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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 km^3 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 km^3, 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 km^3 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 km^2) and CV aquifer (52,000 km^2) 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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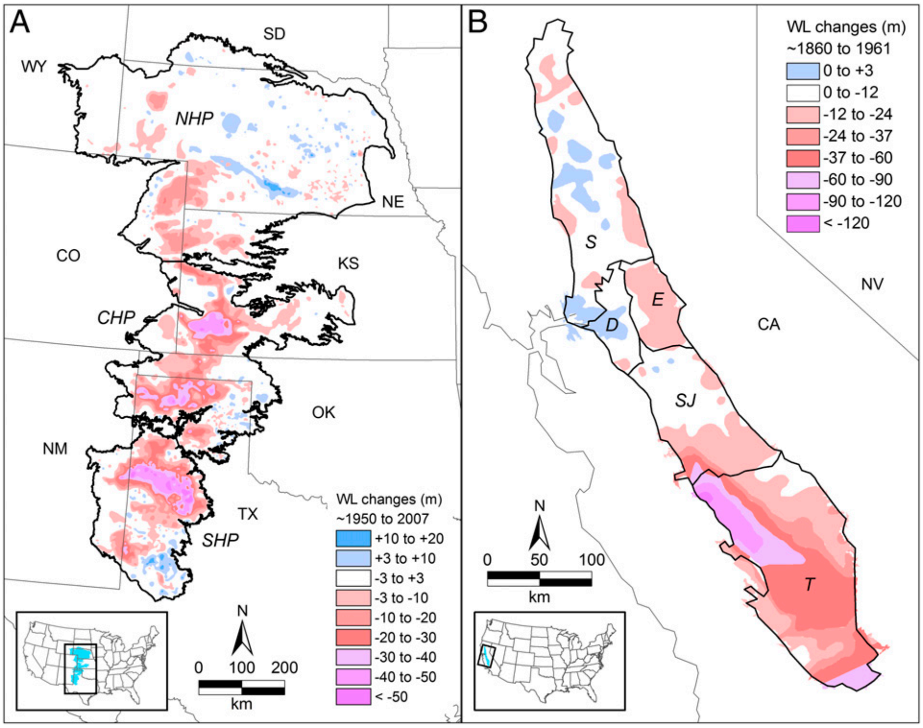

Fig. 1. (*A*) Measured groundwater level changes from predevelopment (∼1950) to 2007 in the HP aquifer [modified from (7)]. (*B*) Simulated groundwater level changes from predevelopment (∼1860) to 1961 in the confined aquifer (17). Groundwater basins include the Sacramento, Delta/East sides, San Joaquin, and Tulare.

cropland) with less irrigation (∼30% of cropland irrigated) than the CV (53% cropland, 90% of cropland and pastureland irrigated; Fig. S3 and Table S1). The importance of these aquifers for crop and food production in the United States is shown by the market value of agricultural products, which was \$35 billion in the HP and \$21 billion in the CV relative to the United States total of \$300 billion in 2007 (16). The HP region has been termed the "grain basket" of the United States, and the CV the "fruit and vegetable basket" of the United States, supporting cultivation of up to 250 different crops.

In the HP, surface water resources are dominated by internally drained ephemeral lakes or playas (∼50,000 playas) because of the extremely flat topography. Integrated surface-water drainage is limited to a few rivers (e.g., Platte, Republican, and Arkansas; Fig. S3*A*). In contrast, the CV receives much of its water from the surrounding mountains and has a dense river network feeding into the valley floor. The main rivers are the Sacramento and San Joaquin Rivers, which flow north or south. Soils also play an important role in groundwater recharge and are generally fine grained in the HP, outside the Nebraska Sand Hills (Fig. S4*A*). Proximity of the Sierra Nevada Mountains to the CV results in coarser soils and sediments in the southeast associated with alluvial fans, and finer soils in the north and west associated with volcanics from the Coast Range (Fig. S4*B*).

Most of the water in the HP is derived from precipitation on the HP (237 km^3, mean 1971–2000), whereas precipitation in the CV is very low (19 km^3), representing ∼15% of total precipitation in the enclosing Sacramento and San Joaquin river basins (115 km^3) (Fig. S5). Therefore, ∼85% of precipitation occurs in the surrounding mountains, e.g., as snow in the Sierra Nevada Mountains to the east and the Klamath Mountains to the west of the Sacramento Valley; snowpack forms a critical reservoir for the region. Distribution of precipitation is much more uniform from north to south in the HP (475–501 mm/y) than in the CV (611–165 mm/y; 1971–2000). The HP is dominated by summer convective storms (72–77% April–September), which coincides with crop production, whereas the CV is dominated by winter frontal storms (79–85%, November–March), typical of the Mediterranean climate, and asynchronous with crop production (Fig. S6). The north-to-south temperature gradient is much greater in the HP (9.2–14.6 °C) than in the CV (16.5–17.5 °C; 1971–2000; Fig. S7).

How Much Groundwater Has Been Depleted? Groundwater has been depleted by ∼330 km^3 in the HP aquifer on the basis of groundwater level data from 3,600 wells from predevelopment (∼1950s) to 2007 (Fig. 1*A* and Table S3) (7). This depletion represents ∼8% of groundwater in storage available before irrigation (∼4,000 km^3; Fig. S8). Likewise, in the CV, groundwater depletion was estimated to be ∼140 km^3 from models [60 km^3 from the 1860s to 1961 (Fig. 1*B*) and 80 km^3 from 1962 to 2003] and represents ∼14% of estimated groundwater in storage before irrigation (1,000 km^3) (11, 17). Groundwater storage reductions in the HP aquifer account for 36%, and those in the CV aquifer 15% of total estimated water storage declines in all aquifers in the United States from 1900 to 2008 (18).

How Does Groundwater Depletion Vary Spatially? If groundwater depletion were uniform in the HP, it would result in an average water table decline of ∼4 m. However, there is almost no depletion in the northern HP (NHP; Nebraska; mean 0.3 m); depletion is much greater in the central and southern HP (e.g., Kansas, mean 7 m; Texas, mean 11 m; Figs. 1*A* and 2*A* and Fig. S1). In fact, spatial depletion is localized with about a third of depletion restricted to 4% of the HP area where groundwater levels have declined ≥30 m in Kansas and Texas (Fig. S9). Extrapolation of the depletion rate from the past decade (1997–2007) indicates that the saturated thickness would decrease to ≤6 m in 35% of the southern HP within 30 y and would not be able to support irrigation. Similar to the HP, groundwater depletion in the CV area before 1961 was restricted mostly to the Tulare Basin in the south with declines ≥30 m in the shallow unconfined aquifer and ≥120 m in the deeper confined aquifer before 1961 (Figs. 1*B* and 2*B* and Fig. S2) (17). Declines since 1961 are also focused in the Tulare Basin (2.3 km^3/y; 97 km^3, 1962–2003; Fig. S2).

How Does Groundwater Depletion Vary Temporally? The HP aquifer displays essentially monotonic depletion in groundwater storage with a rate of ∼5.7 km^3/y since predevelopment in the 1950s to

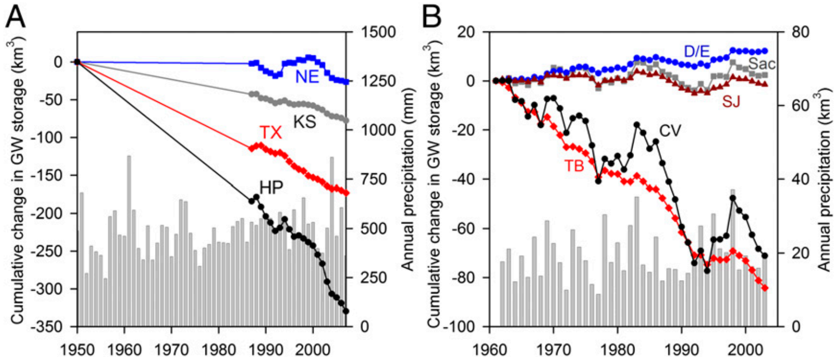

Fig. 2. Trends in groundwater depletion in (*A*) the HP and (*B*) the CV aquifers. Depletion is concentrated in the southern regions of both basins, Texas in the HP and Tulare Basin in the CV. The HP data show generally monotonic declines based on water level monitoring in 3,600 wells (1950s) to 9,600 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 (~7 km^3/y during the 20-y period of intensive monitoring, 1987–2007; Fig. 2*A*). 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. 2*B*). 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 (Pu) 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):

$$(R + \Delta R) - (D + \Delta D) - Pu = \Delta S \qquad [1]$$

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. 1*A* and 2*A* 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 ~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 km^3/y), which supported high predevelopment groundwater discharge to streams; however,

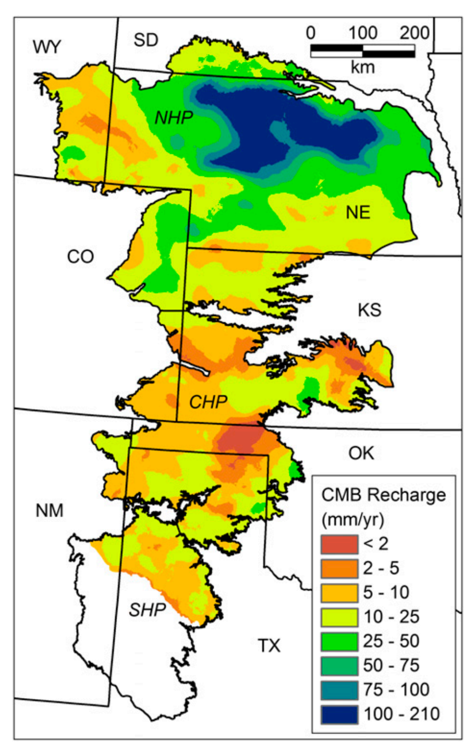

Fig. 3. Long-term mean annual recharge rates for the HP aquifer based on the chloride mass balance approach applied to groundwater chloride data. Recharge rates could not be estimated for the southern part of the SHP because groundwater chloride is impacted by upward movement of saline water from deeper 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 km^3/y in the CHP, and 10 mm/y corresponding to 0.27 km^3/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. S4*A*). 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 ~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 km^2 area) exceed recharge by a factor of 10 [10 mm/y recharge over 60 y = 10 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 ~10× 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. S5*B*) 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 km^3/y during predevelopment to 17.2 km^3/y) and discharge, including pumpage, by a factor of 7.8 (from 2.5 km^3/y during predevelopment to 19.4 km^3/y; Table S2). The deficit between increased recharge and groundwater discharge (2.2 km^3/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. 2*B*). 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 (~2,400 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 aquifer, the results suggest a lifespan of 630 y for the HP (Table S3). However, there is essentially no depletion in the NHP (Nebraska), and depletion is concentrated in the CHP and SHP. Estimated lifespans of the aquifer in these regions are 240 y for Kansas and 140 y for Texas. However, depletion is even more localized than in these regions, with ∼35% of depletion in 4% of the land area (Fig. S9), resulting in much shorter lifespans in these regions. Aquifer lifespans only pertain to fossil groundwater and are extremely variable spatially.

The estimated lifespan of the CV aquifer is 390 y based on remaining water storage in 2000 of 860 km^3 and depletion rate of 2.2 km^3/y from the CV hydrologic model (11). However, depletion is focused in the Tulare Basin in the south, with little or no depletion in the San Joaquin and Sacramento Basins; therefore, aquifer lifespan is much shorter in the Tulare Basin.

How Can We Monitor Groundwater Depletion? There is considerable interest in using GRACE satellites to monitor changes in groundwater storage at basin scales because they provide continuous coverage globally and complement long-term water-level monitoring and regional hydrologic modeling. GRACE measures changes in total water storage, which are used to estimate changes in groundwater storage (GWS) by subtracting changes in storage in snow (snow water equivalent) from the Snow Data Assimilation System, surface water from reservoir monitoring, and soil moisture derived from Global Land Data Assimilation System models (31).

In the HP, estimated GWS changes from GRACE data are highly correlated with those from detailed groundwater level monitoring data (∼1,000 wells, r^2 from 0.7 to 0.8) (12, 32). In the CV, GWS depletion during the late 2000s drought calculated from GRACE data (6–8 km^3/y totaling 24–34 km^3 from April 2006 to March 2010) is similar or lower than depletions estimated from groundwater modeling for previous droughts (1976–1977; 12 km^3/y; 1987–1992; 8 km^3/y) (11, 13, 14). Therefore, GRACE data can monitor basin-scale changes in GWS, which complement much higher spatial-resolution GWS changes from ground-based monitoring and modeling analyses.

How Can Irrigation Be Managed to Increase Sustainability of Groundwater Resources? Groundwater depletion is likely to increase in the future with increasing temperatures and projected more severe and prolonged droughts associated with climate change (33, 34). Limited analysis of potential impacts of climate change (Geophysical Fluid Dynamics Laboratory A2 scenario) suggests persistent droughts in the second half of the 21st century; decreasing water supplies through reduced surface water inflows by 20–65% and reduced groundwater recharge from stream flow by up to 50%; and increased demands for irrigation and urban growth, reducing groundwater storage in the CV by ∼110 km^3 (2050–2100) (35). Increasing supply of surface water and/or reducing demand of groundwater can reduce groundwater depletion to increase sustainability. Increasing water storage can help resolve the temporal disconnections between supply and demand. There are no obvious options for increasing water supply in the HP or the CV. Although building canals in the CV to transfer water represented the traditional approach to water resources management, it is increasingly difficult to adopt these approaches because of cost and environmental concerns (36).

On the demand side, groundwater depletion can be reduced in areas dominated by groundwater-fed irrigation by increasing irrigation efficiency, i.e., transitioning from flood to sprinkle and drip systems. In the CV, ∼50% of crops are still produced under flood irrigation (36). The ability of improved irrigation efficiency to result in real water savings has been questioned because much of the irrigation excess is thought to return to streams or replenish aquifers (37, 38), and the saved water is often used to expand irrigation or irrigate more water-intensive crops (38, 39). It is important to determine whether excess irrigation water recharges aquifers, because fine-grained soils in much of the CHP prohibit recharge from irrigation water (25, 28). There is also a limit to the efficiency of irrigation systems because of the potential for soil salinization. Center pivot systems, dominant in the HP, are up to 98% efficient in parts of the Texas HP but are salinizing soils because of insufficient water to flush salts and lack of winter precipitation (40). Ultimately, irrigated crops could be converted to rainfed crops to reduce groundwater depletion in the HP; however, this may require changing crop types (e.g., from water-intensive corn to cotton) and would decrease crop yields by a factor of 2.0–2.5 relative to their irrigated counterparts in the Texas HP with related impacts on the economy (41). Conversion from irrigated to rainfed cropland is infeasible in the SCV, which is essentially a desert and cannot support rainfed agroecosystems, as shown by the large increase in land fallowing (9–14%) during the recent drought from 2006 to 2009.

Temporal disconnects between water supply and demand can be managed through conjunctive use of surface water and groundwater and increased water storage. In the CV, surface water is used during times of precipitation excess, and groundwater is used during droughts. Water transfers from the humid north to the arid south actually amplify impacts of droughts because they supply water during times of excess but restrict transfers during droughts, particularly in recent years (e.g., only 10% transferred at the end of the last drought in 2009) (42). Conjunctive use is of limited value in the HP because surface water is restricted to a few rivers. The storage capacity of existing reservoirs in the CV can be increased by raising the elevation of the dams. Managed aquifer recharge or groundwater banking provides a valuable alternative to traditional surface water reservoirs for storing water and has been used in the CV since the 1960s. Storing excess surface water underground decreases the impacts of increased evaporation associated with climate warming (34). Ponds or spreading basins are used to percolate water from canals or rivers, eventually recharging underlying aquifers. This increased groundwater storage is then available for pumping during droughts. Groundwater banks are being operated in the Tulare Basin, including the Arvin Edison and Kern Water Banks with cumulative storage volumes of up to 1–2 km^3 of water each, with abstractions restricted to droughts (Fig. 4 and Fig. S12). The storage capacity of surface water reservoirs is limited in the CV (∼49 km^3) and represents ∼150% of mean annual discharge (43). In addition, water storage has to be reduced to capture flood flows. This excess water could be stored in aquifers through managed aquifer recharge for later use during droughts. Groundwater banks may provide a valuable approach to mitigation of impacts of climate change related to increasing intensity of the water cycle associated with extreme floods interspersed with longer-term droughts by storing floodwater and abstracting stored water during droughts. Although the CV has great

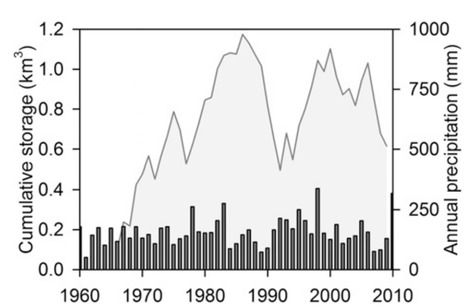

Fig. 4. Cumulative water storage in the Arvin Edison groundwater bank relative to precipitation. The data show declines in storage mostly restricted to droughts in 1976–1977, 1987–1992, and 1998–2003.

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

$$R = \frac{P \times Cl_P}{Cl_{gw}}, \tag{2}$$

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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Supporting Information

Scanlon et al. 10.1073/pnas.1200311109

SI Text

The following describes groundwater recharge estimation in the High Plains aquifer using the chloride mass balance approach. A total of ~6,600 wells were used for estimating groundwater recharge in the High Plains with the chloride mass balance approach. These wells were derived from ~9,900 of wells completed in the Ogallala/High Plains aquifer from the US Geological Survey National Water Information Systems and Texas Water Development Board databases. The recharge estimates were based on chloride analyses from the most recent samples. A total of ~2,500 wells were excluded because they were (*i*) in the zone of high total dissolved solids from underlying aquifers in the southern High Plains; (*ii*) had chloride concentrations ≥500 mg/; (*iii*) were in the Arkansas River corridor with elevated chloride; or (*iv*) had high Cl/Br ratios in the north Texas Panhandle region extending into Oklahoma Panhandle and into Kansas based on results from Scanlon et al. (1). The ratio of Cl/SO_4 was used to delineate high Cl/Br ratios because the previous study in the Texas Panhandle showed high correlation between the two, and there are more analyses of SO_4 than Br. Well depths ranged from 0.3 to 330 m (mean 70 m, median 62 m). Recharge rates for each point were calculated from chloride analysis for that well, long-term (mean 1971–2000) precipitation from PRISM at that point (http://www.prism.oregonstate.edu/), and an interpolated value for chloride deposition from the National Atmospheric Deposition Program based on kriging. Chloride input from National Atmospheric Deposition Program was doubled to account for dry deposition. Recharge rates were extrapolated from the point estimates using kriging.

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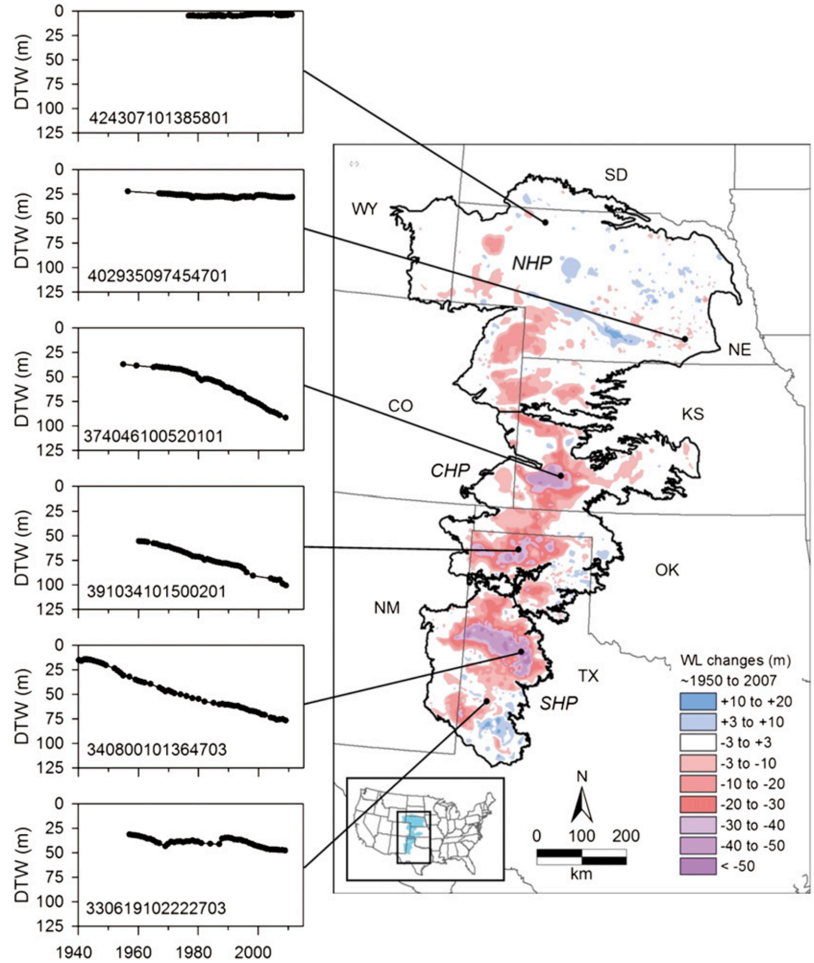

Fig. S1. Groundwater depletion in the High Plains (HP) aquifer along with representative hydrographs showing changes in depth to water (DTW) for wells. State well numbers are provided for wells. The map shows minimal depletion in the northern HP and much greater depletion in the central and southern HP. Rises in groundwater storage are mostly found adjacent to the Platte River and in the Sand Hills in the north and in the southeastern region of the southern HP in response to increased recharge related to land use change (1). Although there is limited depletion in the northern HP, the areas of greatest depletion are in the upgradient (western) part beneath cropland (high demand) but far from rivers (sources of captured groundwater discharge and decreased recharge from surface-water diversions). Therefore, in the northern HP, there is a west–east gradient in depletion along with the more general north–south gradient throughout the HP.

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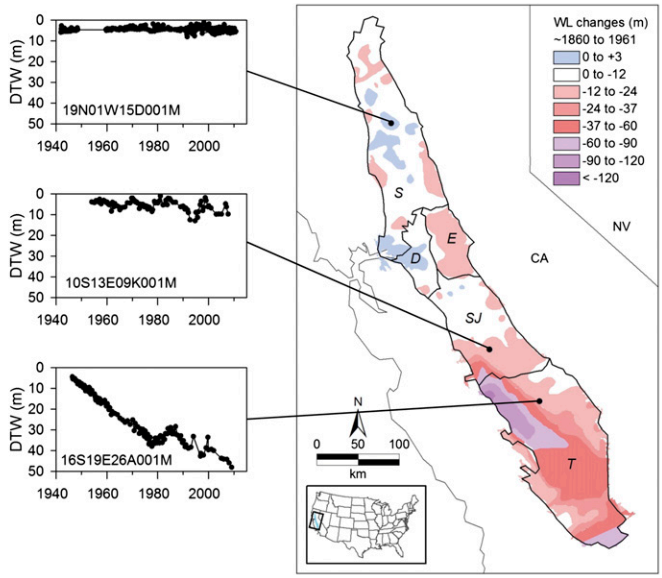

Fig. S2. Groundwater depletion in the confined Central Valley aquifer along with representative hydrographs showing changes in depth to water (DTW) for wells. State well numbers are provided for wells (1).

1. Williamson AK, Prudic DE, Swain LA (1989) *Ground-Water Flow in the Central Valley, California*. US Geological Survey Professional Paper 1401-D (US Government Printing Office, Washington, DC).

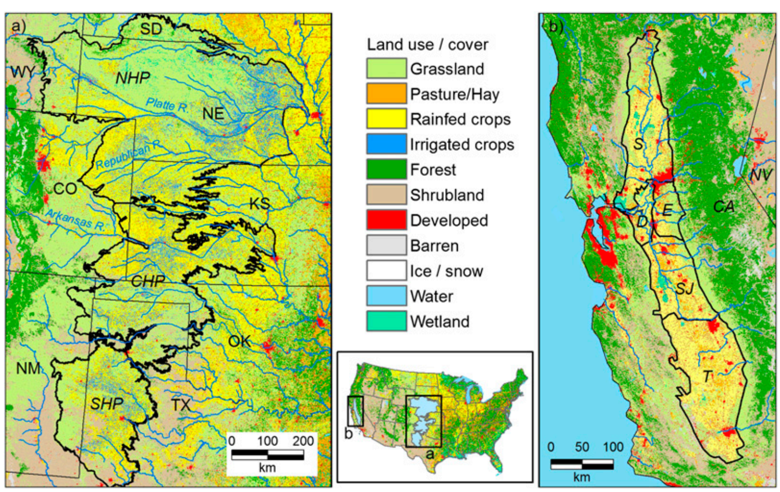

Fig. S3. Land use in (*A*) the High Plains and (*B*) the Central Valley aquifers from National Land Cover Data (2001). The High Plains aquifer extends across eight states: Wyoming (WY), South Dakota (SD), Nebraska (NE), Colorado (CO), Kansas (KS), New Mexico (NM), Oklahoma (OK), and Texas (TX). The High Plains has also been subdivided into the northern, central, and southern High Plains. Irrigated crops shown in *a* are from Qi et al. (1). Subbasins within the Central Valley aquifer include the Sacramento (S), Delta (D), Eastside (E), San Joaquin (SJ), and Tulare (TU). Irrigation is not shown for the Central Valley because it covers 90% of cropland and pastureland based on satellite analysis from Faunt (2) and would obscure these cropland classes. Land areas and land use/cover percentages are given in Table S1.

1. Qi SL, Konduris A, Litke DW, Dupree J (2002) *Classification of Irrigated Land Using Satellite Imagery, the High Plains Aquifer, Nominal Data 1992*. US Geological Survey Water Resource Inventory Report 02-4236 (US Government Printing Office, Washington, DC).
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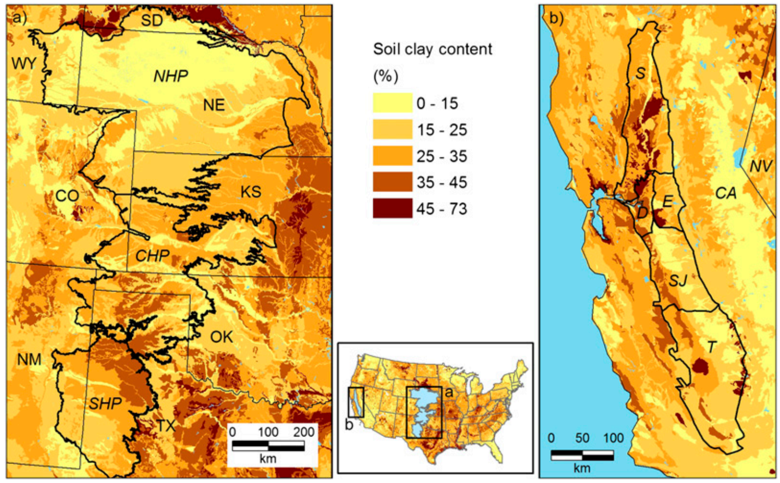

Fig. S4. Soil clay content for (*A*) the High Plains and (*B*) the Central Valley regions based on the US Department of Agriculture State Soil Geographic database (1).

1. US Department of Agriculture (1994) *State Soil Geographic (STATSGO) Data Base*. National Resource Conservation Service, Miscellaneous Publication No. 1492 (National Soil Survey Center, Lincoln, NE).

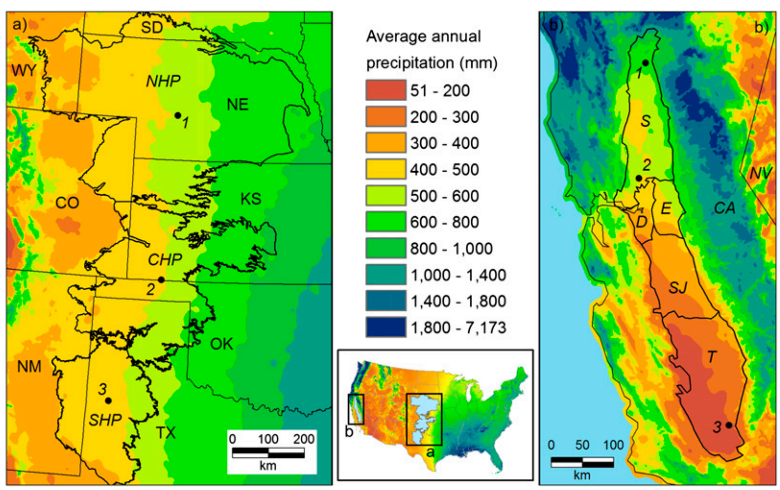

Fig. S5. Mean annual precipitation (1971–2000) for (*A*) the High Plains and (*B*) the Central Valley. Points shown in *A* represent precipitation monitoring locations shown in Fig. S6*a* for (1) North Platte, NE, (2) Liberal, KS, and (3) Littlefield, TX. Points shown in *B* represent precipitation monitoring locations shown in Fig. S6*b* for (1) Red Bluff, (2) Davis, and (3) Bakersfield, CA. (Data from PRISM, http://www.prism.orgegonstate.edu/.)

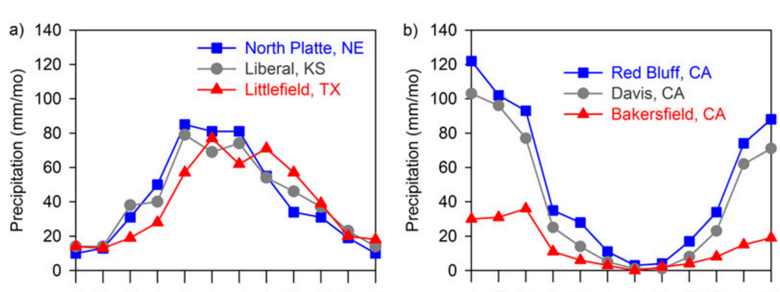

Fig. S6. Seasonal variations in precipitation in selected stations in the (*A*) High Plains and (*B*) Central Valley. For location of precipitation stations, see Fig. S5. Mean annual precipitation (1971–2000) for stations in the High Plains are North Platte, NE (499 mm), Liberal, KS (501 mm), and Littlefield, TX (475 mm), and in the Central Valley are Red Bluff (611 mm), Davis (484 mm), and Bakersfield (165 mm).

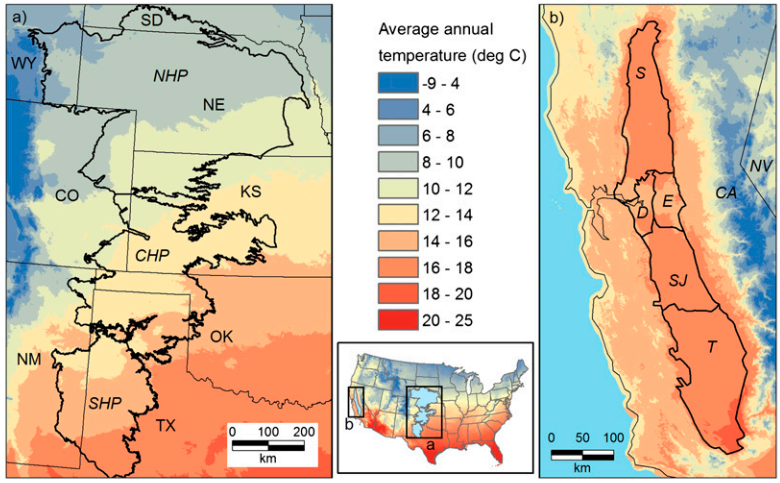

Fig. S7. Spatial variation in mean annual temperature (1971–2000) for the (*A*) High Plains and (*B*) Central Valley. (Data from PRISM, http://www.prism.orgegonstate.edu/.)

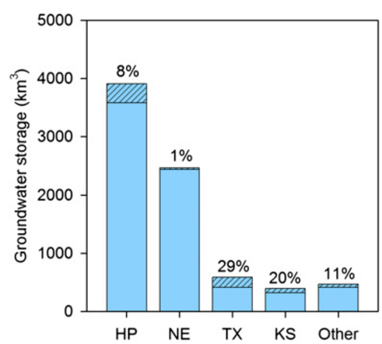

Fig. S8. Initial groundwater storage (total column height) and depletion (hatched area) between predevelopment and 2007 (1) in the High Plains, Nebraska, Texas, Kansas, and combined other states (Colorado, New Mexico, Oklahoma, South Dakota, and Wyoming). Most of the groundwater is stored in Nebraska where depletion has been the least. An estimated 8% of total groundwater storage (330 km^3) has been depleted.

1. McGuire VL (2009) *Water Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005–06, and 2006–2007*. US Geological Survey Scientific Investigations Report 2009-5019 (US Government Printing Office, Washington, DC).

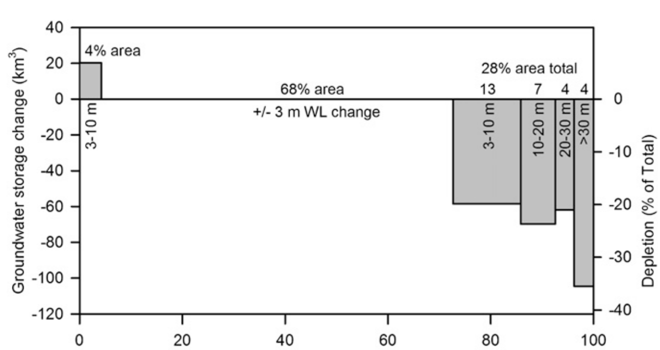

Fig. S9. Land area percentages in the High Plains with different groundwater storages changes from predevelopment (~1950) to 2007 (1), including areas with increased storage [4% of area, water level (WL) increases ≥3 m], areas of no change in storage (68% of area, WL changes <3 m), and areas of decreased storage (28% of area, WL declines ≥3 m). Axis on the right indicates percent of total depletion (e.g., 36% of total depletion is restricted to 4% of the land area and occurred where water levels declined ≥30 m).

1. McGuire VL (2009) *Water Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005–06, and 2006–2007*. US Geological Survey Scientific Investigations Report 2009-5019 (US Government Printing Office, Washington, DC).

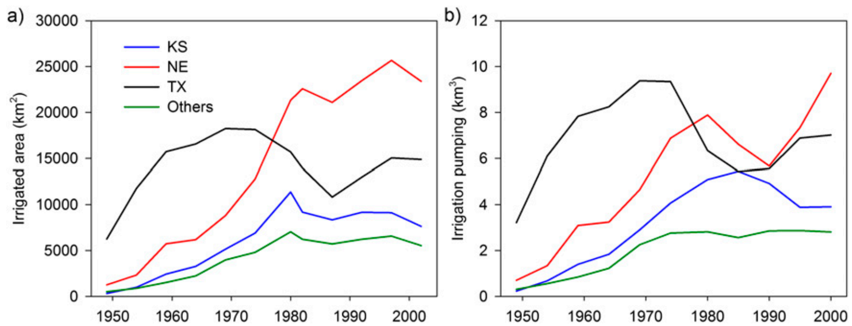

Fig. S10. Temporal changes in (*A*) irrigated area and (*B*) irrigation pumping in the High Plains of Nebraska, Texas, Kansas, and combined other states (Colorado, New Mexico, Oklahoma, South Dakota, and Wyoming) (1).

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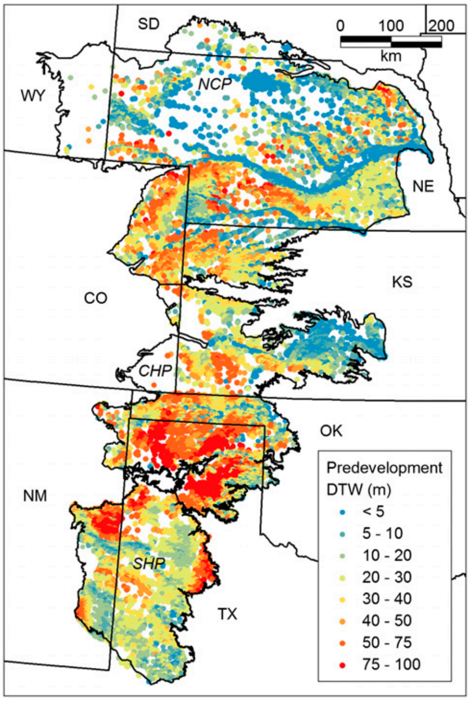

Fig. S11. Depth to water (DTW) for predevelopment (~1950s) based on measured groundwater levels in 3,600 wells in the High Plains aquifer.

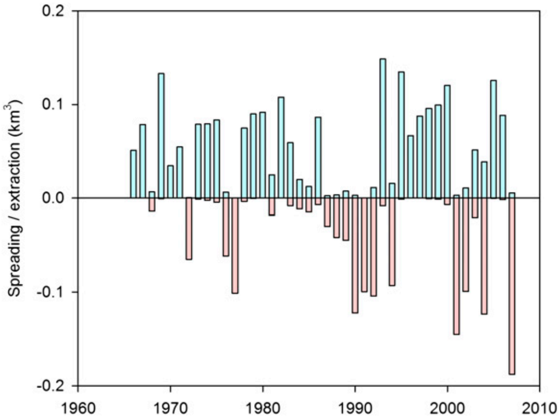

Fig. S12. Spreading/extraction in Arvin Edison water bank, emphasizing groundwater storage increases during wet years and abstractions during droughts.

Table S1. Land areas and land use/cover percentages for the High Plains, Central Valley, and subregions based on the National Land Cover Database 2001

Region	Area, km^2	Grassland, %	Pasture/hay, %	All crops, %	Irrigation, %*	Forest, %	Shrubland, %	Developed, %	Barren, %	Open water, %	Wetlands, %
High Plains	454,247	48.9	0.8	38.8	11.6	0.8	5.8	3.0	0.1	0.4	1.3
NHP	250,938	55.3	0.6	35.7	12.0	1.2	1.6	2.8	0.1	0.6	2.0
CHP	128,230	43.9	1.5	43.2	11.0	0.3	7.4	3.0	0.1	0.3	0.3
SHP	75,079	36.1	0.0	42.0	11.5	0.1	17.3	4.0	0.1	0.1	0.4
Central Valley	51,917	21.1	7.4	53.0	54.0	0.3	1.7	10.9	1.5	1.2	2.8
Sacramento	15,104	26.6	5.3	44.7		0.8	4.0	10.7	1.0	1.6	5.2
Delta	2,937	5.5	7.6	60.4		0.0	0.0	12.8	0.3	7.6	5.8
Eastside	3,625	41.6	7.6	29.9		1.4	1.4	14.8	0.6	1.2	1.5
San Joaquin	9,947	20.4	11.6	52.3		0.0	0.2	9.7	0.9	0.7	4.1
Tulare	20,305	15.9	6.8	62.5		0.0	1.0	10.6	2.6	0.3	0.3

Percentages represent within-region values and may not sum to 100% due to rounding. CHP, central High Plains; NHP, northern High Plains; SHP, southern High Plains.

*Percent of HP irrigated based on Qi et al. (1), and percent of Central Valley irrigated based on Faunt (2). Irrigation in the HP is restricted to cropland (~30% of cropland), whereas irrigation in Central Valley is assumed to be distributed between cropland and pasture (~90%).

1. Qi SL, Konduris A, Litke DW, Dupree J (2002) *Classification of Irrigated Land Using Satellite Imagery, the High Plains Aquifer, Nominal Data 1992.* US Geological Survey Water Resource Inventory Report 02-4236 (US Government Printing Office, Washington, DC).
2. Faunt CC, ed (2009) *Groundwater Availability of the Central Valley Aquifer, California*. US Geological Survey Professional Paper 1766 (US Government Printing Office, Washington, DC).

Table S2. Steady-state predevelopment and transient water budget (in km^3/y) for 1962–2003 on the basis of the Central Valley hydrologic model (1)

Model/basin	Precip	ET_{tot}	R_{off}	SW_{Deliv}	R_{P+I}	R_{str}	D_{Pu}	D_{str}	D_{ET}	ΔS
Central Valley*					2.5			2.5		
					1.9	0.6		0.4	2.1	0.0
Central Valley†					17.2			19.4		−2.2
	19.4	32.1	1.4	12.8	14.1	3.2	11.9	2.8	4.7	−2.2
Sacramento	8.1	7.6	0.6	2.1	5.2	0.3	1.6	2.0	1.9	0.0
Delta/Eastside	3.6	4.4	0.2	0.5	2.2	1.1	1.9	0.2	1.3	−0.1
San Joaquin	3.2	6.5	0.2	3.7	2.4	0.6	1.2	0.4	1.2	0.2
Tulare	4.5	13.5	0.3	6.4	4.3	1.1	7.2	0.2	0.3	−2.3

Precipitation (Precip); evapotranspiration (ET, total); surface water delivery; recharge (R) from precipitation and irrigation (P + I) and from streams (str); discharge (D) from irrigation pumpage (Pu), from base flow to streams (str), and from riparian ET; and change in groundwater storage (ΔS). Recharge equals discharge during predevelopment (both 2.5 km^3/y). The postdevelopment transient simulation shows that discharge increases markedly, mostly from pumpage and exceeds recharge by 2.2 km^3/y, which results in groundwater depletion. Totals for storage change and the Central Valley were calculated using rounded numbers in the table and differ slightly from model output.

*Steady state; †transient.

1. Faunt CC, ed (2009) *Groundwater Availability of the Central Valley Aquifer, California*. US Geological Survey Professional Paper 1766 (US Government Printing Office, Washington, DC).

Table S3. Water budget parameters for the High Plains aquifer, subdivided into northern, central, and southern, and also for states within the HP (Nebraska, Kansas, and Texas)

Region/ state	Precipitation, km^3/y*	Recharge, km^3/y*	Storage, km^3†	Storage, km^3‡	Depletion, km^3*	Depletion, km^3/y*	Lifespan, y
HP	227	12.00	3,912	3,584	328	5.66	633
NHP	129	9.96	2,882	2,820	62	1.07	
CHP	65	1.28	735	591	144	2.48	238
SHP	33	0.77	296	173	123	2.12	81
NB	92	8.6	2,464	2,438	26	0.45	
KS	43	0.77	396	318	78	1.34	237
TX	44	1.17	587	414	173	2.98	139

Recharge estimated from groundwater chloride data (Fig. 3) and estimated from field data in the southern part of the High Plains. Storage for predevelopment (~1950s) and 2007 obtained from Scanlon et al. (1). Groundwater depletion estimated from storage changes from 1950 to 2007, and lifespan estimated from storage in 2007 and annual rate of depletion. The lifespan was not calculated for the NHP or NB because groundwater pumpage is sustainable.

*1950–2007; data from PRISM, http://www.prism.oregonstate.edu/.

†1950.

‡2007.

1. Scanlon BR, Reedy RC, Gates JB, Gowda PH (2010) Impact of agroecosystems on groundwater resources in the Central High Plains, USA. *Agric Ecosyst Environ* 139:700–713.