Prepared in cooperation with Playa Lakes Joint Venture

Recharge Rates and Chemistry Beneath Playas of the High Plains Aquifer—A Literature Review and Synthesis

Circular 1333

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

FRONT COVER: Playas of the High Plains at sunrise (Brian Slobe, photographer; published with permission).

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
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Contents

Figures

Conversion Factors and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Abbreviations Used in This Report

µg/L	micrograms per liter
CAFO	confined animal feeding operation
Cl^-	chloride
in.	inch, inches
in./hr	inches per hour
in./yr	inches per year
ft	feet
ft^3	cubic foot, cubic feet
ft/day	feet per day
mg/kg	milligrams per kilogram
km	kilometer
mg/L	milligrams per liter
mi^2	square miles
mm/yr	millimeters per year
MCL	maximum contaminant level
N	nitrogen
NAWQA	U.S. Geological Survey National Water-Quality Assessment Program
NO_3^-	nitrate
P	phosphorus
PLJV	Playa Lakes Joint Venture
SDWA	Safe Drinking Water Act
TU	tritium unit
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	volatile organic compound

Recharge Rates and Chemistry Beneath Playas of the High Plains Aquifer—A Literature Review and Synthesis

By Jason J. Gurdak and Cassia D. Roe

Abstract

Playas are ephemeral, closed-basin wetlands that are important zones of recharge to the High Plains (or Ogallala) aquifer and critical habitat for birds and other wildlife in the otherwise semiarid, shortgrass prairie and agricultural landscape. The ephemeral nature of playas, low regional recharge rates, and a strong reliance on ground water from the High Plains aquifer has prompted many questions regarding the contribution of recharge from playas to the regional aquifer. Considerable scientific debate has led to more than 175 publications about the potential for water to infiltrate the relatively impermeable playa floors and subsequently recharge the High Plains aquifer. Since the early 1900s, many conceptual models about recharge beneath playas have been proposed. Some early conceptual models indicate that playas are evaporative pans that do not allow recharge beneath playas, whereas other more recent models indicate that playas are effective recharge basins. A variety of data supports various aspects of these competing conceptual models.

The competing conceptual models have developed because of the sporadic nature of rainfall to the region, the large number of playas in the region (more than 66,000), a range of physical characteristics in playas, the relatively thick unsaturated zones (often greater than 100 feet) separating most playas from the regional water table, and the inherently uncertain nature of most methods used to estimate recharge. An accurate understanding of recharge rates beneath playas is important from the perspective of ground-water management and the sustainability of rural agricultural economies, particularly in light of the substantial water-level declines in the High Plains aquifer. Other environmental concerns, such as erosion and transport of sediment and contaminants from surrounding land and modification of playas to allow artificial recharge, also have made accurate understanding of recharge an important priority from the perspective of wetland function and habitat health, protecting ground-water quality, and the substantial costs associated with land and water management, conservation, and regulation.

To address these questions and concerns, the U.S. Geological Survey, in cooperation with the Playa Lakes Joint Venture, present a review and synthesis of the more than 175 publications about recharge rates and chemistry beneath playas and interplaya settings. Although a number of questions remain regarding the controls on recharge rates and chemistry beneath playas, the results from most published studies indicate that recharge rates beneath playas are substantially (1 to 2 orders of magnitude) higher than recharge rates beneath interplaya settings. The synthesis presented here supports the conceptual model that playas are important zones of recharge to the High Plains aquifer and are not strictly evaporative pans. The major findings of this synthesis yield science-based implications for the protection and management of playas and ground-water resources of the High Plains aquifer and directions for future research.

Introduction

Playas are ***ephemeral,*** closed-basin ***wetlands*** that have been hypothesized by some researchers to be important zones of ***recharge*** to the ***High Plains*** (or ***Ogallala***) ***aquifer*** (note: see ***glossary terms*** in appendix 1). Playas are critical for maintaining biodiversity (Tsai and others, 2007) and are wetlands unique to the Great Plains physiographic province (fig. 1*A*) because they are zones of recharge and do not receive ground-water discharge as do prairie potholes and many other types of wetlands. The floors of most playas are lined with relatively impermeable clay soils and are commonly separated from the regional water table by tens to hundreds of feet of ***unsaturated zone (vadose zone)***, which have generally confounded a detailed understanding of the role that playas have in recharging the High Plains aquifer.

Although numerous studies have investigated the role of playas in recharging the High Plains aquifer, relatively few have directly measured water and chemical movement beneath playas and ***interplaya*** settings. Most studies rely on indirect methods to estimate water and chemical movement beneath playas. Although results from these studies indicate that playas enhance recharge at rates higher than rates in interplaya settings (Scanlon and Goldsmith, 1997), the water fluxes beneath playas are highly variable in both space and time. No studies to date have systematically characterized all the factors that control spatial or temporal variability of water and chemical movement within and beneath playas. A more detailed understanding of these controls is needed for best management of the ground-water resources of the High Plains aquifer and of the ecosystems and wetland habitat within each playa. In 2008, the U.S. Geological Survey, in cooperation with the Playa Lakes Joint Venture, began a study to gain more understanding by reviewing and synthesizing scientific literature related to the playas of the High Plains aquifer.

The purpose of this report is to present previous information from investigations of playas in the High Plains aquifer and to synthesize the existing knowledge about the rates and chemistry of recharge beneath playas and interplaya settings. The information presented in this report is designed to inform and assist ground-water resource managers and partners, such as the Playa Lakes Joint Venture, responsible for playa management and conservation.

The Playa Lakes Joint Venture (*http://www. pljv.org/)* is a nonprofit partnership of Federal and State wildlife agencies, conservation groups, private industry, and landowners dedicated to conserving bird habitat in the Great Plains. The mission of the Playa Lakes Joint Venture is to conserve playas, other wetlands, and associated landscapes through partnerships for the benefit of birds, other wildlife, and people. There are approximately 66,000 playas throughout the southern Great Plains, most of which are located within the joint venture's boundary (fig. 1*A*) (McLachlan, 2008). Approximately 61,000 playas are on the High Plains aquifer and have the highest density in the ***southern High Plains*** (or ***Llano Estacado***) aquifer in Texas and in part of the ***central*** and ***northern High Plains aquifer*** in Kansas and Nebraska (fig. 1*B*) (Smith, 2003; LaGrange, 2005; McLachlan, 2008). The playas of the Playa Lakes Joint Venture region are essential habitat in one of the most important inland migratory corridors in North America for many waterfowl, shorebirds, and waterbirds, and for many other migratory and resident birds.

Playas are an integral component of resource management in the High Plains (Brian Slobe, photographer; published with permission).

Summary of Major Findings and Implications

Understanding how playas affect the quantity and quality of recharge to the High Plains aquifer has important implications for the sustainability of the High Plains aquifer, human and ecosystem health, the sustainability of rural agricultural economies, and the substantial costs associated with land and water management, conservation, and regulation. The major findings of the literature synthesis are outlined in this section and yield science-based implications for assessing and managing playas and ground-water resources of the High Plains.

Movement of recharge and chemicals to the water table follows fast and slow pathways. Different pathways are available for recharge and chemical transport to reach the water table, and some paths are relatively faster than others. In locations that represent ***diffuse recharge*** (slow paths), estimated time of chemical transport from land surface to the water table exceeds the period of agricultural activity (more than 100 years in some locations) and imply that agricultural chemicals should not be present at the water table yet. In fact, agricultural chemicals are commonly detected in ground water. This apparent discrepancy is explained by local fast paths that may enable water and chemicals from the land surface to reach the water table in months to decades. By comparison, slow paths may enable water and chemicals from the land surface to reach the water table in centuries to millennia.

Ground-water quality is changing with time. Changes in water quality are occurring with time that may affect the sustainability of the High Plains aquifer. Understanding ground-water quality is important because it directly affects how water can be used. Studies show that at some local and subregional scales, particularly where pumping is intense or where environmental and topographic settings are conducive to fast-path recharge and chemical transport, water quality may be a limiting factor for some intended uses such as drinking water or irrigation water.

The High Plains aquifer has a limited ability to naturally attenuate contaminants. The High Plains aquifer is limited in its ability to naturally attenuate contaminants, such as nitrate (NO_3^-) by means of denitrification, and it generally has slow recharge rates—both of which suggest that once the aquifer is contaminated it will remain so for decades and even millennia. Denitrification rates are slow and would take between 250 to 14,000 years to lower nitrate concentrations by 1 milligram/liter (***mg/L***) as nitrogen (N) in ground water of the High Plains aquifer. Additionally, because transport times to the water table are generally long—decades to millennia along slow paths—the amount of chemical mass reaching the aquifer will most likely increase with time. These results highlight the importance of managing land use to minimize contaminants in recharge.

Playas help recharge the High Plains aquifer. Most playas represent fast pathways for recharge and provide an important component of recharge to the High Plains aquifer. Although the exact amount of recharge to the High Plains aquifer from any individual playa or group of playas is unknown without detailed investigation, substantial evidence in the literature shows that some portion of water that is stored seasonally in playas is able to infiltrate and eventually intercept the High Plains aquifer as recharge.

Recharge from interplaya settings is relatively low compared with playa settings. Interplaya settings generally represent slow paths for recharge and chemical transport because of high ***evapotranspiration*** and low precipitation rates in the southern High Plains. Reported interplaya recharge rates average 1 to 2 orders of magnitude smaller than most estimated recharge rates beneath playas.

Playa recharge varies in space and time. Large variations in estimated recharge rates beneath playas indicate that recharge is controlled, in part, by the spatial and temporal patterns in the physical characteristics of the playas, in climate, and in surrounding land-use practices. The physical characteristics of playas that have apparent influence on recharge rates are the drainage area, playa volume, depth of the playa floor, vertical extent of shrink-and-swell clay that lines playa floors, depth of sediment overlying clay-lined floors, unsaturated-zone sediments underlying the playa, and depth to the water table. Climate factors that affect the shrink-and-swell characteristics of the playa floors are likely to have important controls on changes in recharge with time. Some land-use practices, such as cultivation, increase sedimentation to playas and thus affect the physical characteristics that influence infiltration and recharge beneath playas. However, existing studies do not provide data to support the development of a reliable predictive model (or models) of recharge beneath any individual playa or group of playas. Future studies are needed to develop models that predict the recharge rates beneath playas.

The terms infiltration and recharge are not equivalent but are commonly used interchangeably in the literature. Our literature search indicates that many authors commonly use the terms ***infiltration*** and recharge interchangeably. However, the two terms are not synonymous. Infiltration of water from playa or interplaya settings into the subsurface does not necessarily guarantee that the infiltrating water will intercept the water table as recharge.

Cost-benefit analyses of artificial recharge need to consider natural infiltration rates beneath playas. Given the ecological importance of unmodified playa wetlands to the biodiversity of the Great Plains region and the substantial infiltration rates reported for some natural playas, cost-benefit analyses for ***artificial recharge*** need to consider any added improvements that playa modification may have on rates of infiltration and recharge that exceed the rates reported for unmodified playas. Therefore, considerations of playa modification for artificial recharge need to weigh the costs associated with the difference between the estimated recharge rate under modified playas and the recharge rate under natural playas.

Methods used to estimate recharge have inherent and unavoidable uncertainty. The same is true for the methods used by studies to estimate recharge beneath playas. However, these studies rarely report errors or uncertainties associated with recharge estimates. Furthermore, many studies use only a single method to estimate recharge. Recent research has shown that the use of many different methods can help constrain recharge estimates and reduce uncertainty. Thus, future studies that use as many different approaches as logistically and financially possible to estimate recharge will likely help answer important remaining questions about recharge rates and chemistry beneath playas.

Important questions remain about the role of playas recharging the High Plains aquifer. The existing literature does not bring data to bear on important questions that include the following:

1. What are the effects of current and future rates of sedimentation on infiltration and recharge beneath playas?
2. How much of the water that infiltrates beneath playas is lost to lateral subsurface flow and subsequent evapotranspiration before reaching the water table, and how do such processes affect the results of studies that assume that all water infiltrated beneath playas becomes recharge?
3. Are innovative and wetland-friendly approaches for ***artificial recharge*** beneath playas available?
4. How much contamination reaches the ground water beneath playas, and does playa modification that increases artificial recharge also increase transport of contaminants to the water table?
5. How important are playas for recharge to the northern High Plains aquifer, for which comparatively little research has been reported?
6. How will climate change and climate variability affect recharge beneath playas?

These and other questions may be answered using interdisciplinary studies of water and movement of chemicals through the playa-wetland system to the High Plains aquifer as recharge

Methods

The synthesis of previous work that is outlined in this report is based on an extensive literature search of databases such as Cambridge Scientific Abstracts, First Search, Web of Science, and Dissertation Abstracts. In addition, keyword and citation searches were conducted in library catalogues (U.S. Geological Survey and Texas Tech University) and on the World Wide Web using *http://www.google.com*. Many hundreds of publications have been written on the topic of playas in the High Plains. This report presents a synthesis of findings from more than 175 publications that are related to recharge (quantity and quality) beneath playas to the High Plains aquifer. Because the vast majority of these publications describe playas of the southern High Plains, the following synthesis focuses on recharge beneath playas of the southern High Plains. Approximately 40 larger saline lakes, which are sites of ground-water discharge, exist in the High Plains (Wood and Osterkamp, 1987) but are not included in the following synthesis.

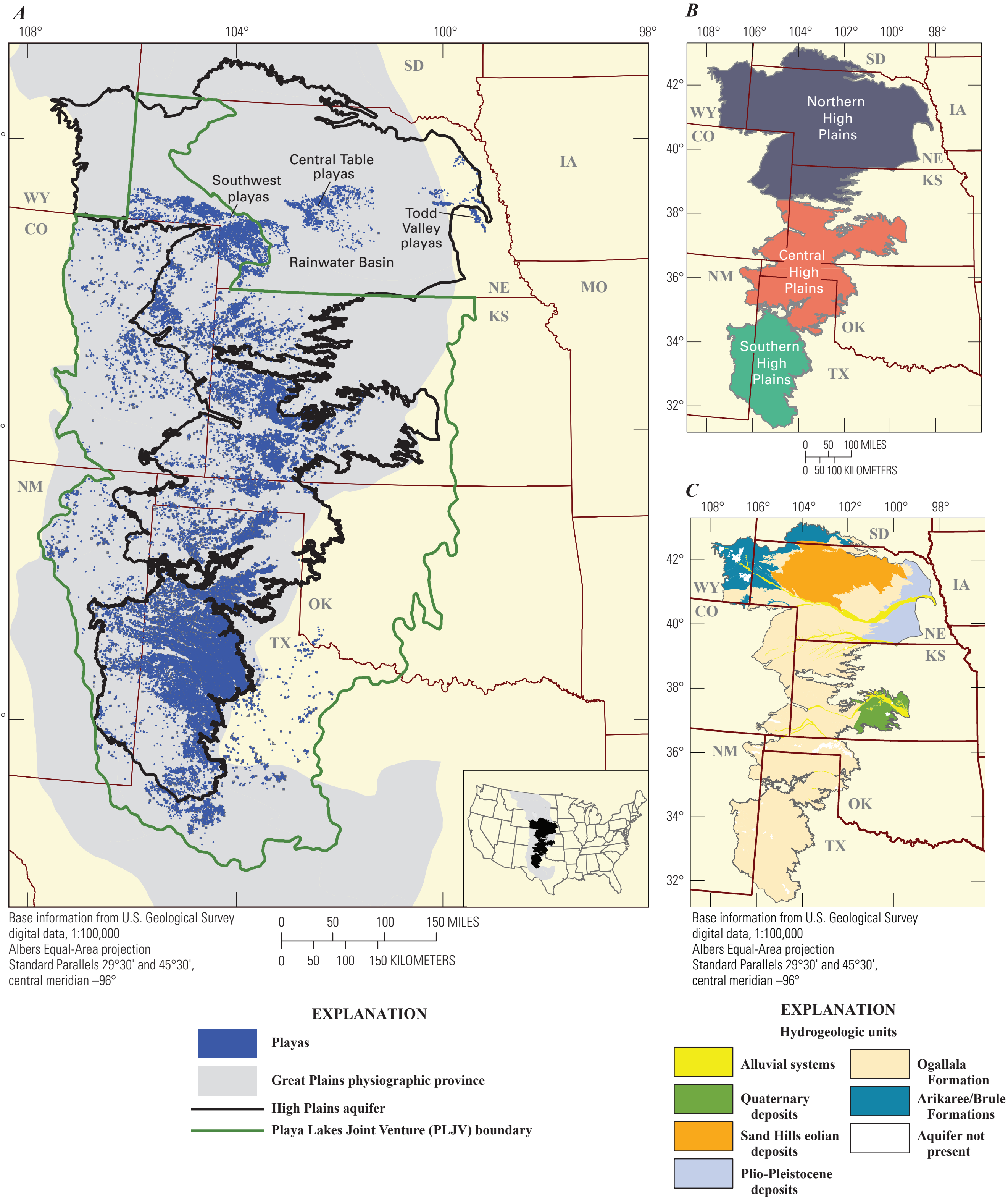


Figure 1. *A*, Playas on the High Plains (or Ogallala) aquifer. Approximately 92 percent of the more than 66,000 playas of the southern Great Plains and Playa Lakes Joint Venture (PLJV) region are located on the High Plains (or Ogallala) aquifer (modified from McLachlan, 2008); *B*, northern, central, and southern High Plains subregions; and *C*, hydrogeologic units of the High Plains aquifer (modified from McMahon and others, 2007). Playas in southeastern Wyoming are not shown in figure 1*A* because these playas are not within the PLJV boundary (Mike Carter, PLJV, written commun., 2008).

Background

High Plains Aquifer

The High Plains (or Ogallala) aquifer underlies about 174,000 square miles (mi^2) in parts of eight States (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming) (fig. 1*B*). The aquifer includes six primary hydrogeologic units (fig. 1*C*), of which, the Ogallala Formation is the largest (McMahon and others, 2007). In 2000, the aquifer had an estimated 2,980 million ***acre feet of water*** in storage (McGuire and others, 2003), thus making it one of the largest aquifers in the world.

Use of ground water from the aquifer as a source of irrigation water has transformed the High Plains into one of the largest and most productive agricultural regions in the United States, earning it the nickname “breadbasket of the world” (Opie, 2000). Ground-water withdrawals from the High Plains aquifer account for about 20 percent of total ground water withdrawn in the United States, of which 97 percent is for irrigation (Maupin and Barber, 2005). In 1989, the economic value of the aquifer was estimated to be 20 billion dollars (Moody, 1990); this value was based largely on the agricultural production that relies on water from the aquifer. Although public and domestic uses account for a relatively small percentage of the total ground-water use, these two uses provide drinking water for about 82 percent of the 2.3 million people who live within the High Plains (Maupin and Barber, 2005).

The sustainability of the High Plains aquifer is in question for a number of communities that rely on this aquifer as their principal source of water for irrigated agriculture and for public and domestic drinking supplies (Dennehy and others, 2002). The agricultural productivity of the region has come at the cost of declining water tables and nonpoint-source contamination. Since the 1940s, aquifer development has lowered the water-table more than 150 feet (ft) in parts of the region (McGuire and others, 2003). Water tables have declined (fig. 2) substantially since ***predevelopment*** times because ground-water withdrawals, largely for irrigated agriculture, have greatly exceeded recharge throughout much of the aquifer. This imbalance is particularly true in the central and southern High Plains. Such ground-water depletion has increased pumping costs and reduced water discharge to streams, among other things.

Additionally, many agricultural contaminants have been detected in ground water of this aquifer, including nitrate (Gurdak and Qi, 2006; Qi and Gurdak, 2006; Gurdak, McCray, and others, 2007; Gurdak, 2008) and arsenic (Fahlquist, 2003) at concentrations that exceed current maximum contaminant levels (MCLs) for drinking water that are set by the U.S. Environmental Protection Agency (2008). Therefore, the question of sustainability of the High Plains aquifer is a function of changes in the quantity as well as the quality of ground water.

Quantity of Recharge to the High Plains Aquifer

“Recharge” refers to the amount or flux of water that enters ground water. Water that infiltrates the land surface and moves downward through the soil and unsaturated zone becomes recharge only after the water intercepts the water table. As used in this report, recharge is the vertical and volumetric flux of water across the water table of the aquifer. Upward discharge of water from underlying formations is another source of recharge to the High Plains aquifer (Nativ, 1992; McMahon and others, 2007) but is not discussed in detail in this report. Rates of recharge are commonly expressed as length per time (that is, inches per year, in./yr).

Recharge replenishes aquifers. Therefore, the rate of recharge (or how fast recharge occurs in a given space and time) affects ***ground-water availability*** and ***sustainability***. Accurate knowledge of recharge is important for making informed decisions about ground-water management.

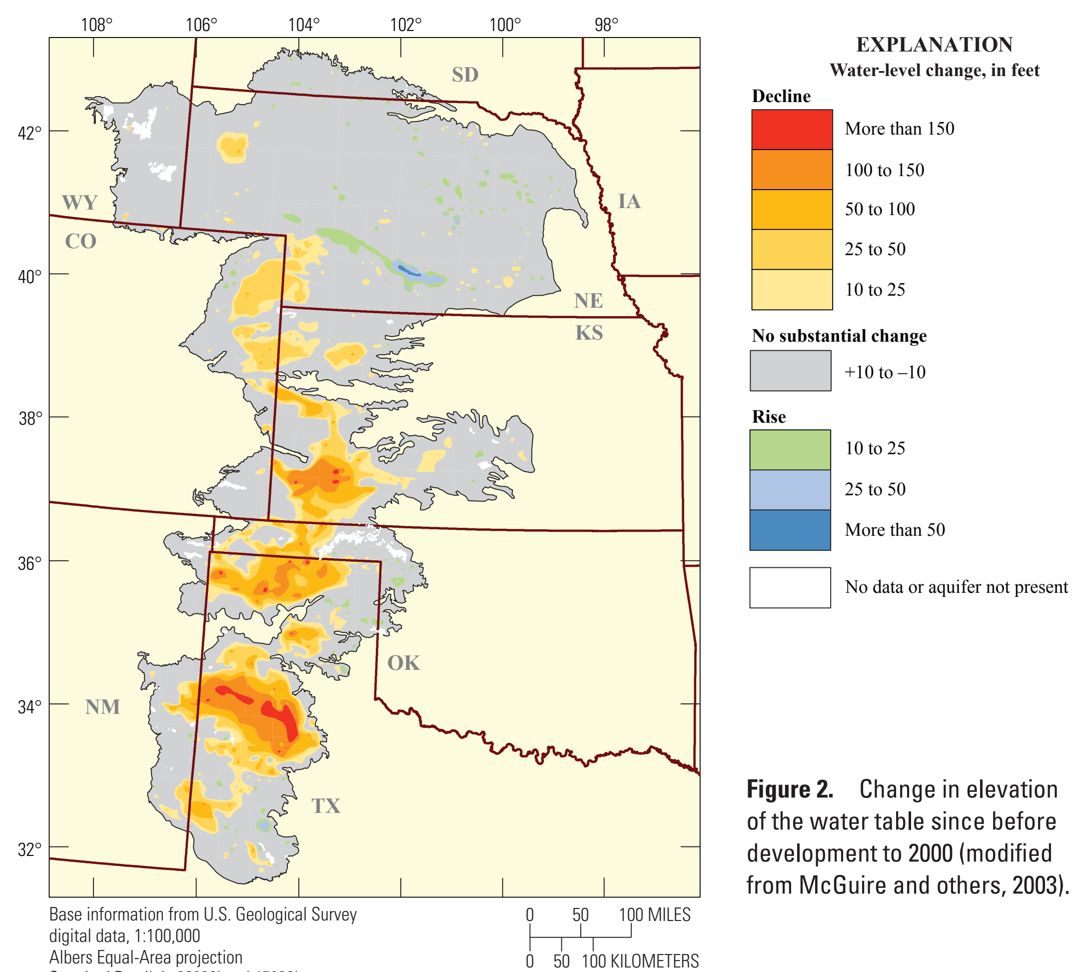
In many aquifers of the Western United States, including the High Plains aquifer, recharge rates vary under different land uses and with time owing to changes in climate that occur seasonally or during longer periods that are controlled by natural factors and (or) by human activities (Gurdak, Hanson, and others, 2007). Accurate measurements of recharge are very challenging to obtain in most aquifers because there are no easy and direct methods for observing and measuring moving water that intercepts the water table. In the High Plains aquifer, for example, the water table is commonly many tens to hundreds of feet below the land surface (Gutentag and others, 1984). Furthermore, the methods used to directly estimate recharge commonly represent the rate of recharge at a particular space and time and therefore may not adequately represent recharge at another location in the aquifer or under different conditions that may affect recharge with time.

As a result of the inherent challenges in direct methods of recharge estimation, indirect methods generally have been used in the High Plains aquifer to estimate recharge. Indirect methods commonly use information from other components of the ***water cycle***, such as precipitation, evapotranspiration, streamflow, and infiltration, to infer information about recharge. Because indirect methods do not directly measure moving water that intercepts the water table, recharge estimates from indirect methods are subject to uncertainty. The degree of uncertainty associated with any recharge estimate, whether from direct or indirect methods, depends upon the assumptions used by the investigator and the accuracy and precision of any measurements or calculations. Uncertainty associated with recharge estimates are unavoidable given the spatial scale of the High Plains aquifer and the historical and future time scales on which ground water in this aquifer is managed. Those uncertainty estimates that are reported with recharge rates are valuable information for ground-water managers.

Previous studies of recharge to the High Plains aquifer indicate that the direction and rate of water movement in the unsaturated zone, and in turn recharge, are likely controlled by differences in land use and land cover (Scanlon and others, 2005), irrigation-return flow (Scanlon and others, 2003), spatial patterns in climate (McMahon and others, 2006), temporal patterns in climate (Gurdak, Hanson, and others, 2007), geomorphological features such as playas (Wood and Sanford, 1995a,b; Scanlon and Goldsmith, 1997; Fryar and others, 2001) and other topographic depressions (Gurdak and others, 2008), and vegetation and soils (Keese and others, 2005). These and other controlling factors result in slow and fast paths for recharge to the High Plains aquifer (McMahon and others, 2006). Slow paths are characterized by diffuse recharge that may occur after rainfall, melting snow, or irrigation-return flows infiltrate across a uniform area of the aquifer, that ***percolates*** relatively uniformly through the unsaturated zone, and that eventually intercepts the water table. Slow paths commonly occur in fine-grained sediments or under flat terrain (Scanlon and Goldsmith, 1997). Conversely, ***focused recharge*** may result from fast paths under depressions in the land surface (Gurdak and others, 2008), such as playas (Wood and Sanford, 1995a,b; Scanlon and Goldsmith, 1997; Fryar and others, 2000, 2001) or other types of preferential-flow processes through the unsaturated zone (Hendrickx and Flury, 2001). Focused recharge is characterized by water that follows rapid pathways to the water table; those pathways bypass a large portion of the areal extent of the soil and unsaturated zone.

Water movement in the unsaturated zone is fundamentally controlled by differences in energy potential (the sum of gravity, soil-matric potentials, and osmotic forces), which is conceptually similar to hydraulic head in the saturated zone of an aquifer. The water in the unsaturated zone moves from areas having a higher energy potential to areas having a lower energy potential. The energy potential varies with depth in an unsaturated zone and is generally controlled by local precipitation and evapotranspiration rates and by the hydraulic properties of unsaturated-zone materials.

Previous measurements of the energy-potential gradient at the U.S. Geological Survey High Plains Unsaturated-Zone Research Network (fig. 3) in the northern High Plains of Nebraska indicate the potential for downward water movement within the unsaturated zone, with little seasonal change below the root zone (McMahon and others, 2006). In contrast, ***rangeland*** of the southern High Plains in Texas has energy-potential gradients that increase substantially with depth



Base information from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area projection
Standard Parallels 29°30' and 45°30', central meridian –96°

Figure 2. Change in elevation of the water table since before development to 2000 (modified from McGuire and others, 2003).

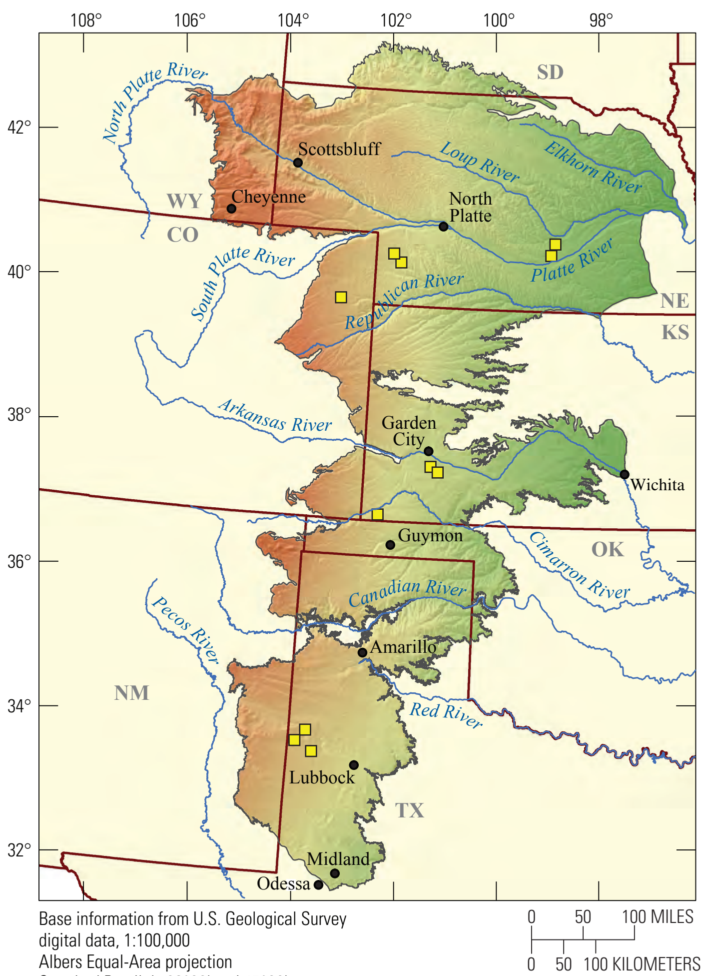
(McMahon and others, 2006). This finding indicates the potential for upward water movement from the water table to the zone of plant roots, which is consistent with interplaya observations by Scanlon and Goldsmith (1997). These findings indicate that substantial recharge is not likely to occur in interplaya settings under the current climate of the southern High Plains.

The energy potential gradients in the unsaturated zone ultimately affect water movement and recharge rates. At the U.S. Geological Survey High Plains Unsaturated-Zone Research Network (fig. 3), estimated downward water fluxes (or recharge rates) ranged from 0.008–4.37 in./yr (McMahon and others, 2006). Irrigated agricultural sites had larger fluxes (0.67–4.37 in./yr) than rangeland sites (0.008–2.76 in./yr). The largest water fluxes were observed at sites in the northern High Plains (2.76–4.37 in./yr) followed by central High Plains (0.20–2.13 in./yr) and southern High Plains (0.008–1.26 in./yr). This order is due in part to climate differences from north to south and lower evapotranspiration rates in the northern High Plains than in the southern High Plains. McMahon and others (2006) suggested that the measured downward water flux (0.008 in./yr) at the southern High Plains rangeland site represents past hydrologic conditions because upward hydraulic gradients were observed.

The southern High Plains aquifer, where the majority of the playas are located, was incised by the Canadian, Pecos, and Red Rivers (fig. 3) and cut off from the more humid central High Plains and its recharge sources (Seni, 1980; Gustavson, 1986; Nativ, 1992). Nativ (1992) noted that the exact portion of annual precipitation that recharges the southern High Plains aquifer has been debated since at least the 1930s; estimates differ by more than two orders of magnitude (0–1.61 in./yr) under playas and diffuse-recharge settings and beneath sand dunes. Studies of diffuse-recharge settings in the southern High Plains indicate that the recharge from direct precipitation is minimal (Nativ, 1992). Fine-grained soil and ***caliche*** (calcium carbonate) and climate conditions likely limit recharge in diffuse-recharge settings of the southern High Plains (Broadhurst, 1942; Barnes and others, 1949; Ries, 1981; Knowles and others, 1984).

Quality of Recharge to the High Plains Aquifer

The relatively thick unsaturated-zone sediments of the High Plains aquifer contain pore-water with chloride (Cl^-) and nitrate (NO_3^-) concentrations from natural evapoconcentration during thousands of years of precipitation (Walvoord and others, 2003) and from anthropogenic nitrogen (N) primarily



Base information from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area projection
Standard Parallels 29°30' and 45°30', central meridian -96°

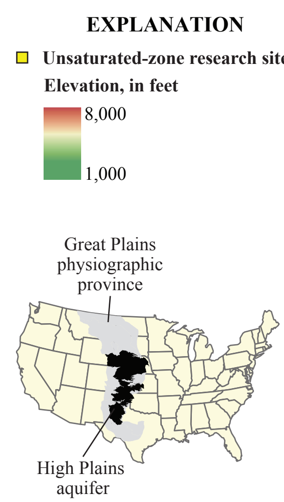


Figure 3. Locations of the High Plains aquifer and U.S Geological Survey High Plains Unsaturated-Zone Research Network that monitors recharge.

from agricultural fertilizers (McMahon and others, 2003, 2006, 2008). Ground-water quality in the High Plains aquifer is potentially vulnerable to contamination from these natural and anthropogenic Cl^- and NO_3^- reservoirs (Gurdak and Qi, 2006). Ground water may be contaminated if processes mobilize and transport the Cl^- and NO_3^- reservoirs to the water table; such processes might be conversion of rangeland to irrigated and rain-fed cropland (McMahon and others, 2006) or natural climate variability (Gurdak, Hanson, and others, 2007). For example, McMahon and others (2006) suggested that the downward displacement of NO_3^- in some unsaturated zones was the result of mobilization by irrigation-return flow after rangeland was converted to irrigated cropland.

The chemical traveltimes from land surface to the water table are substantially different beneath fast and slow recharge paths; this fact has important implications for ground-water quality. McMahon and others (2006) suggested that, for water moving from land surface to the water table in the High Plains aquifer (fig. 4), NO_3^- fast-path traveltimes are faster within irrigated cropland (months to decades) but slower under rangeland (years to centuries). NO_3^- slow-path traveltimes are faster under irrigated cropland (decades to centuries) but slower under rangeland (millennia). Some playas likely represent fast paths for recharge and chemical transport whereas others may represent slow paths, as discussed below.

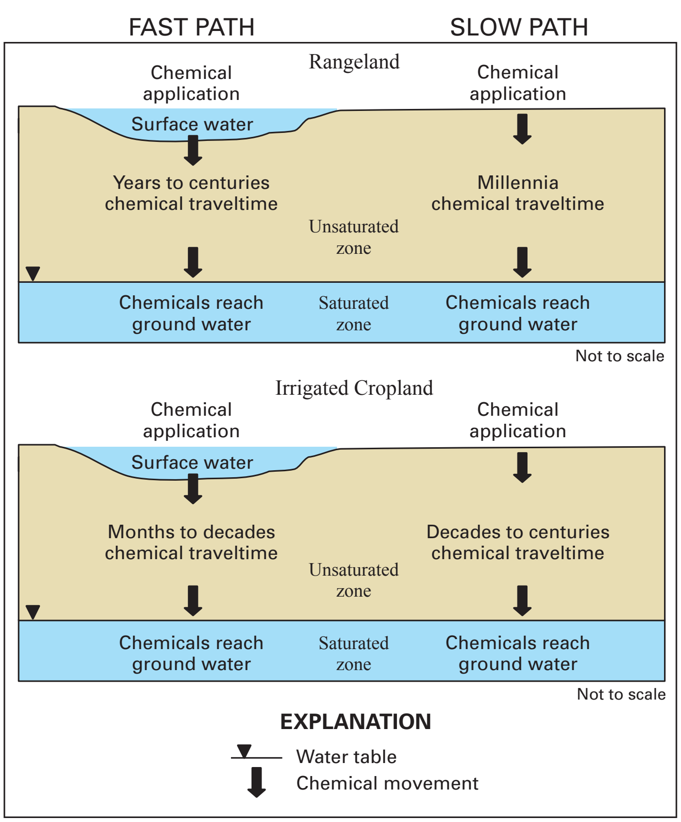


Figure 4. Chemical travel times from land surface to water table under fast and slow flow paths in rangeland and irrigated cropland (modified from McMahon and others, 2006).

The High Plains aquifer is limited in its ability to naturally attenuate contaminants, such as NO_3^- through denitrification, and it has, in general, slow recharge rates—both of which suggest that once the aquifer is contaminated it will remain so for decades and even millennia (McMahon and others, 2007). The slow denitrification rates would require between 250 to 14,000 years to lower NO_3^- concentrations by 1 mg/L (as N) in ground water of the High Plains aquifer. Additionally, because traveltimes through the unsaturated zone are generally long—decades to millennia along slow flow paths—the amount of chemical mass reaching the aquifer will most likely increase with time. These results highlight the importance of managing land use in the High Plains to minimize NO_3^- concentrations in recharge. Additionally, changes in water quality with time may affect the ground-water resource in the High Plains aquifer (McMahon and others, 2007). The quality of ground water generally has been overlooked because the primary focus has been on obtaining a sufficient water supply, and it has been broadly assumed that the High Plains aquifer contains high-quality water. For the most part, findings from McMahon and others (2007) supported that assumption. At some local scales, however, particularly where pumping is intense or where topographic settings are conducive to flow paths that are relatively fast, water quality may be a limiting factor for intended uses such as drinking water or irrigation water.

What Are Playas?

Playas are small and shallow closed-basin wetlands that have no external drainage and commonly contain ephemeral lakes. About 80 percent of playas of the High Plains have surface areas that are smaller than 30 acres and are generally less than 3 ft deep (Pool, 1977; Haukos and Smith, 1992; Fish and others, 1998). Within the Great Plains region, playas are most abundant in the southern and central High Plains of eastern New Mexico, western Texas, the panhandle of Oklahoma, southeastern Colorado, and southwestern Kansas (Smith, 2003). An estimated 18,679 playas are on the southern High Plains at a frequency of 1 to 2 per square mile (Fish and others, 1998; Quillin and others, 2005), 15,033 playas are on the central High Plains, and 27,671 playas are on the northern High Plains (McLachlan, 2008). Playas also are scattered throughout parts of the central and northern High Plains in Nebraska and Wyoming (Smith, 2003), and an estimated 16,000 playas are in southwestern Nebraska. Playas in Nebraska are found in greatest density in the areas of the Southwest Playas, Rainwater Basin, Todd Valley, and Central Table (LaGrange, 2005) (fig. 1*A*). Smith (2003) described in detail playas in the Great Plains.

The surface area that drains into playas of the southern High Plains is estimated to total 30,000 mi^2 (Ward and Huddlestone, 1979), an area that is about 90 percent of the southern High Plains (Nativ, 1992). Thus, playas are important storage during floods and for irrigation and livestock, provide habitat for a variety of wildlife species, and are likely an important source of recharge to the High Plains aquifer (Steiert and Meinzer, 1995; Luo and others, 1997).

Playas hold substantial volumes of water during wet periods (Brian Slobe, photographer; published with permission).

Many theories have been proposed to describe the physical, chemical, and biological development and formation of playas (Zartman and Fish, 1992): for example, animal activity (Rettman, 1981), wind erosion (Gilbert, 1895; Reeves, 1966; Kuzila, 1994), and dissolution of soil carbonate and piping of sediment into the subsurface (Wood and Osterkamp, 1984a). Finely and Gustavson (1981) noted a linear array of many playas and suggest that playa location may be controlled in part by underlying geologic structures. Most recent interpretations conclude that playas formed as the result of complex ***pedogenic***, geomorphic, hydrochemical, climatic, and biologic processes (Gustavson and others, 1995; Holliday and others, 1996; Hovorka, 1997).

Numerous studies have characterized the geomorphology of playas (Curtis and Beierman, 1980; Osterkamp and Wood, 1987; Wood and Osterkamp, 1987; Zartman and Fish, 1992; Gustavson and others, 1995). From a spatial-analysis perspective, the most valuable characterizations to date have been the digitization of 20,577 playas across the southern High Plains aquifer by Fish and others (1998), Quillin and others (2005), and the digitization of 66,000 playas across the southern Great Plains by McLachlan (2008). These geographic information system data sets includes attributes of physical and morphological features such as playa area, perimeter, soil type, elevation, depth to playa floor, and length of shoreline. Some National Wetland Inventory data are also available from the U.S. Fish and Wildlife Service, and these data are available digitally for the entire state of Nebraska (McLachlan, 2008).

The spatial distribution of playas varies across the High Plains (Brian Slobe, photographer; published with permission).

The spatial distribution of playas in the southern High Plains may not be completely random (Zartman and others, 2003). Playas tend to be more clustered north of the Canadian River, at the eastern edge of the Llano Estacado escarpment, and in the southwestern High Plains region (Quillin and others, 2005). Lotspeich and others (1971) noted larger but fewer playas in the northern half of the southern High Plains, which has finer soil cover than in the southern area.

Playas have three distinct physical features (fig. 5)—the playa floor, which is the flat floor of the playa that is characteristically lined by ***hydric soils***; the ***annulus***, which is the sloped surface at the playa margin; and the interplaya region, which is the area between the annuli of different playas and includes the uplands that drain into playas (Hovorka, 1995). Most playas in the southern High Plains are located within the Blackwater Draw Formation, which consists of silty clay loam sediments (Holliday and others, 1996). The playa floor is characterized by 1 to 5 ft of hydric soils and ***Vertisol*** clays (typically Randall clay in the southern High Plains and Lodgepole, Fillmore, Scott, and Massie soil series in the northern High Plains), which swell when wet and shrink when dry to form cracks as much as 3 ft deep (Hovorka, 1997). Clay-rich lacustrine sediments occur as much as 30 ft below the floor (Parry and Reeves, 1968; Claborn and others, 1985) and are sometimes interbedded with sand units that reflect the migration of historical sand across the playa (Hovorka, 1995). Additionally, numerous soil horizons buried in the subsurface, called paleosols, are common beneath playas and were formed under past climate conditions that were more stable and ideal for soil development (Hovorka, 1995; Bauchert, 1996). The water table of the High Plains aquifer is usually many tens of feet below the paleosols. The annulus is characterized by interbedded clay and loam that reflect past changes in the size of playa lakes (Hovorka, 1995). The interplaya settings contain silty clay loam soil horizons and caliche layers that are usually many tens of feet thick below land surface (Hovorka, 1995). Caliche is a cement-like layer of deposited calcium-carbonate material that forms as the result of evaporative concentrations of calcium carbonate in pore waters of soils and sediments.

Several hundred test holes were drilled in the floors of many playas in 1937 and 1938 and indicate caliche layers at various depths below many playas (White and others, 1946). However, many of these caliche layers contained sand and were relatively permeable (Nativ, 1992). Solution channels that are common in the caliche may provide pathways for water movement below the playa floor (Lotspeich and others, 1971; Nativ, 1992). More recent test holes drilled in playas indicate a relative absence of carbonates beneath playa floors and are interpreted as evidence of recharge beneath playas (Scanlon and others, 1994, 1995; Hovorka, 1997).

The capacity to hold water enables playas to support a diverse flora and fauna (Bolen and others, 1989; Haukos, 1991; Haukos and Smith, 1993, 1994; Hoagland and Collins, 1997). A number of plant species are found exclusively in playas (Reed, 1930), and many species of birds use playas for winter, breeding, and migratory stopover habitats (Curtis and Beirman, 1980; Davis and Smith, 1998; Smith, 2003). In general, playas hold water and form lakes for many weeks to months, and thus the land within and generally immediately adjacent to playas is not suitable for crops. Playas may be suitable for pastures during the dry periods, however, when the lakes are dry.

Playas are important habitat in the High Plains. An American coot is pictured here on a playa lake surrounded by smartweed (Brian Slobe, photographer; published with permission).

Playas of the High Plains are substantially influenced by surrounding land use. The land surface of the southern High Plains generally slopes from the northwest to southeast. As a result, the principal drainage area for most playas is north and west; a smaller region of drainage lies to the southeast (Claborn and others, 1985). The drainage area for most playas includes irrigated and nonirrigated cropland and rangeland that may be used for livestock grazing. In the city of Lubbock, Texas, and other urban environments, playas are important for storm drainage and recreation (Hertel and Smith, 1994; West, 1998). The runoff into urban playas is commonly allowed to evapotranspire or infiltrate (West, 1998). Playas were frequently used in agricultural-irrigation systems for tailwater storage and reuse (Fish and others, 1998). Guthery and Bryant (1982) reported that the number of modified playas on the southern High Plains increased from approximately 150 in 1965 to 10,800 playas in 1980. Modification of playas for irrigation systems has direct effects on the biomass, floral and faunal communities, soil erosion, and runoff, and it alters nutrient and ***pesticide*** input to the playas (Bolen and others, 1989).

Findings from many early investigations of playas indicate that much of the water that enters playas is lost to evaporatranspiration (Theis, 1937), and as little as 10 percent of water entering a playa infiltrates the subsurface (Schwiesow, 1965). Therefore, many early investigators concluded that recharge to the High Plains aquifer is predominantly beneath interplaya settings. More recent investigations indicate that a substantial portion of the water in playas may infiltrate into the subsurface and may ultimately recharge the High Plains aquifer (Wood and Osterkamp, 1984b; Zartman, 1987; Wood and Sanford, 1994; and Wood and others, 1997; Scanlon and Goldsmith, 1997). For example, Wood and Osterkamp (1984b) estimated that approximately 80 percent of the water collected in a playa is recharged through the playa annulus. Furthermore, Allen and others (1972) found no minerals in the playa-floor sediments indicative of mineral precipitation from ***evaporation*** of precipitation. The following sections of this report present information that generally supports the interpretation that recharge rates beneath playas are greater than recharge rates beneath interplaya settings of the southern High Plains.

Hydrology of Playas—An Overview

The hydrology of playas is characterized by cycles of inundation and drying out. Once inundated, the ***hydroperiod*** of playas is variable but may last for many weeks to many months, although some may remain dry for years (Smith, 2003; Melcher and Skagen, 2005a). The characteristic wet and dry phases of playa hydrology are a function of climate and the relatively thin permeable soils of the playa floor. The thick lacustrine sediments beneath playas that have accumulated during many thousands of years (as described previously) indicate that playas have periodically flooded throughout their geologic history (Holliday and others, 1996; Hovorka, 1997).

The large number of playas and their ability to hold large volumes of water in an otherwise arid to semiarid climate have attracted the attention of many who have studied the hydrology of the High Plains aquifer (Nativ, 1992). However, the hydrology of playas has been the center of conflicting hypotheses for much of the last 60 or more years. In general, the conflicting hypotheses differ in the relative amount of inundation water that is lost to evapotranspiration and the amount of water that infiltrates and becomes recharge to the High Plains aquifer. Some studies from the early 1900s indicate that most playa water is lost to evaporation and little remains for recharge, whereas other studies, many from the late 1900s, indicate that substantial volumes of water infiltrate playas and recharge the High Plains aquifer. The following description of playa hydrology outlines the observations and estimates that have been used by those supporting the various conflicting hypotheses.

Much of the rain in the High Plains falls from spring through fall, which coincides with the period of highest annual evapotranspiration (Dvoracek, 1981; Traweek, 1981; Haukos and Smith, 1992, 1996). The southern High Plains has a mean annual precipitation of 13 to 24 in. and a mean annual ***potential evapotranspiration*** of 65 to 69 in. (Dugan and Zelt, 2000); thus most precipitation is lost to evapotranspiration. However, surface runoff (“run-on” in the case of closed-basin playas) collects in playas during moderate to intense rainstorms.

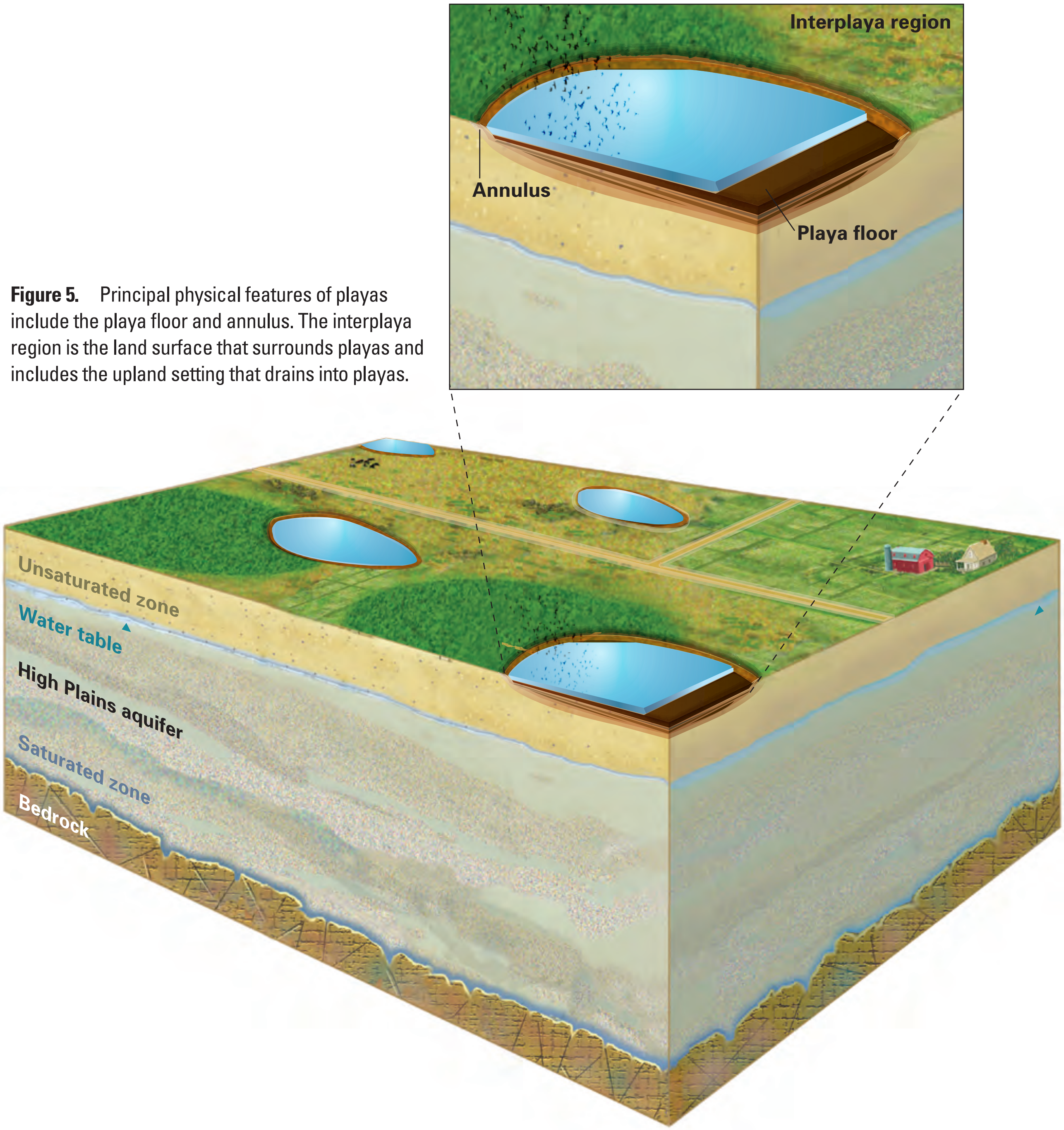


Figure 5. Principal physical features of playas include the playa floor and annulus. The interplaya region is the land surface that surrounds playas and includes the upland setting that drains into playas.

Surrounding soil texture directly influences the size of playa lakes. Grubb and Parks (1968) qualitatively noted that playas in finer textured soils are larger, have a more extensive drainage network, and have larger volumes per unit surface area than those playas in medium- to coarse-textured soils. In addition, for precipitation events of equal duration and intensity, surface runoff occurs more often, earlier, and for longer duration near playas in clayey and finer grained soils than near those playas in more loamy soils (Gustavson and others, 1995). Surface-water runoff to playa lakes carries eroded sediment; clay particles are suspended and tend to settle out further toward the middle of the playa floor (Reeves, 1990; Gustavson and others, 1995). Thus, Vertisol soil is most common on playa floors and has characteristic vertical soil structure built during numerous episodes of expansion and contraction (wet and dry cycles).

The volume of water that collects in playas of the southern High Plains is estimated to range from 1.8 to 5.7 million acre-feet per year (Clyma and Lotspeich, 1966; Hauser, 1966; Hauser and Lotspeich, 1968; Brown and others, 1978). Zartman and Fish (1989) suggested that the annual volume of water in playas, if recharged, is equivalent to approximately 4 to 11.5 in./yr of recharge throughout the irrigated portion of the southern High Plains aquifer. However, the annual volume of water that collects in playas and ultimately recharges the High Plains aquifer is difficult to quantify and is not known. The annual volume of water in playas is equal to a substantial percentage of the volume of water that has been removed from storage by pumping. In Texas alone, the total loss of water in storage in the High Plains aquifer in the interval from predevelopment to the year 2000 is estimated at 124 million acre-feet (McGuire and others, 2003). Dividing the total loss of storage in Texas by the number of years since predevelopment (2000 – 1957 = 43 years) equals 2.88 million acre-feet of water per year that was lost from storage, which is within the estimated range of annual water that collects in playas (1.8 to 5.7 million acre-feet).

Brown and others (1978) noted that the volume of water that collects in playas depends upon the frequency and intensity of precipitation and on the characteristics of the drainage area. Runoff rates are slower and runoff generally contains less suspended sediment in playas with greater coverage of vegetation (Brown and others, 1978). Playas in natural settings are commonly flooded for 1 to 3 months per year (Gustavson and others, 1994). Playas in urban areas that are modified to hold stormwater may be flooded throughout the year. James (1998) estimated that the volume of water in five urban playas in Lubbock, Texas, ranged from 75.8 to 264 acre-feet of water at full stage.

Once water collects in playas, the rate of water loss to evaporation is substantial during the summer and fall months (Traweek, 1981; Haukos and Smith, 1992) and may be as high as 0.5 in./day (Brown and others, 1978). Other estimates indicate as much as 55 to 60 percent of the available water in playas is lost to evaporation (Reddell, 1965; Ward and Huddlestone, 1979). However, Nativ (1992) and Harris and others (1972) noted the lack of evaporite minerals within the playa-floor sediments and a lack of halophytic (salt loving) flora indicate that the playas do not accumulate salts as a result of evaporation. Additionally, playa water generally has low salinity (Wells and others, 1970; Felty and others, 1972; Lehman, 1972).

Water that is not lost to evapotranspiration may leave the playa as infiltration into the subsurface. Infiltration in playas has been reported to follow three distinct stages (I–III). In playas of natural setting that experience seasonal wet and dry periods, the infiltration rates during the stage I are relatively high while the soil is dry. Claborn and others (1985) noted that numerous researchers and farmers have observed a rapid decline in water levels immediately following a large runoff event, followed by a much slower decline of water level as playa lakes become shallower. The rapid declines in water levels are hypothesized to be due to rapid infiltration through cracks in the clay-lined floors or to rapid infiltration through the playa annulus (Claborn and others, 1985). The amount of water in the soil controls the rate of infiltration during stage II infiltration. As the soil becomes wetter, infiltration rates slow during stage II. Stage III of infiltration occurs if the soil becomes saturated. In stage III, the infiltration rate is constant and determined by hydrologic properties of the soil and unsaturated zone. Playas in urban settings that are modified to hold storm-water drainage year round are likely to have constant infiltration rates that indicate stage III infiltration processes.

Caliche, which occurs widely throughout the southern High Plains, may act as a second barrier to water flow and chemical transport beneath the playa floor sediments (Knowles and others, 1984). However, Stone (1984) and Wood and Osterkamp (1984a) observed substantially less dissolved solids in soil samples beneath playas than beneath interplaya areas of the southern High Plains, which may indicate increased flushing by percolating water (Nativ, 1992) or that dissolved solids never formed beneath playas.

Recharge Rates and Chemistry Beneath Playas

Recharge Beneath Playas

For the purpose of synthesizing the existing knowledge of recharge beneath playas, the following section has been subdivided on the basis of four general types of studies to estimate water movement and recharge beneath playas. The four study types are water-budget studies, infiltration studies, unsaturated-zone studies, and ground-water studies. Results from each study type provide information on a particular component of water movement through a playa. Additionally, results from each study type may represent different spatial and temporal scales of water movement, provide a range of values, and have inherent uncertainty that is associated with each recharge-estimation method (Scanlon and others, 2003). Therefore, the most reliable recharge estimates come from those studies that use many different approaches in an effort to help reduce the inherent uncertainties in estimating recharge. Such considerations are necessary when applying recharge estimates in scientific studies or management decisions. The following section ends with a discussion of the efforts to artificially increase recharge and the effects of sedimentation and of climate change and variability on playa hydrology and recharge.

Water-Budget Studies

Water budgets provide indirect (or residual) estimates of infiltration and recharge beneath playas (Reed, 1994; James, 1998; West, 1998). Studies that use water budgets do not directly measure infiltration or recharge beneath playas.

The fundamental assumption of a water-budget analysis is that the water entering a playa equals the water leaving a playa. In the case of playas, the runoff is assumed to leave the playa by means of either evapotranspiration or infiltration (West, 1998). Therefore, if the total volume of water runoff to a playa and the total volume of water that leaves the playa because of evapotranspiration are known, then the residual value is assumed to equal the volume of water that infiltrates beneath the playa. Water-budget studies rarely, if ever, use more direct methods to estimate infiltration or recharge for the purpose of evaluating the accuracy and reliability of the water-budget estimates of recharge.

According to Reed (1994), water-budget analyses indicated that substantial volumes of water infiltrate beneath playas and that infiltration rates substantially exceed evaporation rates from playas. James (1998) used water budgets to estimate infiltration rates of playas in urban settings and reported that infiltration was substantial and controlled by several factors, including the year-round supply of water in urban playas. West (1998) estimated average-infiltration rates beneath urban playas that hold water year-round to range from 0.06 to 0.56 in./day. Similar infiltration rates were reported by James (1998) for five urban playas; those rates ranged from 0.12 to 1.68 in./day. The estimated volume of daily infiltration beneath the five urban playas ranged from 4,181 to 30,679 ft^3/day. Interestingly, the water table beneath Lubbock, Texas, rose substantially during the 1980s and 1990s, while much of southern High Plains aquifer experienced substantial water-table declines (Rainwater and Thompson, 1994; McGuire and others, 2003). Kier and others (1984) indicated that the rising water table beneath Lubbock may have been caused by recharge from the approximately 100 urban playas in Lubbock (West, 1998) and the reduction in ground-water use within the city.

A water-budget study of 22 playas in the southern High Plains found that 30 to 50 percent of runoff into playas may be available to infiltrate through the playa annulus and may ultimately become recharge (Claborn and others, 1985). However, Claborn and others (1985) used indirect methods to estimate the volume of water above the clay-lined floor and did not collect data that could be used to verify either the actual volume of water in the playa or whether water actually infiltrated into the annulus.

Although the water-budget method has many advantages, including ease and flexibility of use, a number of substantial limitations reduce the accuracy and reliability of the recharge estimated by this method. The accuracy of the recharge estimate depends upon how accurately other components in the water-budget equation are measured, particularly when the magnitude of the recharge rate is small relative to that of the other variables (Scanlon and others, 2003). To illustrate this point, Scanlon and others (2003) noted that errors of 5 to 10 percent in various terms of the water-budget equation may result in errors in the recharge estimate of more than 100 percent.

Many types of unavoidable measurement errors are introduced during water-budget calculations that may lead to uncertainty in the estimates of infiltration or recharge beneath playas. For example, investigators commonly record the water-surface elevation in playas to estimate the volume of water in a playa with time (West, 1998). This approach requires an accurate determination of the playa-floor and -annulus geometry to accurately use water-surface elevation to determine the volume of water in the playa. Surveying methods that are used to determine the geometry usually introduce unavoidable errors that may lead to uncertainty in infiltration or recharge rates. Furthermore, studies that use a water-budget method rarely collect data about subsurface water movement. These data could be used to determine if, in fact, water that infiltrates below playas actually intercepts the water table as recharge. Evapotranspiration has the potential to cause subsurface water to move from depth toward the land surface, and such movement has been well documented in interplaya regions of the southern High Plains aquifer (Scanlon and Goldsmith, 1997; McMahon and others, 2006; Gurdak, Hanson, and others, 2007). However, studies that use only water-budget methods can not determine the potential for such lateral or upward water movement.

Infiltration Studies

A number of studies have directly measured infiltration in playas (Evans, 1990; Koenig, 1990; Zartman, Evans, and Ramsey, 1994, Zartman, Ramsey, and others, 1994, Zartman and others, 1996; Huda, 1996; Scanlon and Goldsmith, 1997). As Zartman, Evans, and Ramsey (1994), Zartman, Ramsey, and others (1994), and Zartman and others (1996) noted recharge beneath playas depends upon infiltration within the playa. However, recharge rates are not typically equivalent to infiltration rates for a number of reasons, which are discussed below.

Reported infiltration rates range from 0 to 116 inches per hour (in./hr) in playas and from 0.002 to 1.57 in./hr in interplaya settings (appendix 2). Infiltration rates are generally reported to be higher near the playa center than in the perimeter of the playa floor or in the annulus (Zartman and others, 1996) (appendix 2). High rates of infiltration in the playa center are attributed to preferential flow along desiccation cracks in the clay floor (Zartman and others, 1996).

Zartman, Evans, and Ramsey (1994) and Zartman, Ramsey, and others (1994) first observed that infiltration beneath a single playa was significantly and positively related to clay content of the floor. This apparent contradiction to conventional wisdom (that is, high clay content means low infiltration), appears to be caused by rapid water movement down desiccation cracks in the clay floor. Immediately following ponding, large amounts of water can infiltrate though the desiccation cracks in the playa floors. Measured infiltration rates are generally greater during the initial flooding stage and tend to stabilize after the underlying sediments reach saturation (Evans, 1990; Zartman, Evans, and Ramsey, 1994; and Zartman, Ramsey, and others, 1994; Zartman and others, 1996; James, 1998). For example, Parker and others (2001) reported the following average infiltration rate for two playas at various times: 1-minute infiltration rates of 10.87 and 13.62 in./hr; 5-minute infiltration rates of 0.31 and 1.20 in./hr; and 60-minute infiltration rates of 0.05 and 0.09 in./hr (appendix 2). Rapid initial infiltration rates decrease as ponding water causes clays to swell and thus seal desiccation cracks and close preferential flow paths (Zartman, Evans, and Ramsey, 1994; and Zartman, Ramsey, and others, 1994).

Although stage I infiltration rates are high in playa soils because of flow along desiccation cracks, infiltration rates typically slow as the desiccation cracks seal and reach relatively low stage III infiltration rates that are based on the saturated-hydraulic conductivity of the soil (Evans, 1990). For example, Scanlon and Goldsmith (1997) suggested that even when playa floor sediments are fully saturated, they are not completely impermeable, and they cite a saturated-hydraulic conductivity of 2.8×10^{-5} in./hr from a playa floor as evidence. Such a saturated-hydraulic conductivity is approximately equivalent to a 0.25 in./yr water flux through the playa floor (Scanlon and Goldsmith, 1997). Parker and others (2001) reported a similar range of saturated-hydraulic conductivities for Randall clay soils from floors of two playas in natural settings. These saturated-hydraulic conductivities (1.7×10^{-5} to 7.56×10^{-3} in./hr) are equivalent to water fluxes through the playa floor of 0.15 and 66.23 in./yr, respectively. Because playas are inundated for only a fraction of the year, these water fluxes likely overestimate the actual annual water fluxes and need to be divided by the period of inundation for a more accurate annual water-flux estimate.

Interestingly, Scanlon and Goldsmith (1997) concluded that recharge is strongly related to the volume of ponding in a playa and depth of infiltration. The volume of ponded surface water is directly related to the physical characteristics of the individual playa, drainage pattern of the interplaya setting, and climate patterns. As evidence of their findings, Scanlon and Goldsmith (1997) reported that preferential flow was greater beneath ponding locations in playa floors where surface sediments were initially drier and cracks were more evident than in other locations, such as the playa center, that were more frequently flooded. Preferential-flow paths in playa floors may include desiccation cracks, interpedal pores, root tubules, and other types of macropores (Scanlon and Goldsmith, 1997).

Unsaturated-Zone Studies

The relatively thick unsaturated zones of the High Plains aquifer are ideal for application of unsaturated-zone techniques for estimating recharge, which are commonly used in semiarid and arid regions (Scanlon and others, 2003). These studies typically use physical and chemical-tracer techniques and sometimes numerical models to estimate recharge. Recharge estimates from these techniques generally represent a small spatial scale. Physical techniques usually include the use of infiltrometers, which are field-based instruments that measure infiltration rates. Chemical-tracer techniques typically include the use of applied tracers, such as bromide and nontoxic and visible dyes (Scanlon and Goldsmith, 1997), and historical or environmental tracers (such as tritium, ^3H) that result from human activities or natural evapoconcentration of salts from precipitation (chloride, Cl^-, and nitrate, NO_3^-) (Scanlon and Goldsmith, 1997; McMahon and others, 2006). Although numerical models have been used extensively in other semiarid and arid regions to estimate recharge, the use of numerical models may not be used as commonly because of complications posed by shrink-and-swell processes that are typical in the clay-lined floors of playas. Most techniques used during unsaturated-zone studies provide estimates of water fluxes through the unsaturated zone and do not directly measure recharge. Therefore, researchers commonly assume that water fluxes in the unsaturated zone (estimated below the depth influenced by evapotranspiration) represent actual recharge rates.

Unsaturated-zone studies report recharge rates that range from 0.11 to 4.72 in./yr in playa floors and recharge rates that range from 0.004 to 1.26 in./yr in interplaya settings (appendix 3). The major findings of these studies are in general agreement that recharge rates are higher beneath playas than beneath interplaya settings of the southern High Plains. For example, Scanlon and Goldsmith (1997), who conducted one of the most comprehensive unsaturated-zone studies of playas to date, concluded that playas increase recharge because of the observed results that water contents, water potentials, and tritium concentrations were much higher and chloride concentrations were much lower beneath playas than beneath interplaya settings.

However, the findings reported by unsaturated-zone studies are in less agreement about which processes are most important in controlling recharge beneath playas. For example, Wood and Osterkamp (1984a,b, 1987) suggested that the playa annulus acts as the primary recharge zone during periods of ponding. Furthermore, they suggest that organic material in the playa is oxidized to CO_2, which dissolves in water and forms carbonic acid. The carbonic acid may promote dissolution of the underlying caliche, formation of solution channels, and increased subsurface porosity. However, the comprehensive data sets of Scanlon and Goldsmith (1997) generally support the ***conceptual model*** that infiltration occurs through playa floors and is not necessarily restricted to the annular regions around playas.

Many studies (Wood and Osterkamp, 1984a,b, 1987; Claborn and others, 1985; Osterkamp and Wood, 1987) concluded that recharge is relatively higher through the annulus than through the playa floor; these studies cited coarser sediments in the annulus as evidence. Scanlon and Goldsmith (1997), however, reported only slightly coarser sediments in the near-surface sediments of the annulus as compared with sediments in the corresponding zones beneath the playa floor. Furthermore, Scanlon and Goldsmith (1997) used total energy potential profiles to suggest that water drains more consistently under playa floors than beneath playa annuli. The total energy potential profiles beneath some playa annuli indicate higher water fluxes than beneath corresponding playa floors, whereas other annular potential profiles indicate lower water fluxes than beneath playa floors (Scanlon and Goldsmith, 1997). Lower reported chloride and carbonate concentrations in sediments beneath playas than in sediments beneath interplaya settings may be evidence of high water fluxes; they may indicate that either chloride and carbonate never accumulated or that it was flushed or dissolved out of the playa profiles (Scanlon and Goldsmith, 1997).

Scanlon and Goldsmith (1997) reported qualitative evidence of preferential (fast path) flow beneath some playa floors; however, the preferential flow is apparently terminated at underlying layers of coarser sand. Therefore, the interbedded layers of sediment of different origins and hydrologic properties that are common in the unsaturated zone beneath playas (Gustavson, 1996; Hovorka, 1997) may impede rapid or preferential flow toward the water table. Assuming that most recharge occurs because of preferential flow through these desiccation cracks, Wood and others (1997) estimated that recharge beneath playas could be as high as 5.7 to 10.1 in./yr.

Findings from most geologic studies of sediments beneath playas generally support the conclusion that recharge rates beneath playas are greater than rates beneath interplaya settings

(Holliday and others, 1996; Hovorka, 1997). Hovorka (1997) reported no evidence of increased salinity or permanent ponding beneath selected playas and offered the interpretation that typical playas have been recharging the underlying aquifer throughout their geologic history. Hovorka (1997) concluded that recharge has always drained playas before evaporation concentrated solutes, and neither carbonate nor more soluble salts have accumulated in typical playa sediments. Thus, playa water remains relatively fresh compared with water in the approximately 40 saline lakes in the High Plains (Sanford and Wood, 1995), because recharge to the aquifer exceeds evaporation.

Other evidence of frequent ponding and rapid water flux are the lack of chloride concentrations and calcium carbonate (caliche) profiles in the unsaturated zone beneath playas. Maximum chloride concentrations in interplaya-soil water exceed those in soil water beneath playas by as much as three orders of magnitude (Wood and Sanford, 1995a; Scanlon and Goldsmith, 1997). Low chloride concentrations in sediments suggest that chloride never accumulated or that it was flushed out by rapid water movement. In contrast, several thousand years of chloride accumulation are required to create the chloride concentrations found in sediment of interplaya profiles (Scanlon and Goldsmith, 1997). Gustavson and others (1995) observed that all major interplaya-soil series that have developed on the southern High Plains are calcic soils, which contain substantial secondary accumulations of calcium carbonate, primarily from evaporation and evapotranspiration. Low concentrations of calcium carbonate in playa sediments are caused by surface-water ponding; dissolution of calcium carbonate is facilitated by acidic precipitation, physical flushing by rapid water flux, and by limited plant growth in playas that minimizes deposition of calcium carbonate normally facilitated by evapotranspiration of soil water.

The associated uncertainty from recharge rates that are estimated from unsaturated-zone studies may be substantial. For example, Scanlon and others (2003) suggested that estimates of water flux beneath playas that are based on chloride data are highly uncertain because of relatively large uncertainties in the chloride input to the system (Scanlon and Goldsmith, 1997). Uncertainties in the deposition values are reported as a factor of –0.5 to 2, which would result in uncertainties in water fluxes of 0.12 to 0.79 in./yr (Scanlon and Goldsmith, 1997). Wood and Sanford (1995a,b) provide a recharge estimate (3 in./yr) with an error estimate (0.31 in./yr) (appendix 3).

Ground-Water Studies

The ground-water studies of playa recharge have generally used tracer-based techniques that include dating of groundwater age (tritium, ^{3}H) and environmental tracers (chloride, Cl^{-}). Recharge estimates from ground-water studies represent recharge across much larger spatial scales than recharge estimates from unsaturated-zone studies (Scanlon and others, 2002). Therefore, recharge estimates based on ground-water studies in areas of playas may be more appropriate for ground-water resource investigations, because ground-water studies provide a more spatially averaged recharge rate than the point estimates obtained from unsaturated-zone studies (Scanlon and others, 2003). However, the spatially averaged recharge rates from ground-water studies may not provide the spatial resolution to determine effects from any single playa or group of playas.

Early ground-water based recharge estimates, including that of Brown and Signor (1973), reported that less than 0.07 in./yr (appendix 3) are added to storage to the High Plains aquifer as recharge by infiltration from natural rainfall, whereas more than an average of 12 in./yr of water is being removed from storage because of pumping. Nativ and Smith (1987), using tritium (^{3}H) in ground water as a tracer, estimated recharge beneath playas to range from 0.5 to 3.24 in./yr. On the basis of a comparison of estimated recharge rates in diffuse settings (0.01 to 0.57 in./yr) (Barnes and others, 1949; Klemt, 1981; Knowles and others, 1984; Stone and McGurk, 1985; Stone, 1990), Nativ and Smith (1987) suggested that the High Plains aquifer is predominantly recharged by focused percolation from playa lakes. Wood and Sanford (1995b), using chloride-mass balance approach from ground water (appendix 3), provided a regional estimate of 0.43 in./yr recharge to the northern part of the southern High Plains. Similarly, Fryar and others (2001) reported solute and isotopic data from shallow monitoring wells near playas receiving wastewater discharge; these data indicate a sequence of episodic precipitation, evaporative concentration of solutes, runoff, and infiltration beneath playas. The water in these wells also indicated return flow from wastewater and irrigation.

Using results from a ground-water flow model, Mullican and others (1994) estimated that focused recharge beneath playas could be as high as 8.6 in./yr (appendix 3); however, these model-based estimates were determined by assuming that all water from a regional recharge rate of 0.236 in./yr is focused through playas. No data sets were collected to validate actual recharge rates beneath the playas.

Artificial Recharge

The large storage volume of playas has prompted many questions regarding the ability of playas to supplement water resources of the region (Aronovici and others, 1970; Aronovici and Schneider, 1972; Palacios, 1981), including artificial recharge to the High Plains aquifer (Valiant, 1964). Artificial recharge refers to any manmade modification of playas intended to increase flow of water toward the water table of the aquifer. Artificial recharge has been explored as an approach to stabilize or replenish ground-water supplies from the High Plains aquifer (Schwiesow, 1965).

In order to increase infiltration and recharge by reducing evaporation losses from playas, playa floors have been modified to confine water in smaller, deeper impoundments with less surface area (Dvoracek, 1981). To increase infiltration, surface drainage wells have been installed that use gravity to allow playa water to flow to the High Plains aquifer (Valiant, 1964). These wells have been unsuccessful because the high silt content of the playa water quickly clogs the wells and the sediments in the aquifer (Claborn and others, 1985). Claborn and others

(1985) reported reasonable artificial-recharge rates using water from playa lakes in a pressure injection system at pressures of 50 to 80 pounds per square inch. Energy costs and logistical considerations, however, restrict use of this approach (Claborn and others, 1985).

An alternative to artificial recharge is the direct use of playa water for irrigation (Dvoracek, 1981), which eliminates many of the problems associated with artificial recharge. Jones and Schneider (1972) suggested that the demand on the High Plains aquifer could be reduced by as much as 30 percent by direct pumping from playa lakes for irrigation supplies in combination with recycling irrigation tailwater and artificially recharging the aquifer using playa water. However, the direct use of playas for irrigation has many limitations. Soil moisture is generally sufficient for agricultural requirements in those seasons when playas fill with water. Therefore, playa water needs to be stored until later in the season when irrigation water is required. Dvoracek (1981) proposed various playa modification schemes that may have various degrees of success in reducing water loss to evapotranspiration and increasing the efficiency of playa water storage. These modification schemes have economic costs associated with installation, maintenance considerations because of sedimentation, and effects on playa ecosystems. Additionally, unmodified playas likely provide the best resource and habitat for waterfowl and other species (Pence, 1981).

One of the first systematic evaluations of the use of playas to support artificial recharge to the High Plains aquifer was conducted by Brown and others (1978). This evaluation used results from at least six field experiments and numerous prior publications regarding the use of playas for artificial recharge (Hauser and Lotspeich, 1968; Schneider and others, 1971; Aronovici and others, 1972; Brown and Signor, 1973; Reeder, 1975; Wood and Bassett, 1975). Brown and others (1978) suggested that under specific conditions, using water from playas in water-spreading basins or injection wells may be suitable for artificial recharge of the High Plains aquifer. Artificial recharge from playa lakes is more likely to be successful if the water is free of suspended sediment and recharged in zones of the aquifer that have high infiltration rates and no clay or low-permeability zones in the unsaturated zone.

Schneider and Jones (1984), who investigated infiltration in playas that had been modified by excavation of the top layer of soil, reported infiltration rates that were substantially greater than in unmodified playas. Infiltration rates in these modified plays were initially high (3.28 feet/day (ft/day)), followed by slower rates (1.42 ft/day) (Schneider and Jones, 1984). Dvoracek and Peterson (1970) observed similar infiltration rates (1.54 ft/day) in modified playas. However, suspended sediments in the water column of the modified playas were identified as the cause of surface sealing and a reduction of infiltration rates (Schneider and Jones, 1984). Therefore, Schneider and Jones (1984) concluded that in order to maintain high infiltration rates, modified playas require periodic and costly maintenance to remove or reduce surface seals. Urban and Claborn (1984) reported that geotextile materials buried beneath playas have had some success at filtering sediments.

Although previous studies report greater infiltration rates in modified playas than in unmodified playas, the findings from such artificial recharge studies need to be considered in light of infiltration studies (see Infiltration Studies) that report substantial infiltration rates in unmodified (or natural) playas. Therefore, any cost-benefit analysis of artificial recharge needs to evaluate the potential added benefit that playa modification might have on increasing infiltration and recharge above the natural rates and the potential effects of playa modification on the ecology of the playa-wetland system.

Modification of playas affect the hydrology and ecology of the playa-wetland system (Brian Slobe, photographer; published with permission).

The quality of playa water used for artificial recharge is of concern because of its possible effects on ground-water quality (Felty and others, 1972). For example, Mollhagen and others (1993) observed detectable levels of triazine herbicides and aldicarb insecticides in playa water. Water-quality concerns stem from legal constraints prohibiting water-quality degradation in existing aquifers in Texas. The future use of playas for artificial recharge remains uncertain. Manmade attempts at modifying playas for the purposes of increasing recharge are uncertain because of the logistical and economic challenges, legal considerations that differ by State, water-quality concerns for the High Plains aquifer, and the importance of playas as habitat for various flora and fauna. There is a lack of evidence in the literature that describes the possible effects of playa modification for artificial recharge on chemical mobilization and water quality of the High Plains aquifer.

Sedimentation

Smith (2003) noted that "…sedimentation is likely the single largest immediate threat to the continued existence of properly functioning wetlands in the Great Plains today." The accumulation of sediments from upland erosion has shortened the hydroperiod, decreased water volume, and increased water loss of playas due to evaporation (Tsai and others, 2007). These changes to the natural hydrology of playas may reduce the diversity of flora and fauna habitat and increase flooding and property loss, and they may have effects on recharge to the High Plains aquifer (Luo and others, 1997; Smith and Haukos, 2002; Tsai and others, 2007).

Playas are typically surrounded by cultivated cropland and rangeland that may be used for grazing livestock. Although cultivated cropland and livestock grazing in a playa drainage area may contribute to a reduction in the cover of perennial vegetation and increase the potential for soil erosion and sediment transport to the playas, studies indicate that the sediment load from cultivation-dominated drainage areas is substantially larger than the load from rangeland-dominated drainage areas (Luo and others, 1997; Tsai and others, 2007). Playas in selected cropland settings are reported to contain 8.5 times as much sediment as those playas in rangeland settings (Luo and others, 1997). Average sedimentation rates (0.19 to 0.38 in./yr) of playas in cropland settings are substantially larger than average sedimentation rates (0.026 to 0.033 in./yr) reported for rangeland settings (Luo and others, 1997). Luo and others (1997) concluded that if sedimentation rates remain approximately constant, sediment could fill nearly all cropland playas in less than 100 years.

As a result, Federal, State, and privately funded programs focus on buffering playas to protect them from sedimentation and contamination while simultaneously enhancing wildlife habitat (Melcher and Skagen, 2005a,b). Efforts such as the Conservation Reserve Program, which has established more than 1.7 million acres of perennial grass in the southern High Plains, have likely slowed sedimentation rates (Luo and others, 1997). Conservation practices that support native vegetation surrounding playas are likely to trap sediment and reduce sedimentation rates to playas (Luo and others, 1997). Given the large number of playas, the removal of sediment can be restrictively expensive. Melcher and Skagen (2005a,b) summarized wetland protection strategies and best management practices, including mitigation buffers that are most appropriate for reducing sedimentation and nonpoint-source contamination in playas of the High Plains region.

Agricultural lands surround many playas of the southern High Plains and directly affect the transport of sediment and contaminants to playas (Brian Slobe, photographer; published with permission).

Sedimentation of playas has adverse effects on wetland structure and function (Luo and others, 1997; Smith, 2003). However, the effects of sedimentation on infiltration and recharge are not clear because of a lack of supporting evidence from published scientific studies. Smith (2003) proposed several factors about sedimentation that likely affect infiltration and recharge beneath playas. Smith (2003) hypothesized that the coarser grained sediment that typically erodes from interplaya settings may mix with the clay soils of playas and fill desiccation cracks in the playa floor. Hovorka (1997) identified and attributed subsurface silt mixed with ancient lacustrine clay layers as evidence of silt deposition during dry periods within the geologic history of the playa. However, no studies were identified during this literature search that provide evidence that coarser grained materials are currently filling desiccation cracks in clay-lined playa floors during dry periods. Furthermore, Parker and others (2001) found limited evidence of more permeable material deposited in desiccation cracks of playa-floor soils that would provide conduits for water flow even after the cracks had sealed as the result of wetting. As Smith (2003) noted, it is unknown whether this process is occurring and increasing infiltration, thus enhancing recharge.

Sedimentation results in shallower playas that have less total volume and possibly larger surface areas, and that are more likely to overflow and flood areas outside the playa floor and annulus (Smith, 2003). Larger surface areas over shallower playas are subject to more rapid evaporation than playas that have a deeper annuli and smaller surface area (Smith, 2003). Less water may be available for infiltration if evaporation rates increase as playas fill with sediment.

Finally, sedimentation may result in a clay-lined playa floor completely covered with sediment from interplaya settings. It is unknown how such a surface layer will affect the playa floor's shrink-swell properties, which result in desiccation cracks that have been identified as important controls on rapid infiltration and recharge. The sediment also may allow the underlying clay to maintain a higher moisture content, thus preventing the formation of desiccation cracks. Future studies are needed to determine if the desiccation cracks form near the surface under layers of sediment and how infiltration characteristics may change in playa floors under sedimentation.

Climate Change and Variability

Anthropogenic climate change and natural climate variability are likely to have substantial effects on global water resources, including those across the Great Plains (Intergovernmental Panel on Climate Change, 2007). John Matthews (World Wildlife Fund, written commun., 2008) outlines possible effects of climate change and variability on playa habitat and biodiversity. Climate change and variability may have important effects on infiltration and recharge beneath playas; however, no studies to date (2008) and to the knowledge of the authors specifically explored how climate change and variability may alter recharge beneath playas. Therefore, the following section briefly outlines a few climate projections noted by John Matthews (World Wildlife Fund, written commun., 2008) and possible responses of recharge beneath playas; these responses are based on the playa hydrology and recharge processes outlined in prior sections of this report.

During the next 30 to 100 years, the Great Plains may receive less snowfall in winter, the snow will begin falling later and melt earlier, and more winter precipitation will be rain rather than snow (Intergovernmental Panel on Climate Change, 2007). Under such a climate scenario of more winter rainfall, winter recharge beneath playas might increase because of the relative lack of water loss due to evapotranspiration during winter as compared with summer evapotranspiration loss. Research is needed to test this hypothesis.

The Intergovernmental Panel on Climate Change (2007) reported that annual precipitation across parts of the Great Plains is likely to decrease; the largest decreases are predicted in the southern High Plains region, especially New Mexico and Texas. Under such climate scenarios of less annual precipitation, the potential for recharge beneath playas may decrease because there is less water to run off and collect, infiltrate the playa sediments, and ultimately recharge the aquifer. Research is needed to test this hypothesis.

In contrast to the southern High Plains, the northern High Plains, especially part of Nebraska, may have substantial increases in precipitation during the summer during the next 30 to 100 years (Intergovernmental Panel on Climate Change, 2007). Precipitation across the Great Plains region, however, is likely to continue to be highly random with great local variation in amounts and intensity (Nippert and others, 2006), which could result in local droughts and regional flooding (Covich and others, 1997). Under increased summer precipitation in the northern High Plains, recharge beneath playas may be increased. However, higher rates and intensity of precipitation may increase erosion and sedimentation rates of playas (John Matthews, World Wildlife Fund, written commun., 2008). Sediment may bury the playa floors lined with shrink-swell clay, which have been previously identified as important conduits for infiltration and recharge. Therefore, recharge beneath playas, as well as the wetland habitat, may be reduced under such climate projections. Research is needed to test these and other hypotheses regarding the effects of climate change and variability on the function of playa wetlands and recharge to the High Plains aquifer.

Recharge Chemistry Beneath Playas

The chemistry of recharge beneath playas is a more recent topic of study that has been motivated by concerns about ground-water quality of the High Plains aquifer and the detection of elevated concentrations of nitrate (NO_3^- as N), dissolved solids, pesticides, and other chemicals in ground water that may be harmful to humans and animals. The biodiversity of playas is also at risk from nonpoint-source contamination from soil erosion, agricultural runoff, and direct dumping of wastes into playas. For example, an estimated 35 to 70 billion ft^3/year of irrigation tailwater, which is about 20 percent of the irrigation water pumped from the High Plains aquifer, flowed into playas during the 1960s and 1970s alone (Bolen and others, 1989). Possible nonpoint-source contaminants in playa water may include nutrients, chemical fertilizers and pesticides, feedlot runoff, manure fertilizer, urban wastewater, organic chemicals, and trace metals (Irwin and others, 1996). The increased recharge rates beneath playas, as described in the Recharge Beneath Playas section, could be of concern if the recharge chemistry is of poor quality. Similar to the format of the previous section on recharge rates, the following section synthesizes the movement and reactions of chemicals from water in playa lakes and subsurface processes underlying the playa affecting recharge chemistry to the High Plains aquifer.

Water Quality of Playa Lakes

More than 25 studies have collected various types of water-quality data from playas of the southern High Plains aquifer (Casula, 1995). The objectives of most studies are synoptic in nature and include data collection of playa-water quality at a particular time and place (Sublette and Sublette, 1967; Rekers and others, 1970; Bureau of Reclamation, 1982; Nelson and others, 1983; Buck, 1989; Huang, 1992). The objectives of other water-quality studies vary and include the evaluation of playas for mosquito habitat (Ward, 1964); the suitability of playas as a source of water for irrigation (Lotspeich and others, 1969); the effects of agricultural-wastewater runoff and land-use effects on playa-water quality (Felty and others, 1972; Mollhagen and others, 1993; Pezzolesi, 1994; Irwin and others, 1996; Thurman and others, 2000; Purdy, Straus, Harp, and others, 2001; Purdy, Straus, Parker, and others, 2001; Hudak, 2002); the suitability of playas as storage reservoirs (Reeves, 1970); the potential effects on ground-water quality from artificial or natural recharge beneath playas (Wells and others, 1970; Wood and Osterkamp, 1984a,b; Ramsey and others,1988, 1994); the effects on wetland habitat (Horne, 1974; Parks, 1975; Becerra-Munoz, 2007); and the presence of waterborne-bacterial pathogens (Westerfield, 1996; Warren, 1998; Hamilton, 2002).

The water quality of playa lakes has been reported to differ greatly in space and time because of physical characteristics of the playa floor and annulus, soil and land-use characteristics of the interplaya settings, and variability in the annual and interannual cycles of precipitation, evaporation, and infiltration that affect erosion and runoff chemistry (Curtis and Beierman, 1980; Casula, 1995; Hall and others, 1995; Willig and others, 1995; Fish and others, 1998). Runoff and material transported into playas is proportional to drainage area. Casula (1995) reported that many water-quality constituents show moderate positive correlations between playa drainage area; those constituents include total-dissolved solids (TDS), chloride, sulfate, alkalinity, pesticides, and pH. Lake area is reported to inversely correlate with TDS, specific conductivity, chloride, sulfate, pH, and many pesticides and may directly correlate with dilution of chemical constituents (Casula, 1995). Casula (1995) did not obtain strong statistical relations between playa characteristics and water quality and attributes those findings to a lack of land-use variables in the statistical models. Fish and others (1998) suggested that temporal variability that is likely caused by changes in climate may present a substantial challenge to understanding the effects of land use on spatial variability of playa-water quality.

Playa lakes commonly contain water with less than 200 mg/L dissolved solids and 400 to 500 mg/L suspended solids (Wood and Osterkamp, 1987; Zartman and others, 2001), which is characteristic of freshwater lakes and different from the approximately 40 saline lakes present in the region (Wood and Osterkamp, 1987). The lack of saline playa water, lack of salt accumulation in the playa sediments, and presence of freshwater flora in playas indicates that evaporation that produces salts is not a dominant process affecting water quality. Many researchers suggest that if playa water is lost solely from evaporation, salts and minerals would be concentrated in the water and sediment and more halophytic (salt-loving) flora would be present (Smith, 2003).

One of the more recent and spatially extensive surveys of water-quality conditions in 99 playa lakes throughout the southern High Plains reported elevated concentrations of nitrate (1.64 to 4.23 mg/L as N) and arsenic (5.10 to 67.0 µg/L), and numerous pesticide compounds (Mollhagen and others, 1993). Although the range of nitrate concentrations exceeds the background concentration of 4 mg/L (as N) in ground water of the High Plains aquifer (Gurdak and Qi, 2006), these concentrations do not exceed the MCL for drinking water (10 mg/L as N) (U.S. Environmental Protection Agency, 2008). However, 59 playas from this survey contained arsenic at concentrations that exceed the MCL for drinking water (10 µg/L) (Mollhagen and others, 1993; U.S. Environmental Protection Agency, 2008). Arsenic concentrations in playa lakes sampled by Mollhagen and others (1993) range from 5.10 to 67.0 µg/L and have an average concentration of 13.1 µg/L.

Playa water is not used for direct human consumption; even so, elevated arsenic in recharge water could pose a health concern. Fahlquist (2003) detected elevated arsenic concentrations in ground water of domestic-supply wells at concentrations ranging from 1.7 to 107 µg/L, and 14 (of 48) samples exceeded the MCL. Arsenic concentrations in ground water of the High Plains aquifer have been suggested to originate from organic-rich shale, volcanic ash, discharge from saline lakes, or oilfield brines (Fahlquist, 2003). Others suggest that historical use of arsenic-based pesticides and defoliants elevated the background concentrations of arsenic in the soil surrounding the playa (Mollhagen and others, 1993). Furthermore, Thurman and others (2000) reported the detection of a number of the major cotton and corn herbicides and many of their metabolites (daughter products) in playa water. However, Thurman and others (2000) did not collect ground-water-quality data to determine if the herbicides or metabolites have reached the ground water beneath playas.

Playas are often modified to hold stormwater runoff from feedyards (Brian Slobe, photographer; published with permission).

The southern High Plains is well known for its large confined-beef-cattle feeding operations (Parker and others, 2001). An estimated 7 million cattle are fed in these operations (Southwest Public Service, 1999). Approximately one-half of the confined-animal feeding operations in the High Plains use playas as collection basins for feedyard runoff and as storage basins until solid manure can be dredged for use as agricultural fertilizer (McReynolds, 1994). Playas in such operations are often modified to include primary storage ponds of sedimentation basins between the feedyard and playa (Purdy, Straus, Harp, and others, 2001). These modifications help to catch storm-water runoff that may contain manure, sediment, and other chemicals.

The effects of confined-animal feeding operations on water quality of the playas has not been extensively studied (Purdy, Straus, Harp, and others, 2001). Those studies of water quality of playas in such operations reported elevated concentrations of nutrients, salts, and pathogens, and elevated biochemical oxygen demand (Sweeten, 1994); those playas generally have lower quality water than natural playas (Parker and others, 2001).

Purdy, Straus, Parker, and others (2001) studied the effects of feedyards on ***endotoxin*** concentrations, fecal coliform count, and other water-quality conditions during winter and summer in playas that are located in confined-animal feeding operations. Although Purdy, Straus, Parker, and others (2001) found that such activities reduce playa water quality, including endotoxin concentrations, general water quality, and fecal coliform counts, they suggested that such deteriorated playa-water quality likely does not pose a threat to human or animal health or the environment if the water remains in the playas. The authors based their conclusions "on the premise that feedyard playas play a minor role in recharging ground water" (Purdy, Straus, Parker, and others, 2001). However, Purdy, Straus, Parker, and others (2001) also stated that there is an urgent need to examine ground-water recharge from playas because it is unknown what role playas used in these feeding operations play in recharging the perched aquifers and the deeper High Plains aquifer. Purdy, Straus, Harp, and others (2001) and Purdy, Straus, Parker, and others (2001) concluded that livestock should not be allowed to access playas that receive runoff from confined-animal feeding operations and that water removed from playas in these feeding operations may have serious effects on the health of cattle and humans.

Although recharge is not well characterized beneath most playas in such feeding operations, conditions in feedyard playas may help to minimize chemical mobilization. For example, it has been hypothesized that animal wastes and a certain bacterium create elastic slime that may help to seal the playa floors (Lehman and Clark, 1975; Stewart and others, 1994; Purdy, Straus, Harp, and others, 2001; Purdy, Straus, Parker, and others, 2001). Additionally, reports of ground-water quality near selected beef cattle feedyards indicated no substantial effects on ground-water quality from the feeding operations (Sweeten and others, 1995).

Subsurface Processes Affecting Recharge Chemistry

Previous studies provide evidence of direct relations between the water quality of playa lakes, subsurface processes, and resulting chemistry of recharge to ground water of the High Plains aquifer. The biogeochemical processes in saturated or inundated playa sediments can have substantial effects on the chemistry of recharge (Pezzolesi and others, 2000). The inundation of and biological activity in playas affects dissolved oxygen in playa waters, which influences the movement of nutrients, trace metals, and organic chemicals and, in turn, the decomposition of organic matter (Pezzolesi and others, 1995, 2000).

Because of the dominance of cotton production throughout the southern High Plains and the historical use of arsenic-based and organochlorine pesticides on this crop, greater concentrations of arsenic and other trace metals have been hypothesized to occur in the soils of playas surrounded by cotton crops (Irwin and others, 1996; Venne and others, 2006). Although some studies have shown arsenic concentrations in playa sediments that are generally 6 to 7 times as great as worldwide soil-background levels, results generally indicate no substantial differences in trace-metal concentrations found in soils from playas in cropland and rangeland settings (Irwin and others, 1996; Venne and others, 2006, 2008). Moreover, Venne and others (2006) found that trace-metal concentrations in sediments were at least 5 times as high as concentrations in amphibian tissue, which indicates that bioaccumulation of metals did not occur. This study concluded that no apparent relation exists between land use (cropland and natural grassland), trace-metal concentrations in playa sediments, and trace-metal concentrations in amphibians. Trace-metal concentrations may be ubiquitously distributed in playa sediments of the southern High Plains (Venne and others, 2006).

Evidence supports substantial differences in soil chemistry between playas receiving wastewater from confined animal feeding operations and those playas in natural settings. Stewart and others (1994) reported total soil N ranging from 3,000 to 4,000 milligrams per kilogram (mg/kg) and soil phosphorus (P) to be 2,000 mg/kg from playas receiving wastewater from beef and dairy lots. By comparison, soils of playas not receiving feedlot wastewater had approximately 168 mg/kg total N and 28 mg/kg total P (Haukos and Smith, 1996). However, other studies have shown that playa wetlands are effective at filtering nutrients (N and P) through biomass uptake (Pezzolesi and others, 1998).

Numerous studies have shown that NO_3^- is attenuated in soils of playas receiving runoff from confined-animal feeding operations and in treated sewage and industrial waste (Fryar and others, 2000, 2001). Fryar and others (2000) observed that ponded surface water impeded oxygen diffusion and caused ***anaerobic*** conditions in the near surface of playa-floor sediments, thus promoting denitrification of nitrate within playas. Additionally, chloride concentrations in sediments beneath playas receiving feedyard wastewater have been observed to increase with time and depth (Clark and others, 1975). However, nitrate concentrations did not increase with depth or time below playas receiving feedyard wastewater, which likely indicates that denitrification is removing nitrate (Clark and others, 1975). As a result, smaller concentrations of nitrate are likely present in recharge beneath some playas.

However, the previously mentioned studies focused on playas that were continuously flooded. Fryar and others (2000) noted that the removal of nitrate by denitrification is likely to be more temporally and spatially variable in playas that are not continuously flooded, such as those found in natural settings. Fryar and others (2000) reported elevated nitrate in ground water in the vicinity of one playa that received wastewater. Playas that have short and frequent episodes of flooding and drying are more likely to have desiccation cracks that promote aerobic conditions in the soil as well as the potential for rapid macropore flow. Denitrification in the playa subsurface limits but does not preclude ground-water contamination resulting from wastewater discharge to playas or from other playas that focus recharge (Fryar and others, 2000). Furthermore, geochemical conditions that promote denitrification may promote mobilization and delivery of trace metals and some organic compounds in recharge. For example, Thurman and others (2000) speculated that metabolites from cotton herbicides may have the ability to leach from subsurface sediment beneath playas into the ground water. However, very few studies have installed monitoring wells immediately downgradient from playas to evaluate recharge chemistry from playas. Consequently, and as first noted by Fryar and others (2000), additional monitoring of ground-water quality near playas—especially those that receive feedlot wastewater—is warranted.

Additionally, no research examined the effects of artificial recharge on the fate and mobilization of contaminants in the modified playas. The practice of removing clay-lined floors and dredging playa sediments may reduce the natural attenuation capacity of the playa-wetland system and possibly increase the mobilization of some contaminants moving toward the water table.

Conclusion Regarding Conceptual Model of Recharge Beneath Playas

Three prominent conceptual models of recharge beneath playa have emerged from the literature synthesis:

1. Playas are evaporation pans (for example, Lehman, 1972; Claborn and others, 1985).
2. Playas are not exclusively evaporation pans, and recharge is restricted to the annulus of playa (for example, Osterkamp and Wood, 1987; Wood and Osterkamp, 1987).
3. Playas are not exclusively evaporation pans, and recharge is focused through clay soils of the playa floor (for example, Broadhurst, 1942; White and others, 1946; Wood and Sanford, 1995a,b; Scanlon and Goldsmith, 1997; Wood and others, 1997).

The synthesis provided in this report demonstrates that playa focus recharge is possible at substantially (1 to 2 orders of magnitude) higher rates than in interplaya areas of the southern High Plains aquifer (fig. 6*A*, appendix 3); it thus provides evidence against interpreting playas as strictly evaporative pans (conceptual model 1). Higher recharge rates beneath playas are supported by high water flux, contents, and potentials; by low chloride and high tritium concentrations in the pore water; and by low caliche content in the sediments. Additionally, infiltration rates are significantly and positively related to clay content of the floor. This apparent contradiction of conventional wisdom is caused by rapid infiltration down desiccation cracks.

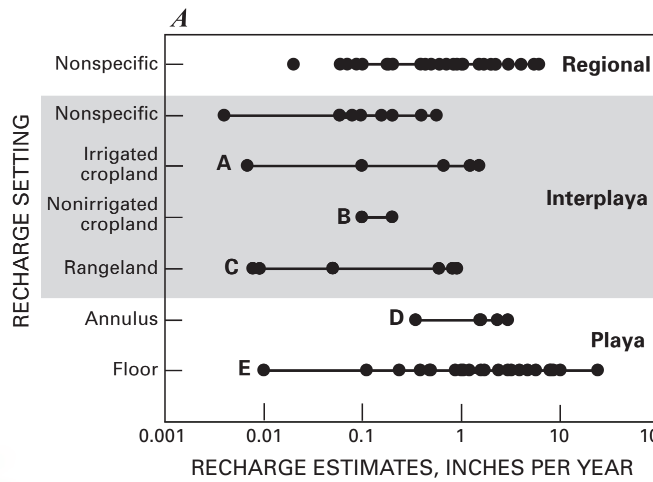
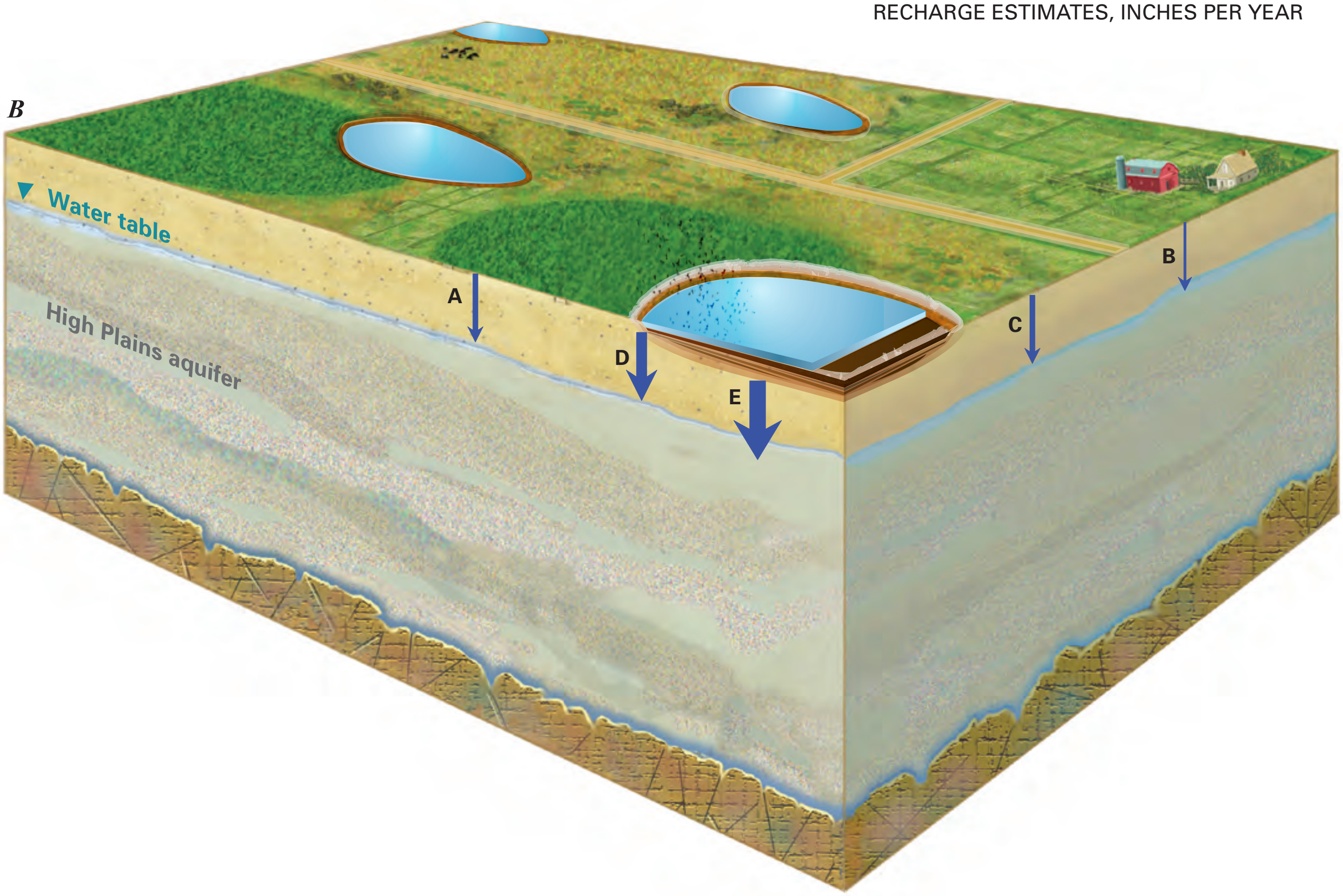


Figure 6. *A*, The recharge estimates listed in appendix 3 are summarized for each recharge setting (A–E); they generally indicate larger recharge rates beneath playas than beneath interplaya settings (note: x-axis is logarithmic). The size of arrows in (*B*) shows relative magnitude of recharge rates, which are approximations based on reported values and locations. Letters A–E refer to recharge settings lettered similarly in figure parts *A* and *B*.



The rapid infiltration rate decreases as ponded water causes expansion of the soil matrix and sealing of desiccation cracks. Studies report strong correlations between ponding and depth of infiltration and recharge, evidence of water movement beneath clay-lined playas, and limited movement through the playa annulus; these studies do not support the interpretation that recharge is restricted to the playa annulus (conceptual model 2).

Many questions remain regarding factors that control recharge beneath playas; however, conceptual model 3 is best supported by most published findings for recharge to the High Plains aquifer (fig. 6*A*). Reported recharge rates beneath playa floors range from about 0.01 to more than 10 in./yr, whereas most interplaya settings in croplands and rangelands have recharge rates reported to range from about 0.01 to 1 in./yr (fig. 6*A*). Although reported recharge estimates through the playa annulus range from about 0.5 to 5 in./yr and are generally higher than most estimates reported for interplaya settings, a number of recharge estimates through the playa floor are higher than the reported rates through the annulus (fig. 6*A*). The reported recharge rates for nonspecific regional recharge settings (fig. 6*A*) range from about 0.05 to almost 10 in./yr, which is similar to the range reported for recharge beneath playa floors. However, the nature of regional-recharge methods makes it very difficult to distinguish focused-recharge processes from diffuse-recharge processes. The nonspecific regional recharge estimates may reflect an average or integration of recharge beneath playas and recharge beneath interplaya settings (fig. 6*A*). Therefore, without recharge contributions from playas, regional recharge to the southern High Plains aquifer could possibly be 1 to 2 orders of magnitude smaller. Properly functioning playa wetlands, which have shrink-swell soils that produce desiccation cracks and rapid infiltration rates, are thus important for the overall recharge contribution to the southern High Plains aquifer. The literature synthesis described in this report did not evaluate recharge beneath playas of the northern High Plains because no published studies were identified. Therefore, until future research on playas of the northern High Plains is published, it is unknown if recharge processes beneath playas in that region are similar to those in the southern High Plains.

Needs for Future Research

The synthesis of previous studies that is outlined in this report indicates that a number of gaps remain in understanding and predicting recharge rates and chemistry beneath playas of the High Plains aquifer. The conditions in and around playas that control recharge rates and chemistry have a direct effect on the diversity of flora and fauna in the playa, land-use characteristics for farmers and ranchers, and the future sustainability of ground water in the High Plains aquifer. Therefore, a number of important research needs remain. These needs are posed as the following questions to help address existing gaps in the current state of knowledge about recharge and chemical transport beneath playas of the region.

What is still unknown about recharge and chemical transport beneath playas to the High Plains aquifer?

Additional data are needed to support an understanding of the subsurface rate of water movement and fate of chemicals after infiltration in the annulus or through the playa floor. For example, the potential for lateral movement of water from the annulus to interplaya sediments and subsequent loss to evapotranspiration is unknown. More important, a relatively small number of recharge estimates have used unsaturated-zone or ground-water studies, which provide much more meaningful and detailed estimates of recharge than water-budget or infiltration studies. Additionally, current research does not clearly describe how playa modification for artificial recharge affects the fate of contaminants in playas and mobilization toward the water table. A number of specific knowledge gaps remain and include the effects of sedimentation on infiltration rates in playa floors and the shrink-swell characteristics of Vertisol soils, transport of organic chemicals and trace metals under anaerobic subsurface conditions in playa sediments and under playa modifications for artificial recharge, and the effects of climate variability and climate change on the hydrology and recharge potential of playas. Future studies that develop predictive models of recharge rates and chemistry beneath playas will likely provide valuable tools for playa and ground-water management and conservation. Are innovative and wetland-friendly approaches for artificial recharge beneath playas possible? How important are playas for recharge to the northern High Plains aquifer, for which comparatively little research has been reported?

What scientific approaches should be considered before implementation of best management practices?

As Melcher and Skagen (2005a) suggested, interdisciplinary and collaborative scientific studies are needed. Collaborative studies between geologists, hydrologists, ecologists, biologists, agronomists, and land-conservation scientists will likely result in knowledge that best fills the remaining gaps in information about playas.

Future studies concerned with the role of playas in recharging the High Plains aquifer will likely refine conceptual model 3 of recharge by using a systematic approach on various spatial and temporal scales and by using a wide range of hydrologic, biogeochemical, and isotopic methods. As described by Nativ (1992), a systematic approach would include data collection of the amount of precipitation and runoff to a playa, the volume of water stored and variations with time, the evapotranspiration of water from the playa, and changes with water contents and total-potential gradients beneath playas and corresponding interplaya areas with time. Additional information may be gained by using biogeochemical and isotopic indicators that trace water and chemical directions and rates of movement within the subsurface.

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Appendixes

Appendix 1. Glossary

Note: Words in ***bold and italics*** throughout the report are described in this glossary.

A

acre feet of water A unit of volume equal to 1 acre of surface area to a depth of 1 foot that approximately equals 43,500 cubic feet or 325,851.4 gallons of water.

anaerobic As used in this report, lack of oxygen in the soil, unsaturated zone, or water.

annulus The sloped surface at the margin of a playa that separates the playa floor from the interplaya region.

aquifer A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield useable quantities of water to springs and wells.

artificial recharge Recharge at a rate greater than natural, resulting from deliberate or incidental human activities.

C

caliche A white and cement-like layer of calcium carbonate ($CaCO_3$) that is deposited in the shallow subsurface. Caliche is common in semiarid and arid regions; it forms by evaporative concentration of calcium carbonate contained in pore water that originated as precipitation.

central High Plains See ***High Plains aquifer***.

central High Plains aquifer The part of the High Plains aquifer system that underlies the ***central High Plains***.

conceptual model A mental model or idea of the specific workings of a particular physical, chemical, or biological process. Conceptual models are commonly developed by scientists to test specific hypotheses and often represent the initial step in developing more quantitative models of the process of interest.

D

diffuse recharge A type of recharge in which precipitation or melting snow infiltrates throughout a uniform area of an aquifer, percolates relatively uniformly through the unsaturated zone, and eventually intercepts the water table. Diffuse recharge often occurs along slow flow paths.

E

endotoxin A potentially toxic natural compound found inside pathogens such as bacteria and released when bacteria die.

ephemeral Lakes, wetlands, streams, or other bodies of water that are intermittently wet and dry.

evaporation The transformation of a liquid to a vapor.

evapotranspiration — The loss of water from a given area by evaporation from the land combined with transpiration (loss of water to the atmosphere) from plants.

F

focused recharge A type of recharge characterized by rapid movement of water through the soil and unsaturated zone that bypasses a large portion of the soil and unsaturated-zone matrix. Focused recharge often occurs along fast flow paths.

G

ground-water availability The amount of ground water that is available to support current uses of a particular aquifer or ground-water resource.

ground-water sustainability The amount of ground water that will be available to support future uses of a particular aquifer or ground-water resource. Alley and others (2002) state that ground-water sustainability is the development and use of ground water in such a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

H

hydric soil A characteristic soil of many wetlands that are saturated or flooded for prolonged periods of time, which produces ***anaerobic*** conditions.

hydroperiod The number of consecutive days that a wetland is inundated with surface water.

High Plains aquifer The High Plains aquifer (174,000 square miles) underlies parts of eight States (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming) and can be divided into northern, central, and southern subregions of the High Plains (fig. 1*B*). The High Plains aquifer, which is commonly known as the ***Ogallala aquifer***, contains six primary hydrogeologic units (fig. 1*C*), of which the Ogallala Formation is the largest.

I

infiltration The process by which precipitation or melting snow enters soil or rock across its interface with the atmosphere (Wilson and Moore, 1998). Infiltrated water may be consumed by evapotranspiration or become deeper percolation and recharge. Infiltration may follow three distinct stages (I–III). The infiltration rates during the stage I are relatively high while the soil is dry. The amount of water in the soil controls the rate of infiltration during stage II infiltration. As the soil becomes wetter, infiltration rates slow during stage II. Stage III of infiltration occurs if the soil becomes saturated. In stage III, the infiltration rate is constant and determined by hydrologic properties of the soil and unsaturated zone.

interplaya The land surface areas that surround playas and include upland settings that drain into playas.

L

Llano Estacado A term that is used synonymously with the southern High Plains region. The Llano Estacado is bounded by the Canadian River to the north, the caprock escarpment to the east, Edwards Plateau to the south, and the Pecos River Valley to the west. The Llano Estacado is estimated to be 98 percent internally drained by an estimated 20,500 playas (Osterkamp and Wood, 1984). Discharge from the Llano Estacado is found in an estimated 30 saline lake basins and along the eastern caprock escarpment.

M

milligrams per liter (mg/L) A unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water; equivalent to one part per million in most surface and ground water. One thousand micrograms per liter equals 1 mg/L.

N

northern High Plains See ***High Plains aquifer***.

northern High Plains aquifer The part of the High Plains aquifer system that underlies the ***northern High Plains***.

O

Ogallala aquifer See ***High Plains aquifer***.

P

pedogenic Processes related to soil development.

percolation The process of water moving vertically or laterally through the soil or unsaturated zone (Wilson and Moore, 1998).

pesticide A chemical applied to crops, rights-of-way, lawns, or residences to control weeds, insects, fungi, nematodes, rodents, and other "pests."

potential evapotranspiration The theoretical combined loss of water from a given area by evaporation from the land and transpiration (loss of water to the atmosphere) from plants.

playa As described by Smith (2003), playas are "…shallow, depressional recharge wetlands occurring in the Great Plains region that are formed through a combination of wind, wave, and dissolution processes with each wetland existing in its own watershed. As the words depressional and recharge imply, Great Plains playas only receive water from precipitation and runoff. Naturally, water is only lost through evaporation, transpiration, and recharge." Although by definition playas are wetlands, the water that collects in playas often forms lakes and as a result are often referred to as "playa lakes or lakes."

predevelopment As used in this report, the "predevelopment" period is the period before extensive ground-water pumping; conditions in the aquifer in the "predevelopment" period represent its undisturbed state. McGuire and others (2003) indicated that the median measurement year in the predevelopment period was 1957.

R

rangeland As used in this report, rangeland is native short- and mid-grass prairie that was never cultivated but may or may not be used for cattle grazing.

recharge The flux of water to ground water. As used in this report, recharge is the vertical, volumetric flux of water across the water table or saturated zone of an aquifer. Rates of recharge are often expressed a length per time (for example, in./yr).

S

southern High Plains See ***High Plains aquifer***.

southern High Plains aquifer The part of the High Plains aquifer system that underlies the ***southern High Plains***.

U

unsaturated zone The subsurface zone between land surface and the water table, characterized by pore water under pressure less than atmospheric pressure. The matrix of the unsaturated zone is not completely filled with water, and thus gases exist in the pore spaces of the unsaturated zone.

V

vadose zone The unsaturated zone.

Vertisol A type of soil that, when dry, is characterized by wide vertical cracks in the soil profile that swell shut when the soil is hydrated. Vertisol soils are common to the floors of playas particularly in the southern High Plains.

W

water cycle A cycle (also called the hydrologic cycle) that describes the existence and movement of water on, in, and above the Earth.

wetland Areas inundated or saturated by surface water or ground water at a frequency and duration sufficient to support a prevalence of vegetation adapted for life in saturated soil conditions; such areas generally include swamps, marshes, bogs, and ***playas*** (U.S. Army Corps of Engineers, 1987; LaGrange, 2005).

Appendix 2. Infiltration Estimates Beneath Playas of the Southern High Plains.

[Infiltration rates compiled from studies that have directly measured infiltration from playas in the southern High Plains. hr, hour; in., inch; min., minute; s, second; stage I–III infiltration is defined in the Glossary under the term infiltration]

Study	Infiltration rate		Approach	Setting	Notes
Lehman and Clark (1975)—1 playa studied					
	0.04 in./hr 0.002 in./hr 0.0008 in./hr	(day 0) (day 1) (day 10)	Constant head permeameter	Playa floor	Randall clay; feedyard runoff
	1.57 in./hr 0.04 in./hr 0.002 in./hr	(day 0) (day 8) (day 45)	Constant head permeameter	Interplaya	Permeable buried soil; feedyard runoff
Evans (1990)—3 playas studied					
	0.39 in./min. 1.81 in./min. 26 in./min.	(minimum) (average) (maximum)	Double-ring infiltrometer	Playa floor	Stage I infiltration
	0.87 in./min. 3.1 in./min. 41 in./min.	(minimum) (average) (maximum)	Double-ring infiltrometer	Playa floor	Stage I infiltration
	0.47 in./min. 6.4 in./min. 98 in./min.	(minimum) (average) (maximum)	Double-ring infiltrometer	Playa floor	Stage I infiltration
	0 in./min. 1.3 in./min. 1.5 in./min.	(minimum) (average) (maximum)	Double-ring infiltrometer	Playa floor	Stage III infiltration
	0 in./min. 0.47 in./min. 2.5 in./min.	(minimum) (average) (maximum)	Double-ring infiltrometer	Playa floor	Stage III infiltration
	0 in./min. 0.59 in./min. 1.5 in./min.	(minimum) (average) (maximum)	Double-ring infiltrometer	Playa floor	Stage III infiltration
Zartman, Evans, and Ramsey (1994); Zartman and others (1996)—1 playa studied					
	116 in./hr 24 in./hr	(min. 1) (min. 5)	5-in. diameter cylinder infiltrometers	Playa floor (center)	(10 s fill time)
	60 in./hr 20 in./hr	(min. 1) (min. 5)	5-in. diameter cylinder infiltrometers	Playa floor (outerbasin)	(10 s fill time)
	88 in./hr 22 in./hr	(min. 1) (min. 5)	5-in. diameter cylinder infiltrometers	Annulus	(10 s fill time)
	10.6 in./hr 2 in./hr	(min. 1) (min. 130)	80-in. diameter basin infiltrometer	Playa floor (center)	(~1 hr fill time)
	5.5 in./hr 1 in./hr	(min. 1) (min. 130)	80-in. diameter basin infiltrometer	Playa floor (outerbasin)	(~1 hr fill time)
	3.2 in./hr 1 in./hr	(min. 1) (min. 130)	80-in. diameter basin infiltrometer	Annulus	(~1 hr fill time)
	2.1 in./hr 0.37 in./hr	(min. 1) (day 1)	350-in. diameter basin infiltrometer	Playa floor (center)	(~1 hr fill time)

Appendix 2. Infiltration Estimates Beneath Playas of the Southern High Plains.—Continued

[Infiltration rates compiled from studies that have directly measured infiltration from playas in the southern High Plains. hr, hour; in., inch; min., minute; s, second; stage I–III infiltration is defined in the Glossary under the term infiltration]

Study	Infiltration rate		Approach	Setting	Notes
Wood and others (1997)—2 playas studied					
	45 in./yr	(minimum)	Water budget	Playa floor	
	76 in./yr	(average)			
	107 in./yr	(maximum)			
	30 in./yr	(minimum)	Water budget	Playa floor	
	47 in./yr	(average)			
	64 in./yr	(maximum)			
Parker and others (2001) — 2 playas studied					
	4.41 in./hr	(min. 1)	Flexible-wall permeameter	Playa floor 1 (minimum)	15 samples
	0.004 in./hr	(min. 5)			
	0.004 in./hr	(min. 60)			
	10.87 in./hr	(min. 1)	Flexible-wall permeameter	Playa floor 1 (average)	15 samples
	0.31 in./hr	(min. 5)			
	0.05 in./hr	(min. 60)			
	19.92 in./hr	(min. 1)	Flexible-wall permeameter	Playa floor 1 (maximum)	15 samples
	0.99 in./hr	(min. 5)			
	0.13 in./hr	(min. 60)			
	7.60 in./hr	(min. 1)	Flexible-wall permeameter	Playa floor 2 (minimum)	11 samples
	0.004 in./hr	(min. 5)			
	0.004 in./hr	(min. 60)			
	13.62 in./hr	(min. 1)	Flexible-wall permeameter	Playa floor 2 (average)	11 samples
	1.20 in./hr	(min. 5)			
	0.09 in./hr	(min. 60)			
	19.76 in./hr	(min. 1)	Flexible-wall permeameter	Playa floor 2 (maximum)	11 samples
	4.49 in./hr	(min. 5)			
	0.24 in./hr	(min. 60)			

Appendix 3. Recharge Estimates for the Southern High Plains.

[Recharge estimates compiled from water-budget, unsaturated-zone, and ground-water studies in the southern High Plains]

Study type and publication	Recharge (in./yr)	Approach	Setting	Notes
Water budget				
Johnson (1901)	3.0–4.0	Observation	Regional	
Gould (1906)	6.0	Observation	Regional	
Theis (1937)	0.1–0.7	Darcy's law	Regional	
White and others (1946)	0.06	Water budget	Regional	
Barnes and others (1949)	0.098	Water budget	Interplaya—nonspecific	
Cronin (1961)	0.5	Darcy's law	Regional	
Havens (1966)	0.82	Water budget	Regional	
Rayner and others (1973)	0.175	Water budget	Regional	
Lansford and others (1974)	0.39	Ground-water modeling	Regional	
Brutsaert and others (1975)	0.183	Water budget	Regional	
Morton (1980)	0.2–2.2	Ground-water modeling	Regional	
Texas Department of Water Resources (1981)	0.5–1.0	Ground-water modeling	Regional	
Bureau of Reclamation (1982)	0.9	Water budget	Regional	
Bureau of Reclamation (1982)	1	Water budget	Playa floor	
Wood and Osterkamp (1984a)	0.1	Literature	Regional	
Wood and Osterkamp (1984b)	1.6	Literature	Playa annulus	
Wood and Osterkamp (1984b)	2.36	From Luckey and others (1986)	Playa annulus	Evapotranspiration not considered.
Luckey and others (1986)	0.086–1.03	Ground-water modeling	Regional	
Wood and Osterkamp (1987)	1.97	From Luckey and others (1986)	Regional	
Wood and Osterkamp (1987)	1.57	From Luckey and others (1986)	Playa annulus	
Nativ and Riggio (1989)	0.01–1.6	Water budget	Playa floor	
Dugan and others (1994)	0.5–1.5	Water budget	Regional	
Mullican and others (1997)	0.4	Ground-water modeling	Interplaya—nonspecific	Ogallala outcrop area.
Luckey and Becker (1999)	0.06–0.08	Ground-water modeling	Interplaya—nonspecific	Low permeability soils.
Luckey and Becker (1999)	0.6–0.9	Ground-water modeling	Interplaya—rangeland	Sand dune setting.
Dugan and Zelt (2000)	0.1–1.5	Percentage of irrigation water	Interplaya—irrigated cropland.	
Dutton and others (2000)	0.1–1.7	Ground-water modeling	Regional	
Stovall and others (2000)	0.6–5.5	Ground-water modeling	Regional	
Unsaturated zone				
Klemt (1981)	0.2	Neutron probe logging	Regional	
Klemt (1981)	0.1–0.2	Neutron probe logging	Interplaya—nonirrigated cropland.	
Knowles and others (1984)	0.06–0.57	Neutron probe logging	Interplaya—nonspecific	
Knowles and others (1984)	0.83	Neutron probe logging	Interplaya—rangeland	Sand dune setting.
Stone (1984)	0.007	Chloride mass balance	Interplaya—irrigated cropland.	
Stone (1984)	0.009	Chloride mass balance	Interplaya—rangeland	Dryland pastures.
Stone (1984)	0.05	Chloride mass balance	Interplaya—rangeland	Sand dune setting.
Stone (1984)	0.11	Chloride mass balance	Playa floor	
Stone and McGurk (1985)	0.05	Chloride mass balance	Interplaya—rangeland	Sand dune setting.
Stone and McGurk (1985)	0.48	Chloride mass balance	Playa floor	
Wood and Sanford (1995a)	3 (±0.31)	Unsaturated-zone tritium	Playa annulus	
Wood and others (1997)	3 (±0.31)	Unsaturated-zone tritium	Playa floor	
Scanlon and Goldsmith (1997)	0.004–0.16	Chloride mass balance	Interplaya—nonspecific	
Scanlon and Goldsmith (1997)	0.24–0.39	Chloride mass balance	Playa floor	Runoff to playas not factored in.
Scanlon and Goldsmith (1997)	2.4–3.9	Chloride mass balance	Playa floor	Runoff to playas factored in.
Scanlon and Goldsmith (1997)	4.72	Unsaturated-zone tritium	Playa floor	
Wood and others (1997)	1.06–1.22	Unsaturated-zone tritium	Playa floor	Assumes matrix flow only.
McMahon and others (2006)	0.67–1.26	Unsaturated-zone tritium	Interplaya—irrigated cropland.	
McMahon and others (2006)	0.008	Chloride mass balance	Interplaya—rangeland	

Appendix 3. Recharge Estimates for the Southern High Plains.—Continued

[Recharge estimates compiled from water-budget, unsaturated-zone, and ground-water studies in the southern High Plains]

Study type and publication	Recharge (in./yr)	Approach	Setting	Notes
Ground water				
Brown and Signor (1973)	0.02–0.07	Ground-water budget	Regional	
Mullican and others (1994)	0.2	Ground-water modeling	Interplaya—nonspecific	
Mullican and others (1994)	8.1	Ground-water modeling	Playa floor	
Mullican and others (1994)	8.6	Ground-water modeling	Playa floor	
Nativ and Smith (1987), Nativ (1988).	0.5–3.24	Tritium	Playa floor	
Wood and Sanford (1994)	0.35	Chloride mass balance	Playa annulus	
Wood and Sanford (1995a)	0.43 (±0.078)	Chloride mass balance	Regional	
Scanlon and Goldsmith (1997)	7.87–24	Ground-water chemistry	Playa floor	Playa receives long-term wastewater.
Wood and others (1997)	0.87–1.73	Chloride mass balance	Playa floor	Assumes matrix flow only.
Wood and others (1997)	5.7–10.1	Chloride mass balance	Playa floor	Assumes flow in desiccation cracks only.

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