

Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley

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Aquifer overexploitation could significantly impact crop production in the United States because 60% of irrigation relies on groundwater. Groundwater depletion in the irrigated High Plains and California Central Valley accounts for ~50% of groundwater depletion in the United States since 1900. A newly developed High Plains recharge map shows that high recharge in the northern High Plains results in sustainable pumpage, whereas lower recharge in the central and southern High Plains has resulted in focused depletion of 330 km³ of fossil groundwater, mostly recharged during the past 13,000 y. Depletion is highly localized with about a third of depletion occurring in 4% of the High Plains land area. Extrapolation of the current depletion rate suggests that 35% of the southern High Plains will be unable to support irrigation within the next 30 y. Reducing irrigation withdrawals could extend the lifespan of the aquifer but would not result in sustainable management of this fossil groundwater. The Central Valley is a more dynamic, engineered system, with north/south diversions of surface water since the 1950s contributing to ~7× higher recharge. However, these diversions are regulated because of impacts on endangered species. A newly developed Central Valley Hydrologic Model shows that groundwater depletion since the 1960s, totaling 80 km³, occurs mostly in the south (Tulare Basin) and primarily during droughts. Increasing water storage through artificial recharge of excess surface water in aquifers by up to 3 km³ shows promise for coping with droughts and improving sustainability of groundwater resources in the Central Valley.

Gravity Recovery and Climate Experiment satellite | irrigated agriculture | managed aquifer recharge

Irrigation resolves spatial and temporal disconnects between water supply and water demand and allows us to grow crops in semideserts. Irrigation consumed ~90% of global freshwater resources during the past century (1, 2) and represents 20% of cropland and ~40% of food production (2, 3). During the past couple of decades, groundwater has become an increasingly important source of irrigation and currently is used in ~40% of the area equipped for irrigation globally and 60% within the United States (4). Expansion of groundwater-fed irrigation is attributed to the ubiquity of groundwater, ready access to this resource, minimal infrastructure requirements, and general continuity of supply providing a buffer against droughts (5). A recent analysis reports an approximate doubling of global groundwater depletion between 1960 and 2000 and identifies several hot spots of depletion, mostly in irrigated regions, including the High Plains (HP) and California Central Valley (CV) aquifers in the United States (6).

With growing dependence of agricultural production on unsustainable groundwater use threatening future crop production, the following basic questions arise: How much groundwater has been depleted? Are we running out? What is the spatiotemporal variability in depletion? Can groundwater-fed irrigation be managed sustainably? Ground-based monitoring, modeling, and satellites [Gravity Recovery and Climate Experiment (GRACE)] have been used to estimate groundwater depletion in different irrigated regions (6–8). Maximum available blue water resources

(rivers and aquifers) have only been depleted by ~10% globally, suggesting that we are not running out of water; however, we may be running out of water locally and during droughts because of spatiotemporal variability in depletion (9). Unlike oil production, where the objective is to produce all available oil in a reservoir, groundwater production is often restricted by its impacts on surface water through reductions in groundwater discharge to streams, and effects on groundwater-dependent ecosystems, land subsidence, and water quality. Thus, with the exception of mining fossil groundwater, the total amount of groundwater storage depletion is primarily constrained by the effects of depletion on water flows, water quality, and/or heads (in the case of subsidence) (9, 10).

The objective of this study was to quantify spatiotemporal variations in depletion at the aquifer scale, determine controls on depletion, and evaluate approaches to reduce groundwater depletion. The analysis was conducted for the HP and CV aquifers because they are hot spots for depletion and are among the most intensively monitored aquifers globally. Understanding water sustainability of the HP- and CV-irrigated regions is important for future crop production in the United States. Analysis of groundwater depletion is based on water level monitoring in ~9,000 wells in the HP and ~2,300 wells in the CV. A map of groundwater recharge was developed in this study for the HP that complements previous site-specific recharge estimates. Groundwater depletion in the CV was examined using the newly developed CV hydrologic model (11). The GRACE satellites have also been used to monitor groundwater depletion in both aquifers (12, 13, 14). The impact of climate variability on water resources is addressed; however, effects of climate change projections are outside the scope of the study. The wealth of data for these aquifers provides an opportunity to advance our understanding of groundwater depletion and examine approaches to manage groundwater resources more sustainably. Unique aspects of this work are the synthesis of a variety of data from satellite and ground-based observations and numerical modeling and comparisons between the HP and CV aquifers to develop an understanding of spatiotemporal variability in groundwater depletion that is used to assess more sustainable management approaches.

Comparison of General Attributes of the HP- and CV-Irrigated Regions

The HP aquifer (450,000 km²) and CV aquifer (52,000 km²) are ranked first and second, respectively, among aquifers in the United States for total groundwater withdrawals (15) (Fig. 1 and Figs. S1 and S2). The HP is less intensively cultivated (39%

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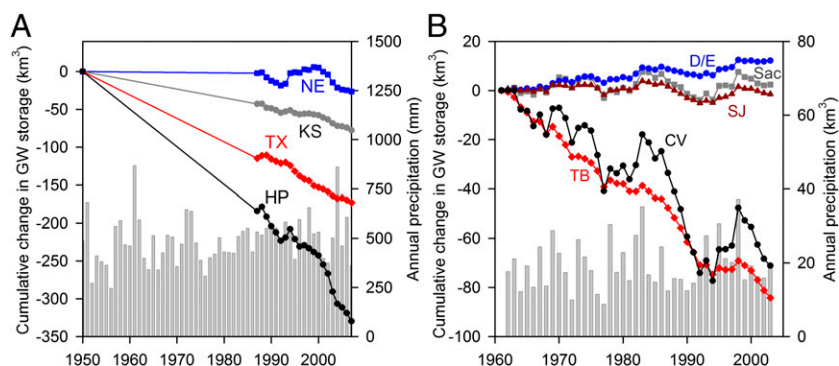


Fig. 2. Trends in groundwater depletion in (A) the HP and (B) the CV aquifers. Depletion is concentrated in the southern regions of both basins, Texas in the HP and Tulare Basin in the CV. The HP data show generally monotonic declines based on water level monitoring in 3,600 wells (1950s) to 9,600 wells (2006) (7). Water level changes in the CV are much more dynamic with declines focused during droughts (1976–1977, 1987–1992, 1998–2003) and recovery at other times. D/E, Delta, Eastside; Sac, Sacramento; SJ, San Joaquin; TB, Tulare Basin.

2007 (Table S3); however, the rate of depletion increased with time ($\sim 7 \text{ km}^3/\text{y}$ during the 20-y period of intensive monitoring, 1987–2007; Fig. 24). In contrast, groundwater levels and modeling in the CV (1962–2003) indicate that depletion is highly episodic, restricted primarily to droughts, with partial recovery at other times (Fig. 2B). Depletion during droughts ranged from 24.6 km^3 during the most severe drought (1976–1977) to 49.3 km^3 during a long-term drought (1987–1992). Many farms are equipped to use both surface water and groundwater. When available, farmers irrigate with less-expensive surface water; during dry periods, groundwater becomes an increasingly important irrigation source. The CV hydrologic model (1962–2003) indicates that droughts are associated with reductions in recharge by up to 60%; however, impacts of droughts are exacerbated by reductions in surface water deliveries from the north by up to 60%, increasing groundwater pumpage by up to 180% relative to the long-term mean for the simulation period (11).

What Controls Groundwater Depletion? Groundwater depletion occurs when water demand through pumpage exceeds water supply through recharge. Depletion varies as sources of water for pumpage change over time. Before irrigation, long-term mean groundwater recharge (R) equals groundwater discharge (D) through baseflow to streams ($R = D$). Groundwater-fed irrigation (P_u) can be derived from groundwater depletion, i.e., change in groundwater storage (ΔS), increased recharge (ΔR), and/or decreased discharge (ΔD) as follows (19, 20):

$$(R + \Delta R) - (D + \Delta D) - P_u = \Delta S \quad [1]$$

Initially, all groundwater for irrigation pumpage is derived from aquifer storage. With time, more irrigation water can be derived from increased recharge and/or decreased discharge through capturing groundwater discharge to streams as base flow. Although recharge is often increased under irrigated areas, only recharge from irrigation derived from surface water represents a net increase in recharge, because changes in recharge from groundwater-fed irrigation simply reflect recycling of groundwater with net groundwater depletion. Ultimately, groundwater-fed irrigation may be derived entirely from increased recharge and/or decreased discharge, with no further change in groundwater storage, equating to some definitions of sustainable pumpage. However, sustainable pumpage may not equate to the much broader concept of sustainability, which includes minimizing adverse environmental impacts (21).

The pervasive belief about the HP aquifer is that it represents fossil groundwater that is being mined. However, conditions are highly variable spatially, ranging from almost no depletion in the north, large-scale depletion in the center and northern part of the south, and limited depletion in other parts of the south (Figs. 1A and 2A and Fig. S1). Variations in depletion may reflect differences in water demand through irrigation and/or supply through recharge. Although irrigation began much earlier in

Texas than in Nebraska, irrigation peaked in Texas in the mid-1970s but continued to increase in Nebraska. Irrigated areas in Nebraska and Texas balanced out over time; however, irrigation pumpage averaged $\sim 30\%$ higher in Texas than in Nebraska (Fig. S10). Therefore, variations in depletion may partially reflect differences in irrigation pumpage.

Variations in recharge may also contribute to differences in depletion. A newly developed recharge map for the HP based on a mass balance approach applied to groundwater chloride data (Methods) shows large variations in long-term mean annual rates of groundwater recharge from precipitation across the HP (Fig. 3, Table 1, and Table S3). The chloride mass balance approach is general and may not accurately estimate recharge in irrigated areas (12% of land area) because of chloride recycling. High natural recharge rates in Nebraska are dominated by recharge in the Sand Hills (area mean 92 mm/y ; $5.6 \text{ km}^3/\text{y}$), which supported high predevelopment groundwater discharge to streams; however,

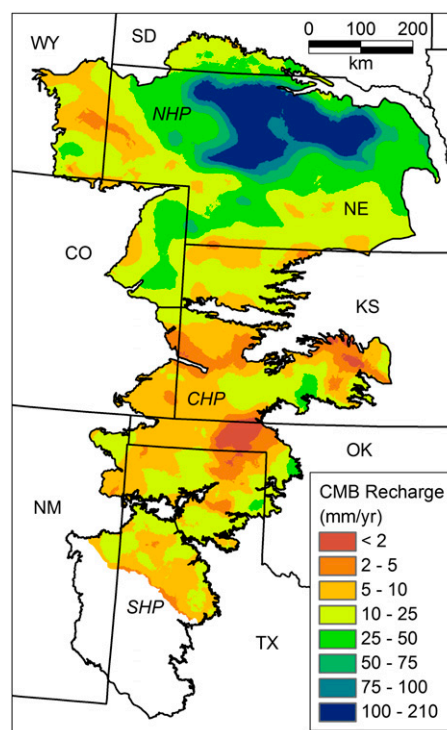


Fig. 3. Long-term mean annual recharge rates for the HP aquifer based on the chloride mass balance approach applied to groundwater chloride data. Recharge rates could not be estimated for the southern part of the SHP because groundwater chloride is impacted by upward movement of saline water from deeper aquifers.

up to 50% of this discharge has been captured by irrigation pumpage (22, 23). Therefore, capture of groundwater discharge, along with increased recharge from surface water-fed irrigation from the Platte River (30% of total irrigation, remaining 70% from groundwater), account for the small decline in groundwater storage in the north (Nebraska). In contrast, in the central HP (CHP) and northern part of the southern HP (SHP), where the largest declines have occurred, low initial recharge (9 mm/y corresponding to $0.77 \text{ km}^3/\text{y}$ in the CHP, and 10 mm/y corresponding to $0.27 \text{ km}^3/\text{y}$ in the northern part of the SHP), based on water balance (24) and groundwater chloride data (Fig. 3), results in low groundwater discharge to streams, limiting water available for capture. In addition, unsaturated zone studies indicate that irrigation has not recharged the aquifer through return flow in areas of fine-grained soils (25) (Fig. S44). The only source of current recharge may be from surface water through playas (26). Irrigation is mostly mining fossil groundwater that was recharged during the past $\sim 13,000$ y on the basis of groundwater age dating (27). Groundwater depletion in areas of Kansas and Texas where water levels declined ≥ 30 m ($17,000 \text{ km}^2$ area) exceed recharge by a factor of 10 [10 mm/y recharge over $60 \text{ y} = 10 \text{ km}^3$ vs. 100 km^3 of depletion (mean 40 m decline, 0.15 specific yield)]. In coarser-textured soils in other parts of the southern Texas HP, increased recharge under irrigated areas simply reflects recycling of water because irrigation is groundwater fed (28). The aquifer in this region is relatively thin (median 16 m thick), and well hydrographs show that groundwater storage has been depleted in some regions (Fig. S1). Leveling off of groundwater levels after depletion suggests that sustainable pumpage has been achieved in parts of this region after aquifer storage was depleted, and demonstrates the self-regulation inherent in the system. Therefore, the situation in the HP ranges from sustainable pumpage in the north to mining of groundwater in the central and northern parts of the south, to sustainable pumpage after depletion in parts of the south. These differences across the HP primarily reflect variations in recharge with $\sim 10\times$ higher recharge in Nebraska than in Kansas or Texas (Fig. S3 and Table S3).

Groundwater depletion in the CV aquifer is controlled primarily by variations in supply related to spatiotemporal variations in precipitation and surface water deliveries that result in variations in demand through irrigation pumpage. Depletion is greatest in the south (up to 120 m in confined aquifers in the Tulare Basin) where precipitation is lowest (Fig. S5B) and surface water availability for irrigation is limited. The CV differs from the HP in the large north-to-south precipitation gradient and engineering approach adopted to reduce water stresses. Large-scale diversions of surface water through the federally funded Central Valley Project (since the early 1950s) and the State Water Project (since the late 1960s) helped relieve water stress in the south and resulted in partial recovery of aquifer storage by up to 90 m in some areas from reduced pumpage and increased recharge. Irrigation increased groundwater recharge by a factor of 6.9 (from $2.5 \text{ km}^3/\text{y}$ during predevelopment to $17.2 \text{ km}^3/\text{y}$) and discharge, including pumpage, by a factor of 7.8 (from $2.5 \text{ km}^3/\text{y}$ during predevelopment to $19.4 \text{ km}^3/\text{y}$; Table S2). The deficit between increased recharge and groundwater discharge ($2.2 \text{ km}^3/\text{y}$) is supplied by groundwater storage, resulting in groundwater depletion. Groundwater depletion in the CV occurs mainly during episodic droughts, with partial recovery at other times (Fig. 2B). In the southern CV (Tulare Basin), groundwater is being mined; groundwater depletion slows or stops during wet periods but has not recovered.

How Renewable Are Groundwater Resources in the HP and CV? Renewable groundwater resources are essentially inexhaustible but are limited by the recharge rates (flow), whereas nonrenewable resources are almost independent of flow but are limited by water storage (9, 10, 29). In the NHP area, renewable groundwater resources are flow limited, whereas in the CHP and SHP,

essentially nonrenewable or fossil groundwater resources are storage limited. However, groundwater storage is highest in the north ($\sim 2,400 \text{ km}^3$ in Nebraska, 2007) and lowest in the south (410 km^3 in Texas, 2007; Table S3). The high groundwater storage in the NHP cannot be pumped further because it is required by regulation to maintain groundwater/surface water interactions. Although only 1% of groundwater storage has been depleted in Nebraska (26 km^3), modeling shows that groundwater pumping has reduced groundwater discharge (base flow) to the Platte and other rivers by up to 50% (22, 23). The shallow water table before onset of irrigation (Fig. S11) suggests connection with surface water in the NHP. Maintaining this connection greatly restricts the amount of groundwater that can be abstracted. Reduced baseflow has negatively impacted endangered species near the Platte River, including the whooping crane, sand plover, least tern, and pallid sturgeon (22). Threatened litigation among the federal government and the States of Colorado, Nebraska, and Wyoming at the US Supreme Court level related to the endangered species in the Platte River was resolved by restricting irrigation abstractions. Similar legal conflicts over groundwater/surface water interactions have occurred in the other NHP river systems, including the Republican River.

Nonrenewable or fossil groundwater resources in the CHP and SHP are essentially independent of recharge and current climate but are limited by storage, similar to oil reservoirs. Connections between groundwater and surface water were limited in many parts of the CHP, as shown by the deep predevelopment water table (Fig. S11). Most surface water drains into ephemeral lakes or playas that are not groundwater discharge points—rather, they recharge the aquifer—and thus are not impacted by groundwater depletion. Where groundwater and streams were connected, such as along the Arkansas River, irrigation has already caused rivers in western Kansas to change from gaining perennial rivers to losing ephemeral rivers; therefore, connection between groundwater and surface water has been lost in these areas (30). Many groundwater conservation districts in Texas allow managed aquifer depletion where groundwater storage can be depleted by up to 50% in 50 y (2000–2050). In these situations, knowledge of groundwater storage is important for managing groundwater development and for assessing the lifespan of the aquifer.

Renewable groundwater resources in the CV are limited by flows rather than storage, as in the HP. Groundwater depletion in this region is restricted by law to maintain baseflow to streams and minimize subsidence. The southern CV is internally drained and the predevelopment water table was high. In the 1800s, tule marshes were prevalent and artesian conditions existed throughout most of the basin that resulted in flowing wells at the land surface. Irrigation and damming of many of the rivers caused these marshes to dry up, groundwater levels to drop, and artesian conditions to no longer exist. Some sections of the San Joaquin River no longer flow, and salmon, which once were prevalent in the river, no longer use the river for spawning. Recently, there have been efforts to evaluate restoration of the San Joaquin River and analyze interactions with groundwater. In the San Joaquin and Tulare Basins, depletion of deeper confined aquifers is constrained by subsidence. Subsidence of ~ 9 m was recorded in the southwestern Tulare Basin (Los Banos Kettleman City region west of Fresno) and generally corresponds to the area of the Corcoran Clay Member of the Tulare Formation (17). When hydraulic heads in the confined aquifer are reduced below a critical value, equal to the previous minimum head, subsidence can recur. Inelastic compaction associated with subsidence represents irrecoverable storage depletion and is a one-time source of groundwater. Therefore, groundwater production in the confined aquifer is controlled by previous minimum heads and not by the total water storage in the system.

What Is the Lifespan of the Aquifers? There is a lot of interest in assessing aquifer lifespan from water storage in aquifers and the current depletion rates. If we apply this approach to the HP

potential for more-sustainable irrigation management, it will come at a cost, including increased energy consumption.

This study significantly advances our understanding of groundwater depletion by integrating ground-based monitoring and modeling analyses using the CV and HP aquifers as case studies. Although satellite data provide information on aquifer scale depletion, ground-based data underscore the large spatial and temporal variability in depletion that needs to be considered for management. Variability in groundwater depletion in the HP is controlled primarily by variations in groundwater recharge. High recharge in the NHP results in sustainable pumpage, whereas low recharge in the CHP and SHP results in monotonic depletion related to fossil groundwater that was mostly recharged during the past 13,000 y. Spatial and temporal variations in depletion in the CV are controlled by water supply from diversions and droughts. Groundwater banking offers great promise for more sustainable management of groundwater in the CV by storing excess water from floods and diversions in aquifers for use during droughts.

Methods

MODFLOW was used to simulate groundwater flow in the CV aquifer for the period 1962–2003. Details of the model can be found in Faunt (11).

Groundwater recharge in the HP aquifer was calculated by applying the chloride mass balance approach to groundwater chloride data obtained from the US Geological Survey National Water Information System database and from the Texas Water Development Board database. The equation for calculating recharge (R) is

$$R = \frac{P \times Cl_p}{Cl_{gw}}, \quad [2]$$

where P is mean annual precipitation (1971–2000 from PRISM database), Cl_p is chloride concentration in precipitation from National Atmospheric Deposition Program (wet deposition $\times 2$ to account for dry deposition), and Cl_{gw} is groundwater chloride concentration. Chloride concentrations in the SHP are impacted by upward flow from underlying more-saline aquifers and could not be used for recharge estimation. Additional details related to recharge estimation are provided in [SI Text](#).

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