occurs can be considered the water table, which is the top of the zone in which the subsurface is saturated with water, and it can vary greatly—generally being deeper in arid climates and near the land surface in humid climates, near surface water bodies, or in areas where human activities have applied water on the landscape. Groundwater can be withdrawn from the subsurface through a well that extends below the water table or through horizontal channels or tunnels that intersect the water table. Water production from groundwater wells depends on several factors, including the well diameter, water level depth below the land surface, ease of water flow through soil or rock near the well, and power of the pump used to extract the groundwater.

Groundwater is rarely static, and it is generally in motion with natural flow rates (or flow velocities) being highly variable and ranging from several tens of feet per day or more to less than several feet per century, depending on the type of soil or rock that the groundwater is flowing through, the proximity to surface water bodies, and well depth. Groundwater flow is always in three dimensions, and the magnitude and direction of the flow depend on the hydraulic properties of the soil it is flowing through and the steepness of the *potentiometric surface*, referred to as the hydraulic gradient. The hydraulic gradient is the difference in potential energy over a given distance and can be characterized simply as the difference in water elevations between two wells along a flow path (Figure 1). Steeper hydraulic gradients bring faster groundwater.

The ease with which water can move through the subsurface (including soils; unconsolidated sands, clays, or gravels; and geologic formations of bedrock) is characterized by its hydraulic conductivity (or similar parameters such as permeability or transmissivity). For a given hydraulic gradient, the flow in an aquifer with a hydraulic conductivity of 10.0 feet/day (ft/d) will be ten times the flow as in an aquifer with the same hydraulic gradient but in which the hydraulic conductivity is 1.0 ft/d. In natural geologic materials, the hydraulic conductivity can vary by more than ten orders of magnitude (with clays, shales, and granitic rocks having very low values and gravels and some porous limestones and basalts having very high values, for example).

In natural groundwater flow systems, before people drilled wells and developed groundwater for their water supply, there was always a dynamic balance between water entering the aquifer (recharge) and water leaving the aquifer (discharge). Although the water levels in the aquifer (and the water table elevation, representing the top of the subsurface zone saturation) can vary over time as precipitation varies on a daily, seasonal, or decadal scale, thereby affecting recharge, the aquifer systems would remain in a more or less long-term equilibrium condition in which there were no persistent changes in the average amount of water in the aquifer (stored in pores of soil and rocks) and discharged to streams and springs—unless long-term climatic changes created permanent changes in the recharge (or boundary conditions) for the aquifer.

When water is pumped from a well, it causes water levels in the well and adjacent aquifer to decline, referred to as "drawdown." This drawdown in turn creates a hydraulic gradient that draws water from the aquifer toward and into the well—to replace water the pump removes from the well. This drawdown and water removal also disturbs the natural equilibrium in the aquifer and the balance between natural recharge and natural discharge. Lowering the water level in the aquifer also means that some water has been removed from "storage" within the aquifer's pore spaces.

Groundwater and surface water are two components of the overall interconnected water resource (Winter et al. 1998). In places or at times when the water table is relatively high, groundwater flow can discharge to streams, lakes, springs, and wetlands, providing base flow and long-term persistence to wetland streams (Figure 2A). Where the

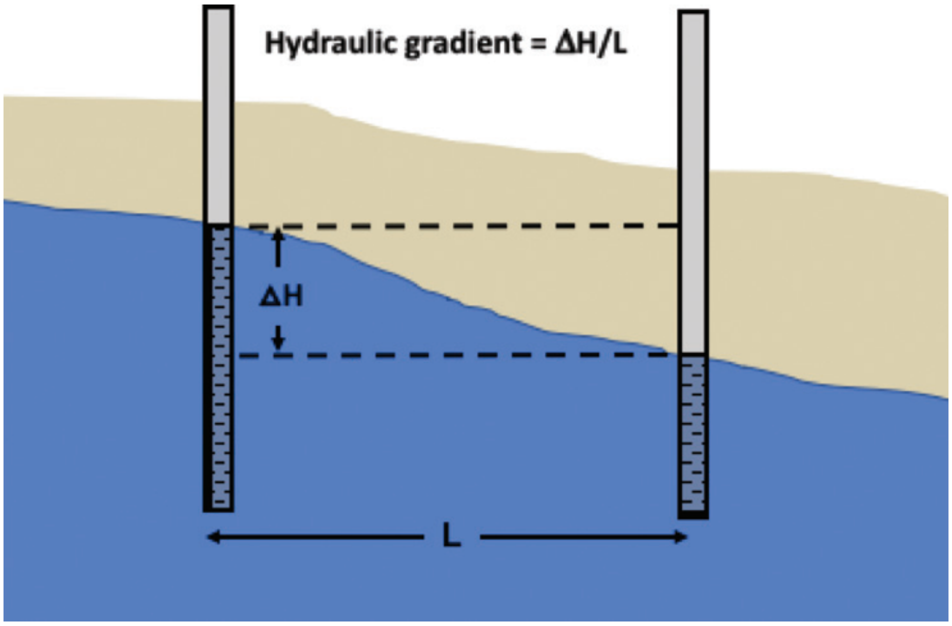


Figure 1. Depiction of groundwater hydraulic gradient.

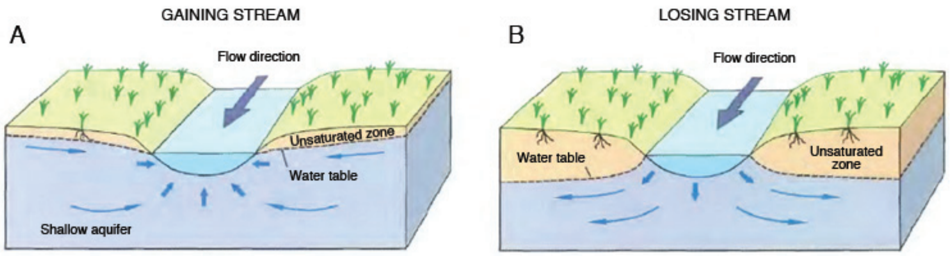


Figure 2. The connection between groundwater and surface water can occur as either a groundwater discharge (A) or a groundwater recharge (B) situation. (Source: Winter et al. [1998].)

water table is below local surface water, however, streams or lakes can lose water by seepage into the subsurface, thereby recharging underlying aquifers (Figure 2B). Because of the interconnection between groundwater and surface water, large-scale development of groundwater through well pumping may disturb the existing groundwater flow system and affect local or regional surface water resources—generally diminishing surface water availability.

Understanding Aquifers

An aquifer is generally accepted as being a geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs (Lohman 1972). Aquifers typically consist of a dominant type of rock material. In some aquifers, the top of the saturated zone is a free surface at atmospheric pressure—the water table. These aquifers are called “unconfined” or water table aquifers. Other aquifers—typically deeper ones—are overlain (or “confined”) by low-permeability formations, such as clays or shales, and the entire aquifer is saturated. Water in such a confined aquifer (or “artesian” aquifer) is under pressures greater than atmospheric, and the water level in a well drilled into a confined aquifer can rise to a height above the top of the aquifer. If the pressure is great enough for the water level in the well to rise above the land surface, the well can flow freely without a pump.

An aquifer’s ability to yield significant quantities of water to a well depends on its porosity and permeability, which depend on the geologic origin of the material, the rock type, and the geological and geochemical processes that affected the rock and soil material after its deposition. Many shallow aquifers are composed largely of unconsolidated sediments, including permeable sands and gravels. These include alluvial aquifers that parallel rivers and basin-fill aquifers that contain erosion products from nearby mountains. Examples of prolific aquifers composed largely of unconsolidated sediments include the Ogallala aquifer, the Central Valley aquifer in California, the alluvial basins of Arizona, and the Mississippi Embayment aquifer in Arkansas, Mississippi, and Louisiana. In such aquifers, permeability is primarily from the interconnectedness and size of the pore spaces.

Other aquifer systems occur in hard-rock (or bedrock) formations. In such systems the permeability can arise from a combination of relatively high primary (intergranular) porosity coupled with secondary porosity features related to fractures or openings caused by the dissolution of the rock material as water flows through these openings. Examples include consolidated sandstones with well-connected pore spaces, such as the Dakota Sandstone in South Dakota and adjacent states; limestone and other carbonate rock aquifers, such as the Floridan aquifer, which underlies much of Florida and some adjacent parts of Georgia and derives its high permeability from primary porosity enhanced by interconnected openings caused by dissolution of the limestone; and volcanic rock aquifers, such as the Columbia Plateau and the Snake River Plain aquifers in the northwest, which derive their permeability from both primary porosity and fractures in rock formations.

An important distinction between unconfined and confined aquifers is the nature of their storage properties—that is, how much water they yield per unit drawdown (or decline in water level). In an unconfined aquifer, water level declines cause drainage (or dewatering) of the pore spaces as the material between the original water table level and the new lower water table position transitions from saturated to unsaturated conditions. In a confined aquifer, however, drawdown does not cause dewatering (except in extreme cases); instead, the reduction in storage comes from a combination of compression of the aquifer (and pore spaces) and expansion of water under the decreased pressure from pumping. Therefore, in a confined aquifer the reduction in mass of water per unit volume of aquifer per unit volume of water removed by pumping a well is much smaller than for an unconfined aquifer; consequently, in a confined aquifer the effects of pumping on water levels will spread much farther and faster than in an unconfined aquifer having a similar permeability.

The Relationship of Drought to Groundwater Use

Groundwater use has grown significantly across the United States over the last century, especially to supply irrigated agriculture. Many factors have led to this increased reliance on groundwater. Technologically, advances in pump technology allowed for submersible pumps that can efficiently extract large quantities of groundwater from deep below the ground surface. This technology began to be deployed extensively across the United States in the 1950s, which coincided with rural electrification across the nation that facilitated use of submersible pumps. This supported cost-effective use of groundwater for water supply, especially for irrigated agriculture. A second factor increasing groundwater use has been long-term regional droughts, especially in regions with large agricultural sectors. Additional factors include over-allocation of surface water and local availability of groundwater as a “point-of-use” resource not requiring expensive distribution infrastructure.

Prior to the 1930s, agricultural production in the High Plains regions of Texas, Oklahoma, and Kansas was mostly dryland farming. Irrigation development in the Texas High Plains began during a major drought in the 1930s, in which a substantial increase in crop yield was noted in response to irrigation (Musick et al. 1990). The significant expansion of irrigation across the High Plains, however, occurred in response to the drought of the 1950s, which affected much of this region and the southwestern United States. Advances in drilling and pumping technologies, along with financial resources made available after World War II, allowed access to a seemingly endless supply of water from the Ogallala aquifer that underlies much of the region (Colaizzi et al. 2009; Musick et al. 1990). Thus many farms converted from dryland (rainfed) to irrigated agriculture with extractions from the High Plains aquifer. The use of water from the High Plains aquifer for irrigation allowed sustained agricultural productivity through the Texas "Drought of Record" (Dethloff and Nall 2018; D. Marble, Personal communication).

This pattern repeated itself in the western United States in the 1970s. The 1976–1977 drought impacted large portions of the United States, especially the western states. Even though California had constructed extensive water supply reservoirs and canal systems to mitigate the effects of interannual droughts, the drought of 1976–1977 resulted in significant curtailment of water deliveries to irrigated farmland, especially in the San Joaquin Valley. This drought in California had wide-reaching impacts from the loss of riparian habitat to decreased recreation activities, such as rafting and skiing, that bring revenue to the state. Agriculture losses were estimated to be $510 million, mostly from nonirrigated acres. As a result of this drought, the state developed a water management plan to address the potential of the drought continuing into 1977 and beyond. This included a conservation plan that directed all users with access to both surface water and groundwater to increase their reliance on groundwater (California Department of Water Resources 1977). The drought resulted in increased groundwater usage and ultimately decreased groundwater levels because of the increased pumping to supplement diminished surface water supplies (Matthai 1979).

UNDERSTANDING GROUNDWATER DEPLETION

Groundwater Depletion across the United States

Several large aquifer systems in the United States are experiencing substantial problems from the depletion of groundwater. The U.S. aquifer system with the greatest long-term groundwater storage depletion is the Ogallala aquifer in the Great Plains region of the United States, with nearly 400 km^3 (325 million acre-ft) by 2013. In the southern part of the High Plains aquifer, water levels have declined more than 50 meters (m) (150 feet) in places (Figure 3), resulting in a loss of more than half of the predevelopment saturated thickness of the aquifer in some places (McGuire 2014). Similar problems are pervasive in many aquifers across the United States and globally. A map of long-term (1900–2008) groundwater depletion in major aquifers across the nation (Figure 4) shows large volumetric losses also occur in the Central Valley of California, the Mississippi Embayment aquifer, the alluvial basins of southern Arizona, and numerous smaller aquifer systems—especially in the arid western states.

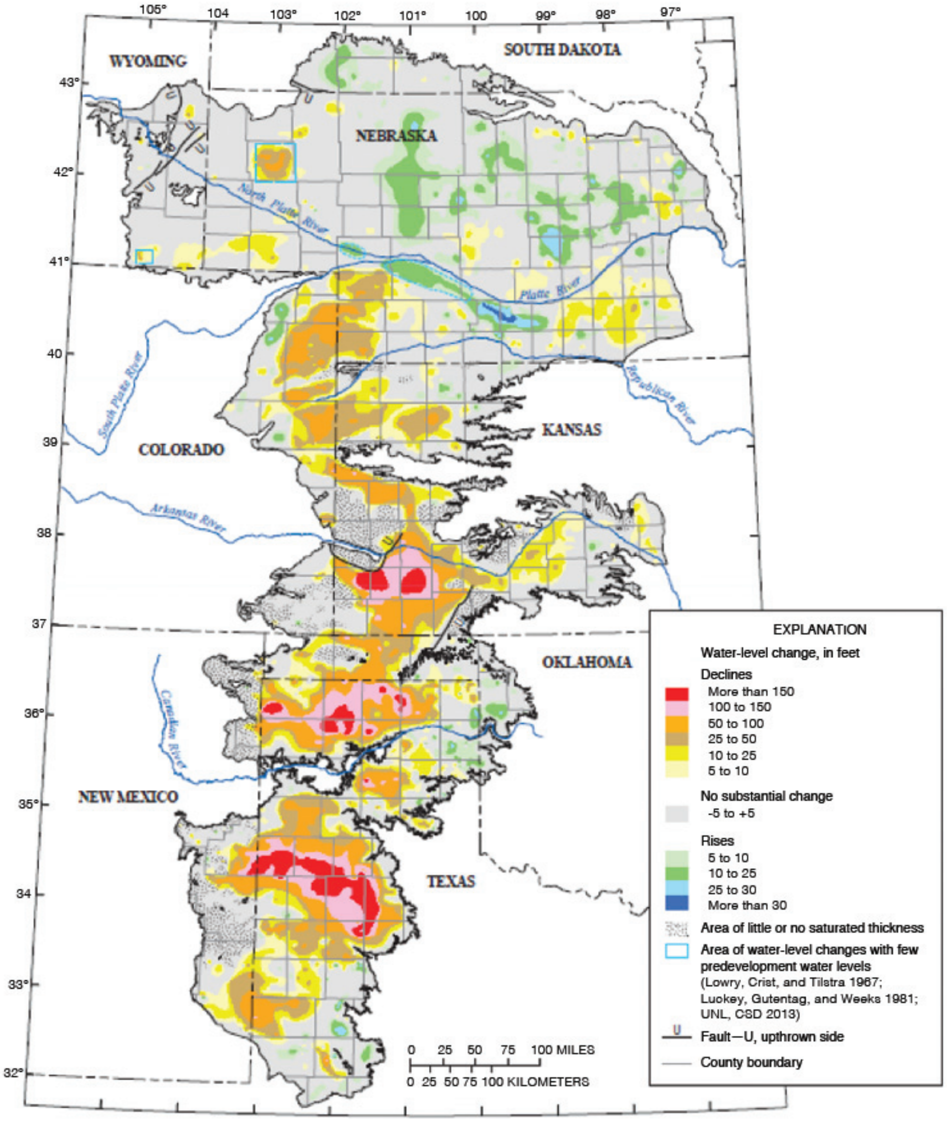


Figure 3. Changes in water levels in the High Plains aquifer, predevelopment (about 1950) to 2013. (Source: McGuire [2014].)

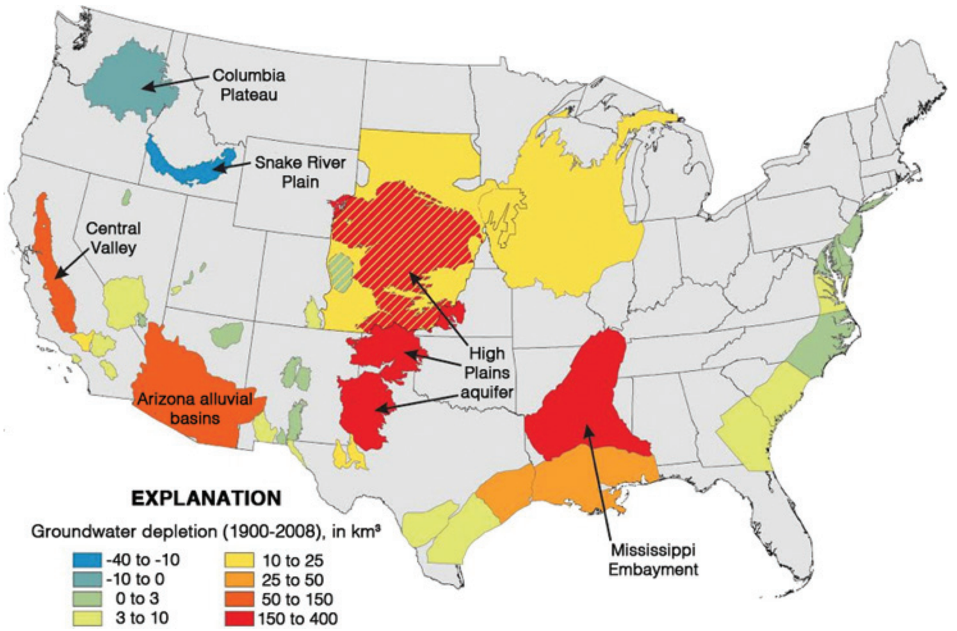


Figure 4. Cumulative long-term volumetric groundwater depletion in the United States during 1900–2008 in km^3 (modified from Konikow [2013]). Hachured areas are where a shallow aquifer overlies a deeper aquifer.

Two large aquifer systems in the Pacific Northwest region of the United States, the Columbia Plateau aquifer (Washington and Oregon) and the Snake River Plain aquifer (Idaho), have had a net accretion of groundwater levels as compared to predevelopment conditions. In other words, on the whole, more groundwater existed in these two aquifer systems in 2008 than before major irrigated agriculture development occurred, primarily from sustained application of diverted surface water to irrigate fields, which increased recharge to the underlying aquifers above that which would occur naturally. In these areas, however, the trends in recent decades have been toward depletion—as groundwater withdrawals have increased, surface water diversions have remained more or less constant, with an increase in the efficiency of delivering these diversions to irrigated fields, which has resulted in a decrease in recharge to groundwater resources.

The High Plains aquifer underlies a very large area—about 450,000 km^2 (110 million acres), and, in absolute terms, has had the highest rate of depletion since 2000 (Konikow 2015). If we assess the intensity of aquifer depletion by accounting for the size of the aquifer, however, then it turns out that the Central Valley of California has had the highest depletion intensity since 2000 (Konikow 2015), with the depletion varying across the aquifer and the most severe depletion occurring in the southern part of the valley. A complete assessment of the rates of depletion, and depletion intensity, for all major aquifers across the United States can be found in Konikow (2015).

Although groundwater depletion continues to worsen in many aquifer systems, some show signs of stabilization. During the 1960s and 1970s, groundwater was used extensively in Arizona, largely to supply crop irrigation. This pumping led to groundwater level declines of more than 100 m (300 ft) in some areas, as well as earth fissures and land subsidence of 6 m (20 ft) in some areas (Galloway, Jones, and Ingebritsen 1999; Tillman and Leake 2010). In 1980, the Arizona legislature passed the Groundwater Management Act (GMA) to protect shared groundwater resources and to control severe depletion of groundwater resources; the GMA created Active Management Areas (AMAs), where groundwater resources were to be actively monitored and managed, including the use of surface water basins to increase the recharge to groundwater systems, often referred to as artificial recharge basins (Tillman and Leake 2010).

An analysis of the trends of water-level changes in groundwater wells in some of the most severely depleted aquifers showed that a large number of the wells (approximately 80%) had declines in water levels from the 1970s through the year 2000, and only a small fraction of the wells (6%) had rising water tables (Tillman and Leake 2010). After the year 2000, however, well after enactment of the GMA (2000 to 2008), about half of the monitored wells continued to have falling water levels, whereas 35% showed rising water levels. This supports the idea that measures Arizona used to remediate the impacts of groundwater depletion worked in some of the AMAs, although increased importation of Colorado River water under the Central Arizona Project in recent decades complicates the analysis. There is a large variability in the ability to stop or reverse the depletion of groundwater resources among the various AMAs, however, and recent analysis of trends in groundwater levels indicates that depletion of many of the aquifers has again increased (Scanlon et al. 2015).

CAUSES OF GROUNDWATER DEPLETION

Aquifer Depletion and the Water Budget Myth

When water is pumped from a well, it causes water levels in the well and adjacent aquifer to decline. This drawdown in turn creates a hydraulic gradient that induces water to flow from the aquifer toward and into the well—to replace water pumped from the well. This drawdown and water removal also disturb the natural equilibrium in the aquifer and the balance between natural recharge and natural discharge to springs and streams. Lowering the water level in the aquifer also means that some water has been removed from “storage” within the pore spaces near the well, although much of this storage depletion may be recoverable when the pump is turned off. If there are many wells pumping large quantities of groundwater for long periods of time from a single aquifer, however, substantial recovery may not be possible within a reasonable time period.

Before major groundwater development (typically, prior to the 1940s), most

Figure 5. Rural family and their well—circa 1930s. (Photo courtesy of U.S. Department of Agriculture–Natural Resources Conservation Service.)

Los Angeles County production well. (Photo by Loren Metzger, USGS)

Large capacity well at a paper mill, St. Marys, Georgia. (Photo by Alan M. Cressler, USGS)

Irrigation well used for flood irrigation of a rice field in the Mississippi Delta region. (Photo by David E. Burt, Jr., USGS)

Figure 6. Examples of modern high-capacity wells for (a) municipal, (b) industrial, and (c) agricultural uses.
Sources: (a) Galloway et al. (2003); (b) Kenney et al. (2009); (c) Barlow and Leake (2012).

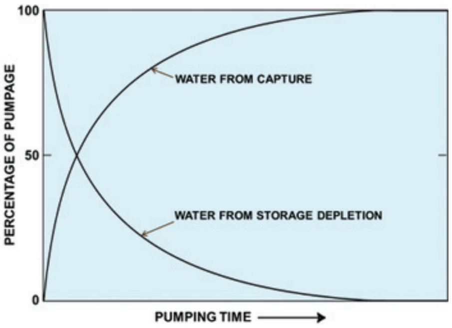


Figure 7. Generalized schematic illustrating how the sources of water to a well may shift over time (modified from Heath [1983]).

wells were shallow hand-dug wells with primitive pumps and limited capacity to produce water (Figure 5). Wells were few and far between, with little chance of pumpage from one well interfering with or affecting another well. With few exceptions, the yield of groundwater from a well was low enough that any depletion of the groundwater was not of significant concern.

Since the 1930s, well drilling and pumping technology have substantially improved, and millions of wells have been drilled throughout the United States and globally—allowing extensive groundwater development to help meet expanding municipal, industrial, and agricultural use with higher water well extractions (Figure 6). The largest use of these groundwater resources is for crop irrigation; with 71% of all groundwater withdrawals in the United States in 2010 being used for irrigation (see Maupin et al. 2014).

In a predevelopment groundwater flow system, the inflows (recharge) are typically in dynamic balance with the outflows (discharge) and the groundwater flow system is in a long-term equilibrium (except for fluctuations caused by seasonal or annual climatic cycles and short-term precipitation variability). In a developed groundwater system, all water pumped from a well must be balanced by some combination of three factors: (1) removal of water from storage in the aquifer (often called depletion); (2) an increase in recharge to the aquifer from some other source of water; or (3) a decrease in discharge from the aquifer (e.g., Barlow and Leake 2012; Theis 1940) to another water body or to the atmosphere. Thus, the natural predevelopment recharge to the aquifer does not define the available amount of water that can be sustainably pumped from an aquifer, which used to be a common belief that is sometimes referred to as "the water budget myth" (Bredehoeft 1997; Bredehoeft, Papadopulos, and Cooper 1982) and has been used as the basis for establishing groundwater rights in some states (e.g., Nevada). Rather, the manner in which groundwater can be sustainably pumped from an aquifer must address all three factors, with the latter two factors together often referred to as "capture" because the groundwater system is capturing water that would otherwise not recharge the aquifer or would otherwise flow out of the aquifer (Leake 2011; Lohman 1972).

When a well is first turned on, all extraction is supplied by storage depletion. Over time, more and more of the water usually is derived from capture of surface water and less is derived from storage depletion (Figure 7). After enough time has elapsed, the fraction of water extracted from storage will reach zero and at that time a new water balance equilibrium has been reached for the aquifer (see Bredehoeft and Durbin 2009). As long as no new pumpage or climatic changes affect the aquifer system, existing withdrawals should be sustainable. If recharge processes and/or surface water resources at the aquifer boundaries are limited, however, sufficient water may not be available for capture to fully balance the well discharge. In such situations, the aquifer system cannot reach a new equilibrium with the established rate of pumpage, which means storage will continue to be depleted and water levels in the aquifer will continue to decline; such a situation is not sustainable in the long run. The actual timing for these effects depends on several factors, which include the hydraulic properties of the aquifer, the rate of groundwater pumping, the location and rate at which aquifers are recharged from other water bodies, and the distance of the pumping wells to these water bodies.

Drought can exacerbate the problem in several ways. During periods of drought, less surface water is available for distribution to farmers, as well as decreased precipitation falling directly on their fields, which leads them to increase their groundwater use for irrigation, if possible. If streamflow adjacent to aquifer boundaries is decreased or other surface water is depleted during drought, the potential for recharge to help balance well withdrawals will be lessened and more pumpage will be balanced by storage depletion, which accelerates water-level declines in the aquifer. Thus groundwater pumping directly affects the extent to which depletion occurs, with the rate and extent of groundwater depletion significantly impacted by changes to land use or surface conditions that impact groundwater recharge and discharge processes.

Impacts of Managing Groundwater as a Common Pool on Depletion

The fact that the flow of groundwater occurs across ownership boundaries (whether boundaries separate individual ownership, water management districts, states, or even sovereign nations) indicates that groundwater is a nonexclusive or common pool resource (CPR). A CPR is an economic term used to identify finite resources whose characteristics make it difficult to exclude persons from obtaining benefits from its use, even if they don't provide support to manage or sustain the use of the resource. Examples of CPRs include open ocean fisheries and open pasture used by multiple livestock owners. The difficulty in sustaining the use of a CPR is that individuals may seek to maximize their benefit from using the resource without regard to long-term maintenance of the resource. This can result in the overuse of the resource and a decline in the overall value of the resource over time unless measures are taken to restrict use of the resource, such as regulations to limit or privatize use of the resource.

Groundwater is not a completely open resource if its use is restricted to owners of land that overlie the aquifer. Because groundwater movement within an aquifer can cross land ownership boundaries, it does have the characteristics of a CPR. Thus when private ownership of a groundwater resource within an aquifer is not clearly defined, or regulations have not been developed to promote sustainable use of groundwater, there is a tendency to use groundwater in a nonsustainable manner and thereby deplete the resource. Over time, overuse of groundwater can be a somewhat self-correcting problem, because the costs of groundwater extraction tend to increase as water levels drop. Thus the costs of extracting groundwater can exceed the benefits for some lower-value water uses, which reduces overall pumpage from the aquifer. This behavior is seen in portions of the High Plains aquifer in Texas, Oklahoma, and Kansas; the Pecos aquifer in Texas; and the Central Valley aquifer in California (Maupin et al. 2014).

Left unregulated, the sustainable use of groundwater could be achieved in an aquifer if some increase in groundwater recharge occurs and the cost of groundwater extraction becomes high enough that groundwater pumpage is decreased to the point of a dynamic equilibrium of the groundwater table. This laissez-faire approach to managing groundwater, however, does not prevent groundwater depletion, nor has it been advocated as a viable policy by any state. Thus an important policy question remains—Is there an optimal method to allocate water to users that will improve the economic benefit of groundwater use of an aquifer?

Studying the Pecos aquifer in eastern New Mexico, Gisser and Sanchez (1980) found that the economic benefits of optimally managing groundwater were insignificant. Their economic analysis showed a near-identical height of the water table (and by implication the amount of groundwater depletion) at a steady state and near-identical future income streams for the scenario in which groundwater use is "optimal" versus one in which groundwater is used with existing controls linked to ownership of overlying land. The work of Gisser and Sanchez (1980) assumed that wells constructed to pump water from the aquifer never went dry, however, which is not always the case when aquifers are severely depleted. As discussed in MacEwan et al. (2017), the capital costs associated with drilling new, or deeper, wells are significant and indicates that avoiding these costs can play an important role in limiting the overdraft in depleting aquifers. Thus, MacEwan et al. (2017) suggest that when the depletion of aquifers leads to dry wells, the optimal allocations of groundwater can provide substantial economic benefits (or avoided costs), contrary to the findings of Gisser and Sanchez (1980).

The High Plains aquifer of West Texas was analyzed (Nieswiadomy 1985) using the approach developed by Gisser and Sanchez (1980) and concluded that "the benefits from groundwater management most likely are small for the Texas High Plains, especially relative to any reasonable cost of regulating pumping." This result was similar to that for the Pecos aquifer analysis, referred to as the Gisser-Sanchez effect (GSE), which has been observed in several aquifer management studies. These studies were reviewed by Koundouri (2004), who found that the most important cause of GSE is the significant benefit to agriculture compared to the costs of developing groundwater for irrigation. In semi-arid regions, water is a major factor limiting agricultural production, with irrigation greatly increasing agricultural yields and profits (Ward and Michelsen 2002). This is especially true for water applied during critical crop growth periods.

The GSE effect often means that a strict regulatory approach to addressing the CPR issue for groundwater may not give the best economic outcome for areas that rely heavily on groundwater, especially for high-value uses. An alternative approach of addressing the CPR problem is through privatization of groundwater pumping rights. This can be done through an allotment or allocation process in which private entities have fixed allocations of groundwater over a specified period of time. This approach is used in Nebraska through the use of natural resource districts (NRDs) that typically allocate water on a five-year basis and occasionally allow some "banking" or carryover of water across allocation periods. In the High Plains aquifer region of Texas, groundwater conservation districts (GCDs) establish pumping limits as part of their management plans to achieve adopted desired future conditions; these limits are to be revisited periodically to assess their effectiveness, and they may be modified as needed (NPGCD 2016). Assessment of the effectiveness of groundwater management plans generally includes groundwater availability modeling and annual water level monitoring (TWDB 2017). The Kansas Groundwater Management Districts are now doing this after a change in state law. Diamond Valley, Nevada, also has a "*water rights*" bundling experiment (see Young n.d.), and Idaho has a program to recharge the Snake River Plain aquifer.

Relationship of Surface Water Use to Groundwater Depletion—The Conjunctive Management Problem

The conjunctive management of surface water and groundwater resources has different administrative definitions depending on how each state defines its water rights. Some states manage surface water and groundwater as a single integrated resource (e.g., Idaho and Kansas). Other states use groundwater more as a supplemental source when surface water supplies are lacking (e.g., Nevada), while others administer groundwater as separate privately or state-owned resources (e.g., Texas, California, and Oklahoma). Managing surface water and groundwater as a single resource, such as the water rights framework in Idaho, can help ensure that water resources are managed in a sustainable and predictable way, because *junior water users* are required to stop diverting when there is not enough water for everyone's needs, regardless of the source of water.

Using groundwater resources when surface water is no longer available can help ensure water availability. If a groundwater system is hydrologically connected to surface water bodies, however, the use of groundwater during one year increases infiltration of surface water to recharge the depleted groundwater in future years. Thus the long-term impact of groundwater pumping on future availability of surface water will decrease both surface water and groundwater resources over time. Recognizing the impact of groundwater pumping, and depletion, on the future availability of water in both surface and groundwater systems is needed to effectively administer water rights in states that follow the *prior appropriations* doctrine.

What is less recognized is the role of surface water management on depletion of groundwater for aquifers that are hydrologically connected to surface water systems. Many areas that use surface water to irrigate agriculture crops recharge to nearby aquifers as a direct result of either conveying water (especially via earthen-lined channels) to the fields or applying it to the fields at rates that exceed crop evapotranspiration. Open-channel water delivery systems typically have some amount of water that seeps into the ground, with seepage rates varying significantly depending on characteristics, setting, and operation of the delivery system. Some systems have seepage as high as 75% of the amount of the diverted water. This seepage is often a large source of recharge to groundwater resources in areas such as the Eastern Snake River Plain and Treasure Valley aquifers in Idaho and the Deschutes Basin aquifer in Oregon. When these delivery systems are made more efficient from the water delivery perspective (i.e., seepage is lessened because of canal lining or replaced by closed conduits), it decreases the recharge to the aquifer and water tables can drop.

Another source of groundwater recharge is through the irrigation of cropland, where applied water not used by crops can seep below the crop's roots, downward to an underlying aquifer. Historical irrigation practices tended to have a higher fraction of applied water seeping below a crop's root zone, which the irrigator sees as a less efficient use of water (e.g., see Urban 2004). These historical irrigation practices include surface flood as well as furrow and subirrigation systems, and they often provide substantial recharge to underlying aquifers. As pressurized irrigation technologies such as sprinkler or drip irrigation have evolved, along with a better understanding of crop water needs, the conversion to more efficient irrigation methods has decreased recharge to underlying groundwater. Increasing water delivery system efficiency to agricultural fields and increasing irrigation efficiency can reduce recharge to aquifers that underlie irrigated agricultural regions (e.g., see Maurer and Berger 2006). In some cases, this reduction in recharge due to changes in how surface water is managed can exceed historical pumpage rates in the aquifers, resulting in a decline in the groundwater table and in essence depleting groundwater resources.

Agricultural Financial Policy Impacts on Groundwater Depletion

Decisions about crop, soil, and irrigation management are complex, affected by many important factors, including producer experience, preferences, available equipment and labor capabilities, and a variety of financial considerations (crop insurance options, credit constraints, landowner/tenant relationships, availability and requirements of loan and cost-share programs). Of special note are crop insurance requirements, because in most cases commodity crops can be insured as either "irrigated" or "not irrigated"—with pilot programs addressing "limited irrigation" not being widely available. Insurance of "irrigated" crops requires adequate facilities and a reasonable expectation of receiving water adequate for "good irrigation practice," as well as other requirements and conditions (USDA–FCIC 2017). Often this is interpreted to mean that during drought, irrigation must continue through the crop season to meet "good irrigation practice" and therefore ensure that drought-related crop loss is due to an unexpected shortfall of normally expected rainfall rather than failure to use the irrigator's full allocation of water.

During extreme drought, however, irrigation sometimes may be discontinued or diverted to salvage crops, with prior approval from the crop insurance company (USDA–RMA 2011). The requirements to follow good irrigation practices can provide incentives for farmers to use their full allocations of groundwater, even for situations in which the full allocation still results in crop failure, because this is perceived as a requirement for a farmer to receive crop insurance payments. Although this is not a primary driver of groundwater depletion, it can result in the nonproductive use of groundwater, thereby increasing groundwater resources depletion.

CONSEQUENCES OF DEPLETING AQUIFERS

Although a large direct consequence of depleting groundwater resources is the loss of water supply, many other consequences of depletion also must be considered. These include impacts of groundwater depletion on hydrologically connected surface water bodies, how declining groundwater levels can decrease well productivity, how falling water tables can cause subsidence of lands that overlie an aquifer, and impacts of declining groundwater levels on aquifer water quality through leakage of poor-quality water from adjacent aquitards or from sea-water intrusion. Furthermore, declining groundwater levels will increase the energy requirements and pumping costs, and drilling deeper wells to access the remaining groundwater may be very costly.

Reduced Flow to Surface Water Systems and Ecosystems

Groundwater can be a source for surface water if the water in the aquifer has an outlet point on the surface. This can include base flow to streams, spring flows, and inflows to lakes and wetlands. When groundwater levels in an aquifer decline to below the level of surface water bodies, or are no longer in contact with surface outlet points, groundwater can no longer replenish surface water bodies but rather drain surface water to recharge groundwater.

The base flow to streams is often a critical resource in the western United States, especially for ecosystems, because this may be the only stream habitat during the dry summer months. In addition, flow from aquifers is typically more moderate in temperature than water flowing on the surface, and it is also typically cleaner because it is filtered as it flows through aquifer soils. In summer, when surface water supplies are typically at their lowest, this cool and clean supply can help maintain habitat for fish and other aquatic species, in addition to supporting human recreation. In the winter, the addition of flow may be warmer than that on the surface and can again improve the aquatic habitat.

Spring flows also are an important source of base flow. In southwestern Idaho, spring flow from Thousand Springs supplies moderate temperature and clean water to fish hatcheries. Groundwater pumping and decreased recharge have led to declines in aquifer levels, with some springs flowing at a decreased rate, resulting in hatcheries no longer having enough water for aquaculture production. They cannot use nearby water from the Snake River because of its lower quality and temperature variation for aquaculture production.

Loss of Productivity of Groundwater Wells

For unconfined aquifers, a decline in the water table results in a decline in the saturated thickness of an aquifer. As the saturated thickness of an aquifer decreases, there is less area for groundwater to flow from the aquifer into a well, which reduces well productivity. At some point the saturated thickness decreases to reduce well productivity below the water needs of a *water user*, which leads to the need to redrill (deepen) the existing well or construct additional newer wells in more favorable aquifer locations to supplement or replace the original well.

In West Texas and the Texas Southern High Plains, declining groundwater resources have often decreased well capacities and led to increased well drilling. In this area, it is common for producers to combine water from multiple wells to provide sufficient water flow for a single center pivot or subsurface drip irrigation system. California irrigators also have begun drilling more wells to replace lost surface water (Richtel 2015), leading to a "well-drilling boom" in the Central Valley, increasing associated problems including tensions between neighboring landowners and local land subsidence. Even municipal water supply customers anticipating restrictions on water use due to the enaction of the Sustainable Groundwater Management Act (SGMA 2014) have resorted to drilling additional wells. This increase in well-drilling activity has raised concern over groundwater depletion (Galbraith 2012) and results in an increased cost for developing groundwater resources for use as water supplies for all groundwater users.

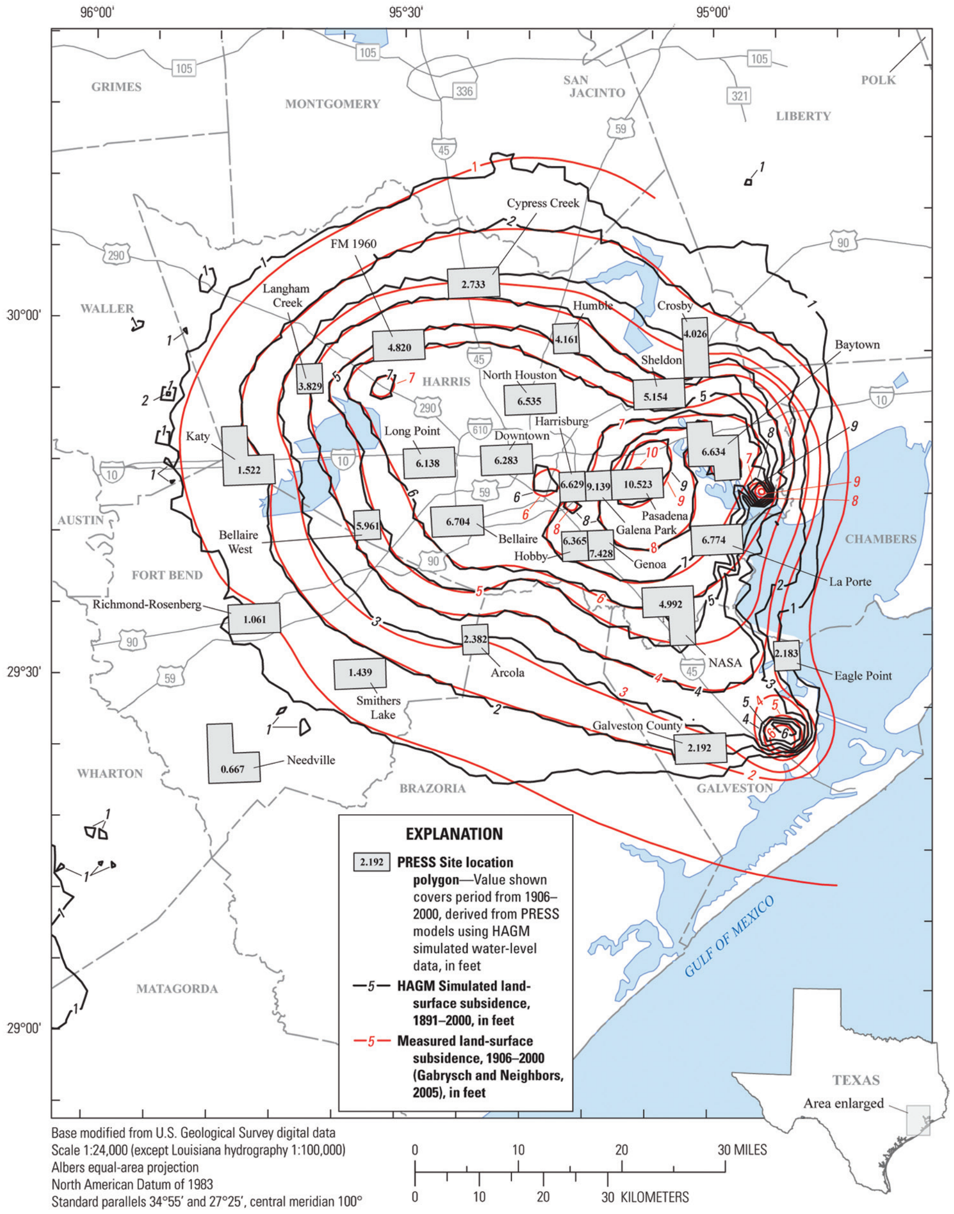
Subsidence of Land and Ground Failures

As groundwater is extracted from an aquifer, the materials that comprise the aquifer and aquitard (confining clay/silt beds) can compact, which can cause the land surface to move in both vertical and horizontal directions. In addition, groundwater pumpage can decrease the volume of water in an aquifer, which can lead to land settlement or subsidence. When groundwater is pumped from the aquifer, pore pressure decreases and the effective stresses between sediment particles increase (total stress minus pore pressure as defined by Terzaghi [1943], assuming total stress is constant). This increase in effective stress causes the volume of the aquifer to decrease.

Aquifers that contain a high proportion of clays, especially as clay lenses, are highly susceptible to compaction, because pore water slowly drains from these lenses from the surrounding deformable sediments. This is accompanied by a reduction of the voids between soil particles and a gradual transfer of effective stress from the pore water to the stress between soil particles for the porous sediments (Li and Sheng 2011). Once the compaction of clayey material has occurred, it cannot simply be reversed by recharging the aquifer with the amount of water that was extracted. This is because the deformation of the fine-grained (clay or silt) material is mostly inelastic; that is, once the soil particles are compressed and the stress between the soil particles has reached a new equilibrium, to expand the soil particles would require a much greater soil water pressure to separate the soil particles to reach the original porosity of the material. The nonrecoverable and cumulative vertical deformation of the different types of sediments in an aquifer manifests itself as land subsidence or settlement of the land surface. Note that coarse-grained material, such as sand and gravel, is often assumed to deform elastically.

Land subsidence from groundwater depletion has occurred in many areas of the U.S. arid southwest, including California, Arizona, Nevada, New Mexico, Texas, and other areas. In Las Vegas, Nevada, land surfaces have subsided about 1.9 m (6 ft) in some areas (Bell and Price 1993; Bell et al. 2002), with some areas of Houston, Texas, seeing around 3 m (10 ft) of land subsidence (Figure 8) (Kasmarek 2013). Parts of Phoenix, Arizona, have seen more than 5.8 m (18 ft) of subsidence (Galloway and Burbey 2011; Miller and Shirzaei 2015), and in California's San Joaquin Valley, some areas have seen 9.5 m (29 ft) of land subsidence (Figure 9) (Faunt et al. 2016; Galloway, Jones, and Ingebritsen 1999).

Ground failure, including surface faulting and earth fissures, also can occur from groundwater pumping and land subsidence (Li and Sheng 2011; Sheng, Helm, and Li 2003). Surface faults have a dominating shear component, whereas earth fissures are primarily soil tensile failure. An earth fissure typically starts as a small (mm-scale) tensile crack in the subsurface sediments, then grows upward because of mechanical piping and additional pumping stress, and eventually reaches the ground surface after breaking the sedimentary cover. Land subsidence and ground failures are closely related to



Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°

PRESS, Predictions relating effective stress to subsidence model
HAGM, Houston Area Groundwater Model

Figure 8. Predicted (1891–2009) and observed (1906–2000) subsidence in Houston, Texas (Kasmarek 2013).

Figure 9. Land subsidence in San Joaquin Valley, California (Galloway, Jones, and Ingebritsen 1999). The person standing by the post in the photo is Dr. J. F. Poland.

aquifer movement caused by groundwater pumping (Helm 1994). It should be noted that ground failure is not necessarily the direct result of land subsidence (Li and Sheng 2011; Sheng, Helm, and Li 2003). Ground failures caused by groundwater pumping have been observed in the Fremont Valley, San Jacinto Valley, and other areas in California (Holzer 1984; Shlemon and Davis 1992; Shlemon and Hakakian 1992); Las Vegas Valley, Nevada (Bell and Price 1993, Sheng, Helm, and Li 2003); southern Arizona (Carpenter 1993; Jachens and Holzer 1982); and Escalante Valley, Utah (Lund et al. 2005).

Both land subsidence and ground failures have damaged buildings, roads, and utilities, resulting in costly repairs needed to maintain and rebuild infrastructure. The lowering of land levels can also result in the changing of land slopes, which can have negative impacts on a variety of water infrastructure. Land subsidence can affect the drainage of water from flood events, which can result in flood drainage infrastructure becoming ineffective, thereby increasing the impacts of flooding events. In addition, land subsidence can result in lowering of the slope of open water canals, which decreases their operating capacity for delivering irrigation water to croplands.

Degradation of Groundwater Quality

Groundwater in coastal aquifers, or that overlies brackish groundwater, may also face degradation of groundwater quality from intensive groundwater pumping (Sheng and Devere 2005). Wherever a freshwater aquifer is hydraulically connected to large bodies of brackish or saline water, such as the ocean, pumping fresh groundwater can induce saltwater to flow into the aquifer to replace the extracted freshwater. Saltwater is denser than freshwater, which drives seawater to move inland under freshwater in an aquifer. Thus coastal aquifers will typically contain freshwater floating nearer the ground surface and saltwater deeper in the aquifer, with an interface between salt- and freshwater usually below sea level. As a general rule of thumb, this depth to the salt/freshwater interface is typically forty times greater than the height of the groundwater table above sea level (Ghyben-Herzberg principle [Freeze and Cherry 1979]). Such an interface is typically in an equilibrium under non-disturbed conditions (no groundwater pumpage).

When fresh groundwater in the coastal aquifer is pumped, the reduction in the groundwater level near the well causes the salt/freshwater interface to move upward. With continued groundwater extraction, the salt/freshwater interface will migrate upward and inland and can degrade groundwater quality as the saline water mixes into the original freshwater zone. An example of seawater intrusion is in the Central and West Coast Basins in southern California, where groundwater pumping has brought large groundwater-level declines (Hendley and Stauffer 2002; Johnson and Whitaker 2003; Reichard et al. 2003). Groundwater development in the Los Angeles area initially supported irrigated agriculture and is now predominantly used for municipal water supplies. To mitigate problems of seawater intrusion, several management measures have been employed, including freshwater well injection, surface spreading, and pumping restrictions to halt saltwater intrusion into freshwater aquifers. Surface water and increased use of reclaimed water have been used to replace the decreased availability of groundwater supplies (Johnson 2007; Reichard et al. 2003; WRD 2018). Inland aquifers, such as the Hueco Bolson, that are underlain by brackish aquifers lack as sharp a salt/freshwater interface as coastal aquifers. Intrusion of the underlying brackish water, however, also can occur as fresh groundwater in the aquifer is depleted (Sheng and Devere 2005) and brackish groundwater begins to mix with the freshwater. Depleting fresh groundwater will accelerate the degradation of groundwater quality and cause further loss of fresh groundwater supplies.

MITIGATING THE CONSEQUENCES OF GROUNDWATER DEPLETION

There is a growing recognition of the consequences of groundwater depletion. This has led to several approaches to mitigate or reverse groundwater depletion. This ranges from more direct approaches that attempt to address the hydrologic imbalance in aquifers that lead to groundwater depletion (e.g., decreasing pumpage or increasing recharge), to changes in how pumped groundwater is managed, to the better alignment of water management institutions and policies at local and state levels to encourage sustainable groundwater use.

Physical Approaches to Mitigating Depletion

The most direct approach to decreasing the depletion of groundwater is to simply extract less groundwater from aquifers. With agriculture being the largest user of groundwater in the United States, this means that any reduction in groundwater pumpage for irrigating cropland could decrease groundwater depletion. Irrigators have become highly savvy in water-limited regions in regard to their water use, applying new technologies to manage their water allotments to maximize crop yields and, ultimately, profits. One widely adopted technique in areas that rely heavily on groundwater for irrigation combines advanced application technology with an understanding of the spatial and temporal crop water needs. Weather, crop type, and soil conditions can help optimize water use by a crop to produce a reasonable yield.

Networks of automated weather stations—such as Agrimet, ASMET, CoAgMet, AgWeatherNet, and CIMIS—collect weather data for agricultural regions and use it to compute reference crop evapotranspiration (ET), which is used with research-based crop-specific coefficients to estimate crop water requirements. Irrigators can use ET-based information to match irrigation applications (rates and timing) to crop water needs, thus decreasing over-irrigation without undue risk of crop yield loss. This practice can have both positive and negative effects on groundwater, depending on where the water is coming from. If the irrigator previously irrigated with a less-efficient practice and used surface water, some of the excess delivery becomes aquifer recharge; eliminating this recharge will decrease recharge to the underlying aquifer. If the irrigator is pumping groundwater, this technique could reduce pumping from the aquifer, decreasing groundwater depletion and the farmer's costs.

Another direct approach to arresting groundwater depletion is to enhance groundwater replenishment using alternative water sources, by either directly injecting water into an aquifer or by increasing recharge using other water sources. Managed aquifer recharge (MAR) has been used to mitigate the effects of groundwater depletion in several areas (Dillon 2005; Pyne 2005; Sheng 2005; Sheng and Zhao 2015). Aquifer recharge typically falls into two categories—passive recharge and groundwater injection—with the cost and legal restrictions being very different for each category. Passive recharge occurs when water is placed on the ground surface or in a shallow infiltration gallery and is allowed to seep into the aquifer by gravity flow. Because the infiltration is similar to natural processes (i.e., rain falling on the ground and seeping into the ground), the permitting process is typically more lenient than injecting water into an aquifer, where water quality is a higher concern. Groundwater injection typically requires a well and typically needs more energy when water is forced into a confined aquifer. In many cases, water must be treated prior to injection to ensure that the interaction of the injected water and the aquifer soils does not clog the injection well and to meet water quality standards for aquifers that can potentially be used for drinking water.

The passive form of MAR has occurred for many years in the western United States with the delivery and application of irrigation water. An interesting example is in the Eastern Snake Plain aquifer in Idaho. Figure 10 depicts the annual-monthly low flow at the King Hill gage, below Thousand Springs (from 1910 to present), along with the difference in flow in the Snake River between the Buhl gage (mostly upstream of Thousand Springs) and the King Hill gage (1950 to present). Figure 10 shows that the trend in annual low monthly flow was increasing from the early 1900s through the 1950s, which corresponded with groundwater wells showing increased water levels over the same period. During this time, water was primarily delivered by unlined canals and applied to cropland using flood irrigation, resulting in significant aquifer recharge.

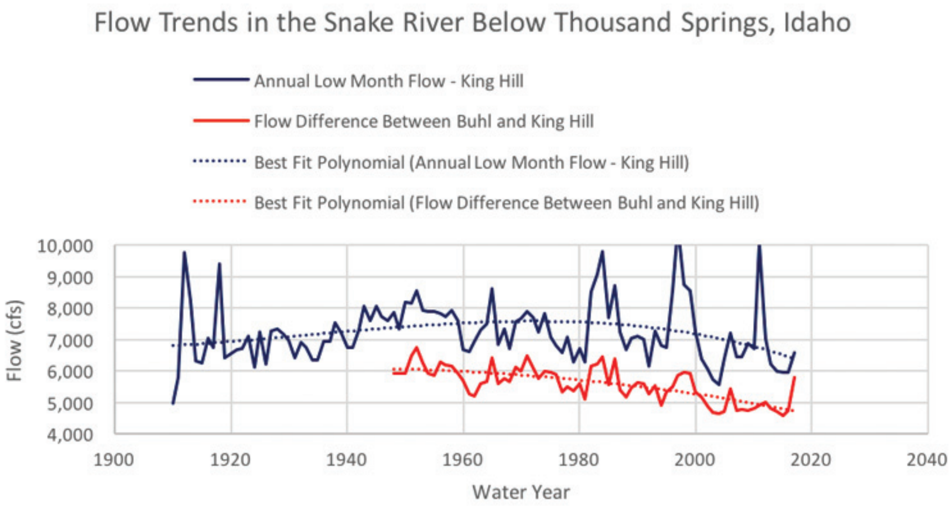


Figure 10. Flow trends in the Snake River below Thousand Springs, Idaho. (Data sources: U.S. Geological Survey National Water Information System.)

Around the middle of the 20th century, however, the annual low monthly flows in the Snake River below Thousand Springs began to fall, along with the discharge of groundwater from the East Snake Plain aquifer to the Snake River. This decline in low flows and groundwater discharge to the Snake River coincided with improved groundwater extraction technologies, resulting in more irrigators sourcing their water from groundwater and declining groundwater levels in the Eastern Snake Plain aquifer. In addition, surface water irrigators improved their delivery and application efficiency through the use of lined canals and sprinklers, which further decreased aquifer recharge and caused groundwater levels to continue to decline. Because many water rights were issued when groundwater levels were higher, there is now a deficit of about 0.75 km^3 (600,000 acre-ft) of water annually (Idaho Water Resource Board 2009). In recent years, to counteract declining aquifer levels, the State Water Board in Idaho began a managed recharge program to use unlined canals and infiltration ponds during the nonirrigation season to increase recharge by as much as 0.31 km^3 (250,000 acre-ft) per year.

The Treasure Valley aquifer in Idaho is an example of how managed recharge occurs as part of an irrigation and delivery system, maintaining groundwater in an annual equilibrium (Urban 2004). This is largely from the irrigation delivery system contributing to aquifer annual recharge. When the canal system was constructed and implemented in the late 1800s, it was noted that groundwater levels increased by as much as 30.5 m (100 ft) in some parts of the valley (Petrich 2004). As of this writing, groundwater pumping has not exceeded the recharge resulting from delivery and application of surface water to fields, and recharge has not been decreased by lining or piping substantial portions of the delivery system. This system presents an opportunity for thoughtful planning when creating efficiencies to maintain the balance that currently exists while improving the delivery and application of water.

Agricultural Management Approaches to Mitigating Depletion

Another method to decrease groundwater depletion is through changes to crop selection and agricultural practices. Changes in cropping in the Texas High Plains reflect responses to limited and declining (quantity and quality) groundwater. In the Northern Texas High Plains, grain corn is the predominant irrigated crop, whereas in the Southern High Plains where aquifer storage and well capacities are more limited, more drought-tolerant crops, including cotton, grain sorghum, and winter wheat, are prevalent (Colaizzi et al. 2009). Applied research programs in the region evaluate—and regional water planning efforts advocate—water conservation strategies, including conversion to higher efficiency irrigation technologies, data-based irrigation scheduling, changes in crop types to less water-demanding or more drought-tolerant crops and varieties, conservation tillage methods, and conversion from "full" irrigated production to limited irrigation or dryland (rainfed) production (Amosson et al. 2016). Adoption of these strategies in the High Plains region of Texas has led to significant reductions in groundwater pumpage, where improved irrigation scheduling for corn has reduced water use by 5.1–7.6 hectare-cm per hectare (2–3 acre-inches per acre); adoption of more efficient irrigation application methods (e.g., conversion from furrow to low-pressure center-pivot irrigation) has decreased water use by 3.3–8.9 hectare-cm per hectare (1.3–3.5 acre-inches per acre); and changes in cropping systems from corn to cotton, wheat, and grain sorghum production have decreased water use by 19.8–21.8 hectare-cm per hectare (7.8–8.6 acre-inches per acre) (Amosson et al. 2016).

In some cases, producers seek to concentrate limited irrigation supplies on smaller acreages of higher value crops, such as wine grapes (Latzke 2017). Considerations of whether or not to adopt cover crops include weighing the relative value of improved soil conditions (soil health) afforded by cover crops against the water demand for establishing the cover crops. Agricultural research programs are advancing—and producers are adopting—drought-tolerant, short-season, and salt-tolerant varieties and irrigation management strategies to lower water use and increase water use efficiency while maintaining yields and quality (Xue et al. 2017).

By 2012, an estimated 87% of irrigated crop acreage (or about1.6 million hectares [3.9 million acres]) in Texas was irrigated with low-pressure center-pivot irrigation (Wagner 2012); an estimated 101,171 hectares (250,000 acres) of subsurface drip irrigation had been installed by 2004 (Colaizzi et al. 2009), increasing to more than 141,640 hectares (350,000 acres) by 2015. Adoption of more efficient irrigation technologies and strategies and more drought-tolerant crops and varieties has been encouraged by water-limited conditions (limited well capacities), availability of low-interest loan programs and cost-share programs, and suitability of the technologies to the local production systems. Where water saved by improved irrigation efficiency is simply used to irrigate more acreage, however, overall consumptive use and aquifer depletion can increase (Grafton et al. 2018).

Policy and Institutional Approaches to Mitigating Depletion

Since each state has primacy over its water resources (in essence allowing each state to set its own rules on access and use of its water resources), a wide range of policy and institutional approaches has developed to address groundwater depletion across the United States. These approaches tend to fall into three categories:

- Centralized regulatory control by including groundwater under prior appropriations doctrine
- Decentralized regulatory control by allowing quasi-independent groundwater management agencies with limited regulatory authority
- Financial incentive programs

Each approach has advantages and disadvantages, and no one approach can be applied to all groundwater depletion situations. All states in the continental western United States (west of the 100th meridian) use the doctrine of prior appropriations for allocating surface water rights. All of these states—except California, Nebraska, Oklahoma, and Texas—also use the doctrine of prior appropriation to allocate rights to use groundwater. The underlying rules of the doctrine of prior appropriation are that (1) no junior water user may negatively impact a *senior water user*, and (2) water must be used in a beneficial manner. If the first rule is to be met, there is an underlying assumption that there is a sustainable amount of groundwater use associated with an aquifer, because any use beyond this sustainable amount would negatively impact the ability of senior water users to receive future water allocations if an aquifer is being depleted over time. Thus, while not often explicitly stated, this implies that groundwater must be used in a sustainable manner under the prior appropriations doctrine.

The governance structure for groundwater under the prior appropriation doctrine is in a state water agency (e.g., the Idaho Department of Water Resources), where disputes of access and use of groundwater are resolved through administrative or legal proceedings. The management of groundwater in these states is typically more localized, where decisions on the timing of water use are at the discretion of individual water users or groundwater districts. On the surface, the underlying principle of requiring that water be used in a "sustainable" manner would appear to prevent the depletion of groundwater resources. In practice, however, governing access and use of groundwater under the prior appropriation doctrine has not addressed groundwater depletion for three primary reasons.

First, the prior appropriations doctrine typically includes a rule for the consistent beneficial use of water. If the water right holder does not use water in a beneficial manner, they can lose their future water use right. Often referred to as the "use it or lose it" rule, this provides incentive to use water by a groundwater rights holder, even in wet years when groundwater is not needed, or profitable, to produce a crop. This increases long-term groundwater extraction and exacerbates depletion of groundwater.

The second prior appropriations doctrine issue is that its governance structure does not address groundwater resources in nonreplenishable conditions, such as the southern High Plains aquifer. Strict interpretation of the prior appropriations doctrine would severely curtail pumpage throughout the southern High Plains aquifer because recharge rates are a small fraction of current water use and the current groundwater use is not sustainable. Because rights to pump groundwater were granted long ago (many more than 50 years old) and significant investments were made to develop an agricultural economy in the region, accommodations have been made within the application of the prior appropriations doctrine to allow for continued use of groundwater within the High Plains aquifer, even though depletion of the aquifer is continuing.

The third issue with the prior appropriations doctrine is that its governance structure does not address the wide range of consequences caused by groundwater depletion—only directly related consequences—impairing other water right holders. Thus, the use of the prior appropriations doctrine does not address the issues of water quality degradation and land subsidence caused by groundwater depletion.

California, Nebraska, Oklahoma, and Texas have taken a different approach for developing frameworks to govern access to and use of groundwater. These states treat access to groundwater as *correlative rights*, in which a land owner has the right to capture groundwater beneath their land for a beneficial use, which is often referred to as the rule of capture. This approach has led to a variety of issues caused by the depletion of groundwater resources, because in its initial form groundwater use was almost completely unregulated. The issues that have occurred across Texas include land subsidence along the Gulf Coast Region, to decreases in spring flows for critical habit in Central Texas, to drying up of wells in the Texas Panhandle.

To address "unregulated use," these states have developed frameworks to require decentralized groundwater regulatory authorities and management. Within Texas these are called GCDs (TCEQ 2017), typically formed along county political boundaries; within California these are being developed as groundwater sustainability agencies (California Department of Water Resources 2018), with administrative boundaries that align more to hydrographic than general political jurisdictions; and within Nebraska they are referred to as NRDs to permit the development and use of groundwater wells within an aquifer or region. These localized, or regionalized, groundwater regulatory entities are responsible for developing metrics of groundwater conditions that address impacts of groundwater depletion and establish limits on groundwater extraction for groundwater users within their jurisdiction, subject to review and approval by state water agencies.

This approach allows groundwater regulatory and management structures to address the broad range of groundwater depletion issues. It appears to only address groundwater depletion issues in a reactive fashion, however, because groundwater regulatory entities have tended to be established in response to groundwater depletion after it has become a concern, and the approach does not provide a mechanism to prevent the consequences of groundwater depletion before they occur.

A final approach to help decrease groundwater depletion is through financial incentives that encourage water conservation. These include low-interest loan programs (TWDB 2016, 2018) and cost-share programs (USDA–NRCS 2016, 2018) to financially assist agricultural irrigators in converting from lower-efficiency to higher-efficiency irrigation methods. These can include replacing furrow irrigation with low-pressure precision irrigation systems, such as center-pivot and subsurface drip irrigation, in addition to the use of soil moisture sensing and ET-based irrigation scheduling. Payment programs that incentivize temporary or permanent conversion of irrigated land to dryland production or taking marginal lands out of production (USDA–FSA 2017) are also being used to decrease the extraction of groundwater from the aquifer. These approaches have the largest positive impact on decreasing groundwater depletion for agricultural areas irrigated using groundwater resources because they provide financial incentives to extract less groundwater with little to no impact on surface water supplies. Conversely, these incentives can have a negative impact on groundwater depletion if used to increase irrigation efficiency for agricultural areas using surface water resources because this can lead to decreased groundwater recharge, as is noted earlier (Grafton et al. 2018).

CASE STUDY ON CAUSES, CONSEQUENCES, AND MITIGATION OF GROUNDWATER DEPLETION

The causes of groundwater depletion, its consequences, and the development of effective measures to mitigate depletion can be complex to describe and understand. A brief case study helps illustrate this topic.

The Causes and Consequences of Groundwater Depletion in the Pumpkin Creek Watershed

The Pumpkin Creek watershed is a small area of the High Plains aquifer in the Nebraska Panhandle, primarily in Banner and Morrill Counties (Figure 11). Pumpkin Creek is a small tributary to the North Platte River. The creek begins about 8 miles east of the Wyoming-Nebraska state line and flows east for about 30 miles to its confluence with the North Platte River near Bridgeport, Nebraska. Flows to the North Platte River ranged from 67,500 to 100,000 m^3/day (100,000 to 150,000 ft^3/hour) from before 1930 to the mid-1960s (Sievers 2005).

The aquifer in this watershed is limited and groundwater is contained primarily in Quaternary Period (2.6 million to 11.7 thousand years ago) alluvium deposited along Pumpkin Creek and its tributaries. The alluvium is sand and gravel deposited in a channel approximately 0.8 km (0.5 mile) wide with a maximum thickness of 30.5 m (100 ft). The sands and gravels have excellent hydraulic conductivity, and irrigation well yields can exceed 3,780 liters per minute (1,000 gallons per minute) in Morrill County where the alluvium is thicker. The underlying Brule Formation (Oligocene Epoch, 33 to 23 million years ago) is a thick sequence, 120–210 m (400–700 ft) of siltstone that is considered bedrock except where it is fractured or has isolated lenses of sand and gravel. The fracture zones of the Brule Formation have excellent hydraulic conductivity but low storage (Sibray and Zhang 1994). The fracture zones are found closely proximate to the alluvium of Pumpkin Creek.

Irrigation wells developed in the fractured Brule Formation can yield large quantities of water where there is a good hydraulic connection to saturated alluvium with good storage characteristics. Fractured Brule Formation wells with little or no hydraulic connection to saturated alluvium will quickly lose yield during the growing season (Smith and

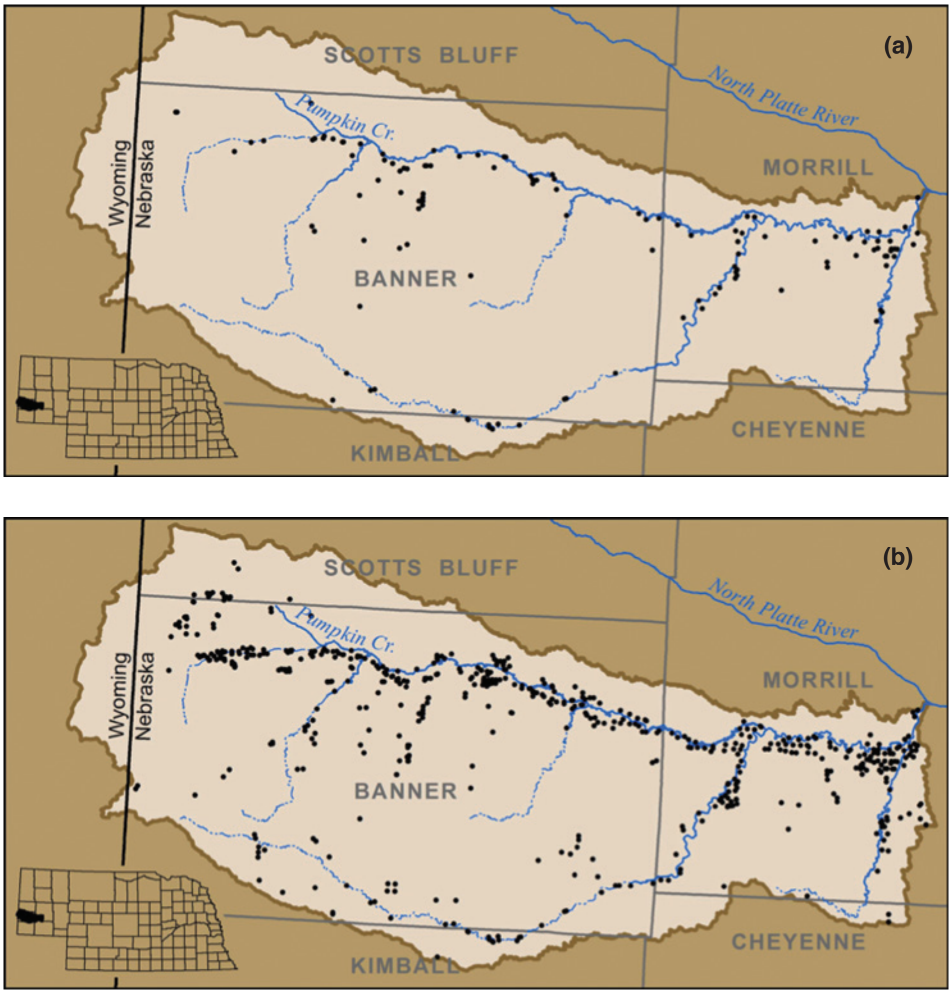


Figure 11. Groundwater pumping wells in Pumpkin Creek Watershed (a) circa 1965 and (b) current (2001).

Souders 1975). The age of groundwater in the fractured Brule Formation had a median value in the 1970s, whereas the water from the alluvial aquifer varied from 1980 to modern (Steele et al. 2005). These age dates indicate the groundwater resource is relatively renewable. Because of the high hydraulic conductivity of both the alluvium and the fractured Brule Formation and the close proximity of the wells to surface water, however, groundwater pumping can impact Pumpkin Creek quickly. As noted by Bredehoeft (1997), pumping does not have to exceed recharge for streams to be depleted.

During the 1890s, the irrigation potential of Pumpkin Creek was recognized and farmers began to obtain water rights from the state of Nebraska under the prior appropriations doctrine. Flows in Pumpkin Creek were highest in spring and decreased through the summer. Beginning in the 1960s, drought and the adoption of center-pivot irrigation technology greatly expanded irrigated acreage using groundwater. In the 1970s, surface water irrigators were experiencing insufficient flows. The Nebraska Department of Water Resources, now Department of Natural Resources (DNR), responded by closing the Pumpkin Creek drainage to any additional surface water permits in 1979. Since the local NRD (North Platte NRD) lacked authority to regulate groundwater in response to impacts on surface water, groundwater-irrigated acres continued to grow. In 1965, there were 123 registered irrigation wells (Figure 11a). Faced with diminishing flows, most surface water irrigators drilled wells and relinquished their surface water rights. A few surface water irrigators were unable to drill wells because of unfavorable geology and were no longer able to irrigate. During the 1990s, precipitation was above average—380–430 mm/yr (15–17 in/yr)—but flows in Pumpkin Creek continued to decline. By 1999, the Nebraska Department of Water Resources recorded zero flow at the Banner/Morrill County line. In 1939, there was as much as 0.4 m^3/second (14 ft^3/second) of flow at this measuring station (T. Hayden, Personal communication).

Beginning in the year 2000, drought greatly exacerbated the situation in Pumpkin Creek and groundwater level declines became noticeable in areas where the surface water was depleted; the North Platte Natural Resource District placed a moratorium on new irrigation wells in the Pumpkin Creek area. At that time, there were 587 registered irrigation wells in the watershed (Figure 11b). Because of highly variable precipitation, allocations are now given on more than a five-year water year basis. Pumping capacity of individual wells is highly variable because of the thin and variable thickness of the aquifer. As a result, in many irrigated fields, pumping capacity is less than allocation and the regulatory burden is on the better producing wells.

Because of drought and groundwater pumping, Spear T Ranch, just east of the Banner/Morrill County line, could no longer provide water for cattle. In 2003, the Spear T Ranch sued 23 upstream groundwater irrigators in a case that went to the Nebraska Supreme Court. In 2005, that court decided that surface water users could sue groundwater irrigators for damages, provided they could prove unreasonable interference. In 2004, due to the drought and potential legal conflict between surface and groundwater users, the Nebraska Legislature passed LB962, which gives the DNR authority to jointly regulate hydrologically connected groundwater and surface water within local NRDs. The Pumpkin Creek area is now in an "over appropriated" groundwater management area in which groundwater depletions of surface water must be decreased to levels that existed in 1997. Beginning in 2006, the irrigated area in the Pumpkin Creek basin was decreased by 1,123.6 hectares (2,776.4 acres) to 15,935.4 hectares (39,377.3 acres) with conservation easements administered by the U.S. Department of Agriculture (B. Cross, Personal communication). These actions give some relief to the Spear T Ranch, but it is uncertain if sufficient water flow in Pumpkin Creek will be restored to allow diversions for surface water irrigation.

Lessons from Pumpkin Creek

The most important lesson from the Pumpkin Creek conflicts is that in an area where groundwater and surface water are scarce and hydrologically connected, groundwater pumping will degrade and possibly eliminate surface water flows and severely impair the ability of senior water users to receive water, unless there are legal protections for surface water users.

Another lesson learned in the Pumpkin Creek case is contrary to the common misperception that groundwater development has a unique sustainable pumping rate directly related to recharge rates because the impacts of groundwater pumping on streamflow happened quickly. The rapid impact was due to the aquifer's high hydraulic conductivity and the close proximity of the wells to Pumpkin Creek. In addition, there were no noticeable groundwater level declines until the surface water was completely depleted because the surface water in Pumpkin Creek replenished water extracted from the alluvial aquifer. In contrast to a simple concept of a single "sustainable" pumping rate policy, there is a range of groundwater pumping policy options depending on the desired flow in Pumpkin Creek.

Because of the heterogeneous nature and the shallow nature of the aquifer, many marginal wells exist in the Pumpkin Creek alluvium, and the current allocation of water puts the regulatory burden on the most productive groundwater wells. Policymakers who would like to increase surface water flows are confronted with whether decreasing water allocations or retiring marginal acres would be the most effective and economic means of restoring flows to Pumpkin Creek. The heterogeneous and renewable nature of the aquifer also leads to the conclusion that as long as pumping is restricted to irrigating overlying land, the complete absence of any other restrictions would result in the "survival of the deepest" well. This may not be an economically optimal outcome for agricultural water users within the Pumpkin Creek watershed and it could deprive downstream surface water irrigators of their water rights during drought.

Summary and Key Points

As highlighted in the above discussion, there are a number of consequences that arise when groundwater resources are depleted, as well as a wide range of factors that cause the depletion of groundwater resources. Thus, it should be no surprise that the development of plans to effectively mitigate or reverse the impacts of groundwater depletion must account for all of these factors, and the key issues that must be understood to address the complex issues associated with groundwater depletion are the following:

- The continued population growth in the United States and the world will increase competition for food and water supplies, which will increase stress on water resources and amplify the importance of sustainable water and food.
- This heightened stress will increase reliance on groundwater systems for direct supply and buffering the variability of surface water supplies.
- Reliance on groundwater will continue to put groundwater at risk of depletion, which is already a growing problem across the United States.
- The direct consequences of groundwater depletion are declines in water tables, which decrease well yields and may cause shallower wells to go dry. Drilling new, deeper wells is expensive, and many agricultural producers will choose (or be forced) to decrease irrigated acreage or take other steps in response to reduced availability of groundwater.
- For aquifers in arid regions primarily recharged by seepage from inefficient water delivery and irrigation, groundwater depletion can be exacerbated by reductions in recharge caused by increases in water delivery and irrigation system efficiencies.
- Several longer-term consequences of groundwater depletion must also be considered, including
    - ▫ reduction of groundwater inflows to streams, springs, and wetlands that degrade the ability of surface water users to receive their allocations and threaten the sustainability of riparian ecosystems;
    - ▫ shifting or subsidence of land surfaces that overlie depleting groundwater; and
    - ▫ degradation of groundwater quality.
- The consequences of groundwater depletion can be mitigated through a mixture of water management policies that directly addresses the hydrologic imbalance in an aquifer, either by
    - ▫ increasing the recharge to an aquifer through the use of MAR or altering land use practices to enhance the infiltration of rainfall below the soil surface; or
    - ▫ decreasing groundwater demand through the use of more efficient irrigation methods and encouraging the transition from irrigation to dryland agricultural production systems at the regional scale.

Use of a groundwater resource requires that the groundwater table must be drawn down to some degree before it can be used in a beneficial manner. This means that lowering of an aquifer's groundwater table in small amounts is unavoidable and not in and of itself a negative condition. Long-term and excessive declines in an aquifer's water table, however, can result in many undesirable impacts. Thus, when developing policies that regulate groundwater and practices that manage the use of groundwater resources, the potential consequences of groundwater depletion need to be fully assessed to determine the trade-offs that exist between the undesired impacts of groundwater depletion and whether these impacts outweigh the benefits associated with groundwater use.

GLOSSARY

To effectively improve understanding of the causes and consequences of groundwater depletion, definitions must be provided for a variety of terms that are used to describe the use of water, the management and governance systems that have been created to determine who has access to groundwater resources, and what is meant by the term groundwater depletion itself.

Correlative right. Limits the rights of a landowner to use a common resource, typically limited by the amount of land owned by the user that overlies the resource, such as groundwater.

Groundwater (or aquifer) depletion. Defined simply as a continuous reduction in the volume (or mass) of water stored in an aquifer. The volume of water in the aquifer naturally can vary with time due to variations in recharge that arise from daily, weekly, or seasonal weather variations. Such short-term variations are not of concern if they average out over the long run. Year over year trends of diminished volumes of groundwater, however, are of concern.

Junior water user. Has a low priority water right date and may be required not to divert water in situations where there is not enough for everyone's needs.

Potentiometric surface. A two-dimensional surface that represents the static head in an aquifer and is defined by the levels to which water will rise in tightly cased wells.

Prior appropriation. The doctrine that determines which and when entities may divert water in the western United States, also known as "first in time, first in right." The doctrine generally states that the entities to first divert water and put it to a beneficial use get first priority every year and subsequent diverters may take their water in the order in which they first started using it.

Senior water user. Has a high priority water right date and in most situations is able to divert the water it needs.

Water right. The mechanism that is used to dictate the diversion priorities in the prior appropriation system. Each water right has a priority date that corresponds to the date they first diverted the water and a volume or flow rate that limits the amount of water they can divert.

Water user. An entity that diverts water from a river or pumps it from an aquifer for agricultural, municipal, industrial, or other beneficial use.

LITERATURE CITED

Amosson, S., S. Nair, B. Guerrero, and T. Marek. 2016. 2016 Panhandle regional water plan task 5 report: Agricultural water management strategies. In *2016 Panhandle Water Plan, Volume II*. Texas Water Development Board.

Barlow, P. M. and S. A. Leake. 2012. *Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow*. U.S. Geological Survey Circular 1376. U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia. 95 pp.

Bell, J. W. and J. G. Price. 1993. *Subsidence in Las Vegas Valley, 1980–91: Final Project Report*. Open-File Report 93-4, Nevada Bureau of Mines and Geology. 181 pp.

Bell, J. W., F. Amelung, A. R. Ramelli, and G. Blewitt. 2002. Land subsidence in Las Vegas, Nevada, 1935–2000: New geodetic data show evolution, revised spatial patterns, and reduced rates. *Environ Eng Geosci* 8 (3): 155–174.

Bredehoeft, J. D. 1997. Safe yield and the water budget myth. *Ground Water* 35 (6): 929.

Bredehoeft, J. D. and T. J. Durbin. 2009. Ground water development—The time to full capture problem. *Ground Water* 47 (4): 506–514, doi:10.1111/j.1745-6584.2008.00538.x.

Bredehoeft, J. D., S. S. Papadopulos, and H. H. Cooper Jr. 1982. Groundwater—The water-budget myth. Pp. 51–57. In National Research Council. *Scientific Basis of Water-resource Management*. National Academy Press, Washington, D.C.

California Department of Water Resources. 1977. The California Drought 1977: An Update—February 15, 1977. State of California, The Resources Agency, Department of Water Resources, http://www.water.ca.gov/waterconditions/docs/12_drought-1977.pdf (10 April 2018)

California Department of Water Resources. 2018. *Actions for Local Agencies to Follow When Deciding to Become or Form a Groundwater Sustainability Agency (GSA)*. 6 pp., https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Sustainable-Groundwater-Management/Groundwater-Sustainability-Agencies/Files/GSA-Formation-Notification-Guidelines-for-Local-Agencies.pdf (16 January 2019)

Carpenter, M. C. 1993. *Earth-fissure Movements Associated with Fluctuations in Groundwater Levels Near the Picacho Mountains, South-central Arizona, 1980–84*. U.S. Geological Survey Prof. Paper 497-H, U.S. Government Printing Office, Washington, D.C.

Colaizzi, P., P. Gowda, T. Marek, and D. Porter. 2009. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *Irrig Drain* 58:257–274, https://doi.org/10.1002/ird.418 (11 April 2018)

Dethloff, H. C. and G. L. Nall. 2018. Agriculture. *Handbook of Texas Online*. Texas State Historical Association, http://www.tshaonline.org/handbook/online/articles/ama01 (11 April 2018)

Dillon, P. J. 2005. Future management of aquifer recharge. *Hydrogeol J* 13 (1): 313–316.

Döll, P., H. M. Schmied, C. Schuh, F. T. Portmann, and A. Eicker. 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resour Res* 50 (7): 5698–5720.

Faunt, C. C., M. Sneed, J. Traum, and J. T. Brandt. 2016. Water availability and land subsidence in the Central Valley, California, USA. *Hydrogeol J* 24 (3): 675–684.

Freeze, R. A. and J. A. Cherry. 1979. *Groundwater*. Prentice-Hall, New York. 604 pp.

Gabrysch, R. K. and R. J. Neighbors. 2005. Measuring a century of subsidence in the Houston-Galveston region, Texas, USA. Pp. 379–387. In *Proceedings: Seventh International Symposium on Land Subsidence*, Shanghai, P. R. China, 23–28 October 2005.

Galbraith, K. 2012. "A rush for water wells as Texas drought drags on." *The Texas Tribune*, February 17, https://www.texastribune.org/2012/02/17/texas-drought-sparks-water-well-drilling-frenzy/ (11 April 2018)

Galloway, D. L. and T. J. Burbey. 2011. Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeol J* 19 (8): 1459–1486, doi:10.1007/s10040-011-0775-5.

Galloway, D. L., D. R. Jones, and S. E. Ingebritsen, eds. 1999. *Land Subsidence in the United States*. U.S. Geological Survey Circular 1182. 177 pp.

Galloway, D. L., W. M. Alley, P. M. Barlow, T. E. Reilly, and P. Tucci. 2003. *Evolving Issues and Practices in Managing Ground-water Resources: Case Studies on the Role of Science*. U.S. Geological Survey Circular 1247. 73 pp.

Gisser, M. and D. A. Sanchez. 1980. Competition versus optional control in groundwater pumping. *Water Resour Res*16 (4): 638–642.

Gleeson, T., K. M. Befus, S. Jasechko, E. Luijendijk, and M. B. Cardendas. 2016. The global volume and distribution of modern groundwater. *Nat Geosci* 9 (2): 161–167.

Grafton, R. Q., J. Williams, C. J. Perry, F. Molle, C. Ringler, P. Steduto, B. Udall, S. A. Wheeler, Y. Wang, D. Garrick, and R. G. Allen. 2018. The paradox of irrigation efficiency. *Science* 361 (6404): 748–750.

Heath, R. C. 1983. *Basic Ground-water Hydrology*. U.S. Geological Survey, Water Supply Paper 2220. 84 pp.

Helm, D. C. 1994. Hydraulic forces that play a role in generating fissures at depth. *Bull Assoc Eng Geol* 16 (3): 293–304.

Hendley, J. W. II and P. H. Stauffer. 2002. *Saltwater Intrusion in Los Angeles Area Coastal Aquifers—The Marine Connection*. U.S. Geological Survey Fact Sheet, http://pubs.usgs.gov/fs/2002/fs030-02/fs030-02.pdf (21 June 2018)

Holzer, T. L. 1984. Ground failure induced by ground-water withdrawal from unconsolidated sediment. In T. L. Holzer (ed.). *Man-induced Land Subsidence, Reviews in Engineering Geology, Vol. 6*. The Geological Society of America, Boulder, Colorado.

Idaho Water Resource Board. 2009. *Eastern Snake Plain Aquifer (ESPA)—Comprehensive Aquifer Management Plan*. January.

Jachens, R. C. and T. L. Holzer. 1982. Differential compaction mechanism for earth fissures near Casa Gande, Arizona. *Geol Soc Am Bull* 93:998–1012.

Johnson, T. A. 2007. Battling seawater intrusion in the Central & West Coast Basins. *WRD Technical Bulletin* 13, http://www.wrd.org/sites/pr/files/TB13%20-%20Battling%20Seawater%20Intrsusion%20in%20the%20Central%20%26%20West%20Coasts%20Basins.pdf (21 June 2018)

Johnson, T. A. and R. Whitaker. 2003. Saltwater intrusion in the coastal aquifers of Los Angeles County, California. Ch. 2 (pp. 29–48). In A. H. Cheng and D. Ouazar (eds.). *Coastal Aquifer Management*. Lewis Publishers, Boca Raton, Florida.

Kasmarek, M. C. 2013. *Hydrogeology and Simulation of Groundwater Flow and Land-surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891–2009*. U.S. Geological Survey Scientific Investigations Report 2012-5154. Prepared in cooperation with the Harris-Galveston Subsidence District, the Fort Bend Subsidence District, and the Lone Star Groundwater Conservation District.

Konikow, L. F. 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys Res Lett* 38 (17), https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011GL048604 (10 September 2018)

Konikow, L. F. 2013. *Groundwater Depletion in the United States (1900−2008)*. U.S. Geological Survey Scientific Investigations Report 2013-5079. 63 pp., http://pubs.usgs.gov/sir/2013/5079 (10 April 2018)

Konikow, L. F. 2015. Long-term groundwater depletion in the United States. *Groundwater* 53 (1): 2–9, doi:10.1111/gwat.12306.

Koundouri, P. 2004. Potential for groundwater management: Gisser-Sanchez effect reconsidered. *Water Resour Res* 40 (6). 13 pp, https://www.researchgate.net/publication/248808771_Potential_for_Groundwater_Management_Gisser-Sanchez_Effect_Reconsidered (12 October 2018)

Latzke, J. M. 2017. “Wine grapes and cotton bring sustainability to Texas farm.” *High Plains Journal*, November 13, http://www.hpj.com/crops/wine-grapes-and-cotton-bring-sustainability-to-texas-farm/article_31d701aa-c650-11e7-bf33-fbdbd75a4f78.html (11 April 2018)

Leake, S. A. 2011. Capture—Rates and directions of groundwater flow don’t matter! *Ground Water* 49 (4): 456–458, doi:10.1111/j.1745-6584.2010.00797.x.

Li, J. and Z. Sheng. 2011. Geological hazards due to groundwater discharge/recharge. Ch. 17 (pp. 238–281). In A. N. Findikakis and K. Sato (eds.). *Groundwater Management Practices* (IAHR Monograph). CRC Press, Boca Raton, Florida.

Lohman, S. W. 1972. *Definitions of Selected Groundwater Terms—Revisions and Conceptual Refinements*. U.S. Geological Survey, Water Supply Paper 1988.

Lowry, M. E., M. A. Crist, and J. R. Tilstra. 1967. Geology and ground-water resources of Laramie County, Wyoming (section on Chemical quality of ground water and of surface water by J. R. Tilstra). Water-supply Paper 1834, U.S. Geological Survey. 71 pp.

Luckey, R. R., E. D. Gutentag, and J. B. Weeks. 1981. Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA–652, 2 sheets, scale 1:2,500,000, http://pubs.er.usgs.gov/publication/ha652 (11 September 2018)

Lund, W. R., C. B. DuRoss, S. M. Kirby, G. N. McDonald, G. Hunt, and G. S. Vice. 2005. *The Origin and Extent of Earth Fissures in Escalante Valley, Southern Escalante Desert, Iron County, Utah*. Utah Geological Survey, a division of Utah Department of Natural Resources, Special Study 115.

MacEwan, D., M. Cayar, A. Taghavi, D. Mitchell, S. Hatchett, and R. Howitt. 2017. Hydroeconomic modeling of sustainable groundwater management. *Water Resour Res* 53 (3): 2384–2403.

Margat, J. and J. van der Gun. 2013. *Groundwater around the World*. CRC Press/Balkema, Florence, Kentucky.

Matthai, H. F. 1979. *Hydrologic and Human Aspects of the 1976–77 Drought*. U.S. Geological Survey Professional Paper 1130. U.S. Government Printing Office, Washington, D.C., https://pubs.usgs.gov/pp/1130/report.pdf (10 April 2018)

Maupin, M. A., J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey. 2014. *Estimated Use of Water in the United States in 2010*. U.S. Geological Survey Circular 1405.

Maurer, D. K. and D. L. Berger. 2006. *Water Budgets and Potential Effects of Land- and Water-Use Changes for Carson Valley, Douglas County, Nevada, and Alpine County, California*. U.S. Geological Survey Scientific Investigations Report 2006-5305. 77 pp.

McGuire, V. L. 2014. *Water-level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011–13*. U.S. Geological Survey Scientific Investigations Report 2014-5218. 14 pp., http://dx.doi.org/10.3133/sir20145218 (10 April 2018)

Miller, M. M. and M. Shirzaei. 2015. Spatiotemporal characterization of land subsidence and uplift in Phoenix using InSAR time series and wavelet transforms. *J Geophys Res-Sol Ea* 120:5822–5842, doi:10.1002/2015JB012017.

Musick, J. T., F. B. Pringle, W. L. Harman, and B. A. Stewart. 1990. Long-term irrigation trends—Texas High Plains. *Appl Eng Agric* 6 (6): 717–724.

Nieswiadomy, M. 1985. The demand for irrigation water in the High Plains of Texas, 1957–80. *Am J Agr Econ* (67) 3: 619–626.

North Plains Groundwater Conservation District (NPGCD). 2016. GMA 1 approves desired future conditions for Panhandle counties. *North Plains Groundwater Conservation District*, http://northplainsgcd.org/news/gma-1-approves-desired-future-conditions-panhandle-counties/ (12 October 2018)

Petrich, C. R. 2004. *Simulation of Ground Water Flow in the Lower Boise River Basin*. Idaho Water Resources Research Institute, University of Idaho. February. IWRRI-2004-02.

Pyne, R. D. G. 2005. *Aquifer Storage Recovery: A Guide to Groundwater Recharge through Wells*. ASR Systems, Gainesville, Florida.

Reichard, E. G., M. Land, S. M. Crawford, T. Johnson, R. R. Everett, T. V. Kulshan, D. J. Ponti, K. J. Halford, T. A. Johnson, K. S. Paybins, and T. Nishikawa. 2003. *Geohydrology, Geochemistry, and Ground-Water Simulation-Optimization of the Central and West Coast Basins, Los Angeles County, California*. U.S. Geological Survey, Water-Resources Investigations Report 03-4065, Sacramento, California.

Richtel, M. 2015. “California farmers dig deeper for water, sipping their neighbors dry.” *The New York Times*, June 15, https://www.nytimes.com/2015/06/07/business/energy-environment/california-farmers-dig-deeper-for-water-sipping-their-neighbors-dry.html (11 April 2018)

Scanlon, B. R., Z. Zhang, R. C. Reedy, D. R. Pool, H. Save, D. Long, J. Chen, D. M. Wolock, B. D. Conway, and D. Winester. 2015. Hydrologic implications of GRACE satellite data in the Colorado River Basin. *Water Resour Res* 51:9891–9903, doi:10.1002/2015WR018090.

Sheng, Z. 2005. An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas. *J Environ Manage* 75 (4): 367–377.

Sheng, Z. and J. Devere. 2005. Understanding and managing the stressed Mexico-USA transboundary Hueco bolson aquifer in the El Paso del Norte region as a complex system. *J Hydrogeol* 13 (5–6): 813–825.

Sheng, Z. and X. Zhao. 2015. Special issue on managed aquifer recharge: Powerful management tool for meeting water resources challenges. *J Hydrol Eng* 20 (3), doi:10.1061/(ASCE)HE.1943-5584.0001139.

Sheng, Z., D. C. Helm, and J. Li. 2003. Mechanisms of earth fissuring caused by groundwater withdrawal. *Environ Eng Geosci* 9 (4): 313–324.

Shlemon, R. J. and P. Davis. 1992. Ground fissures in the Temecula area, Alameda County, California. Pp. 275–288. In B. W. Pipkin and R. J. Proctor (eds.). *Engineering Geology Practice in Southern California, AEG Special Publication 4*.

Shlemon, R. J. and M. Hakakian. 1992. Fissures produced both by groundwater rise and groundwater fall: A geological paradox in the Temecula-Dublin area, southwestern Alameda County, California. Pp. 143–150. In M. L. Stout (ed.). *Proceedings from the 35th Annual Meeting of the Association of Engineering Geologists*.

Sibray, S. and Y. K. Zhang. 1994. Three-dimensional modeling of hydraulic behavior of a highly conductive secondary permeability zone in the Brule Formation. Pp. 445–452. In J. W. Warner and P. van der Heijde (eds.). *Proceedings of the 1994 Groundwater Modeling Conference*. Colorado State University, Ft. Collins.

Sievers, L. W. 2005. Nebraska Water Law facing dramatic changes in our state. *Nebraska Lawyer* 7:14–17.

Smith, F. A. and V. L. Souders. 1975. *Groundwater Geology of Banner County, Nebraska*. Nebraska Water Survey Paper 39. 96 pp.

Steele, G. V., J. C. Cannia, S. S. Sibray, and V. L. McGuire. 2005. *Age and Quality of Groundwater and Sources of Nitrogen in the Surficial Aquifers in Pumpkin Creek Valley, Western Nebraska, 2000*. U.S. Geological Survey Scientific Investigations Report 2005-5157. 68 pp.

Sustainable Groundwater Management Act (SGMA). 2014. California Legislature AB 1739, SB 1168, and SB 1319, https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management (14 January 2019)

Terzaghi, K. 1943. *Theoretical Soil Mechanics*. John Wiley and Sons, Inc., New York, New York.

Texas Commission on Environmental Quality (TCEQ). 2017. What is a Groundwater Conservation District (GCD)? 1 pp., https://www.tceq.texas.gov/assets/public/permitting/watersupply/groundwater/maps/gcd_text.pdf (16 January 2019)

Texas Water Development Board (TWDB). 2016. Texas Water Development Board approves $1 million in financial assistance to the Panhandle Groundwater Conservation District for an agricultural conservation loan program. November 2, http://www.twdb.texas.gov/newsmedia/press_releases/2016/11/panhandle.asp (11 April 2018)

Texas Water Development Board (TWDB). 2017. Water for Texas—2017 State Water Plan. TWDB. 150 pp., https://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf?d=6718.700000026729 (15 October 2018)

Texas Water Development Board (TWDB). 2018. Agricultural Water Conservation Grant and Loan Programs (AG). Financial Assistance Programs, Texas Water Development Board, https://www.twdb.texas.gov/publications/shells/AWCLGP.pdf (11 April 2018)

Theis, C. V. 1940. The source of water derived from wells. *Civil Eng* 10:277–280.

Tillman, F. D. and S. A. Leake. 2010. Trends in groundwater levels in wells in the active management areas of Arizona, USA. *Hydrogeol J* 18 (6): 1515–1524, doi:10.1007/s10040-010-0603-3.

U.S. Department of Agriculture–Farm Service Agency (USDA–FSA). 2017. Conservation Reserve Enhancement Program—Kansas Upper Arkansas River. USDA–FSA, https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2017/crep_kansas_upper_arkansas_river_jan2017.pdf (11 April 2018)

U.S. Department of Agriculture–Federal Crop Insurance Corporation (USDA–FCIC). 2017. *2018 Crop Insurance Handbook*. FCIC, USDA Management Agency. 789 pp., https://www.rma.usda.gov/handbooks/18000/2018/18_18010-2.pdf (11 April 2018)

U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS). 2016. Ogallala Aquifer Initiative. USDA–NRCS, https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/programs/initiatives/?cid=stelprdb1048809 (11 April 2018)

U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS). 2018. Financial assistance. USDA–NRCS, https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/ (11 April 2018)

U.S. Department of Agriculture–Risk Management Agency (USDA–RMA). 2011. Frequently asked questions: Crop insurance and drought-damaged crops. USDA–RMS, https://www.rma.usda.gov/help/faq/drought.html (11 April 2018)

University of Nebraska–Lincoln, Conservation and Survey Division (UNL, CSD). 2013. Groundwater-level changes in Nebraska from predevelopment to spring 2013. UNL, CSD, Lincoln, Nebraska.

Urban, S. 2004. *Water Budget for the Treasure Valley Aquifer System for the Years 1996 and 2000*. Treasure Valley Hydrologic Project Research Report, Idaho Department of Water Resources. 57 pp., https://idwr.idaho.gov/files/projects/treasure-valley/TVHP-Water-Budget-1996-2000.pdf (16 January 2019)

Wagner, K. 2012. *Status and Trends of Irrigated Agriculture in Texas—A Special Report by the Texas Water Resources Institute*. Publication TWRI EM-115. Texas Water Resources Institute, Texas A&M University, http://twri.tamu.edu/docs/education/2012/em115.pdf (11 April 2018)

Ward, F. A. and A. Michelsen. 2002. The economic value of water in agriculture: Concepts and policy applications. *Water Policy* 4 (5): 423–446.

Water Replenish District of Southern California (WRD). 2018. *Engineering Survey and Report, 2018*, http://www.wrd.org/sites/pr/files/WRD%202018%20ESR%20-%20March%207%20Adopted.pdf (22 June 2018)

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley. 1998. *Ground Water and Surface Water: A Single Resource*. U. S. Geological Survey Circular 1139.

Xue, Q., T. H. Marek, W. Xu, and J. Bell. 2017. Irrigated corn production and management in the Texas High Plains. *J Contemp Water Res Educ* 162 (1): 31–41, doi:10.1111/j.1936-704X.2017.03258.x.

Young, M. n.d. Water allocation in the West: Challenges and opportunities, https://bit.ly/2TniyuT (4 December 2018)

The mission of the Council for Agricultural Science and Technology (CAST): *CAST, through its network of experts, assembles, interprets, and communicates credible, balanced, science-based information to policymakers, the media, the private sector, and the public. The vision of CAST is a world where decision making related to agriculture and natural resources is based on credible information developed through reason, science, and consensus building. CAST is a nonprofit organization composed of scientific societies and many individual, student, company, nonprofit, and associate society members. CAST's Board is composed of representatives of the scientific societies, commercial companies, nonprofit or trade organizations, and a Board of Directors. CAST was established in 1972 as a result of a meeting sponsored in 1970 by the National Academy of Sciences, National Research Council.* ISSN 1070-0021

Additional copies of this Issue Paper are available from CAST, Carol Gostele, Managing Scientific Editor, http://www.cast-science.org.

Citation: Council for Agricultural Science and Technology (CAST). 2019. *Aquifer Depletion and Potential Impacts on Long-term Irrigated Agricultural Productivity*. Issue Paper 63. CAST, Ames, Iowa.

CAST®
The Science Source for Food,
Agricultural, and Environmental Issues

4420 West Lincoln Way
Ames, Iowa 50014-3447, USA
(515) 292-2125
E-mail: cast@cast-science.org
Web: www.cast-science.org