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Irrigation aquifer depletion: the nexus linchpin

Richard M. Cruse¹ · Daniel L. Devlin² · Doug Parker³ · Reagan M. Waskom⁴

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Abstract Demand for agriculturally produced food and feed is virtually certain to rise as populations increase and economies of developing countries improve. Irrigation is currently supplying water for a disproportionately large amount of agriculturally sourced food and feed production needed to meet this growing demand. Irrigation supports 40 % of global food production, while it occupies only about 18 % of the agricultural landscape. Irrigation is groundwater sourced in critical food production regions of the world, and a variety of these aquifers are being drained; their rates of water recharge are well below extraction rates. Life expectancy of multiple irrigation aquifers, including selected aquifers in the USA, is decades or less if much improved water irrigation management practices are not implemented. Case examples from Kansas, Colorado, and California, home of arguably the most technologically advanced, economically stable, and well educated agricultural industry in the world, are used to address the question: “Are existing irrigation management approaches preferentially focused on sustaining existing economies or sustaining the longevity of the irrigation aquifers?” In general, irrigation aquifer water stress and need to conserve water is

recognized by a vast majority of stakeholders. The need for stakeholders to maintain short-term financial integrity, which requires continued use of irrigation water, is creating stress in local water management policy development and delaying meaningful action. Pockets of forward thinking plans and even action are evolving, but these pockets must grow, and grow rapidly, to avert major negative social and financial consequences.

Keywords Irrigation · Aquifer stress · Ogallala aquifer · Sustainable aquifer management

Introduction

Today's water and soil resources are knowingly being exploited and degraded at global scales (den Biggelaar et al. 2004) in a process arguably similar to that which occurred with past failed civilizations (Hillel 1991). In response to growing demand, increasing climate instability, and degraded resources, governments recognize a need to manage more soil and water resources to enhance their country's agricultural production and food security. Transnational land agreements, known as land grabbing, accelerated in the last decade, dominantly to enhance food and water security of the ‘grabbing nation.’ Rulli et al. (2013) estimate 45 km³ of water (a combination of rain and irrigation water) are being transnationally reappropriated annually through land grabs representing 47 × 10⁶ ha of grabbed land (data as of 2012). For perspective, this amounts to approximately 1.2 and 1.6 % of Molden et al.'s (2007) estimated annual global total freshwater and irrigation water withdrawals, respectively. Depending on whether one considers areas associated with transactions in progress along with existing “closed deals,” grabbed lands represented 0.7–1.75 % of the world's agricultural land (Rulli et al. 2013). Nations posturing for future food

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production speaks to the known importance of soil and especially anticipated water limitations for food security.

Water resource limitations are arguably the linchpin in the quest for global food security. Agricultural water use amounts to about 70 % of all freshwater consumption (Molden et al. 2007) with high variability in irrigation contributions to agricultural productivity between countries. In numerous countries, irrigated lands account for more than 75 % of agricultural production. While irrigation covers only 18 % of the world's agricultural land, these lands produce about 40 % of global agricultural products today with projections that 45 % of the world's agricultural products will be irrigation-sourced within the next two to three decades (Molden et al. 2007). Irrigated lands' role in food security is unquestionably and disproportionately large. Famiglietti (2014) explicitly recognizes nine major global aquifers experiencing serious groundwater depletion rates and tightly links aquifer stress being observed to irrigation for food production.

In the USA, the High Plains Aquifer, also known as the Ogallala Aquifer, was charged with glacial melt and other water through multiple millennia (Scanlon et al. 2012); the estimated age of the deeper aquifer water ranges from 1800–15,600 years (McMahon et al. 2007). This aquifer occurs in a nation with one of the world's most educated populace and technologically advanced agricultural industries. While relatively small sections of this aquifer are being recharged, the US Geological Survey (McGuire 2014) estimates annually 14.8 km³ of net water loss occurred from this underground reservoir in the 2011–2013 period. This compares to an average annual loss of 5.2 km³ over the 1950–2013 period. Extraction rates compared to recharge rates in this region are seemingly accelerating. Technology, education, and existing policy do not seem to foster sustainable irrigation aquifer management in this area. This aquifer has taken thousands of years to fill, and in the 1950–2060 period, an estimated 69 % of this aquifer will be lost dominantly to irrigation (Steward et al. 2013). This example is not globally unique. Recent studies consistently deliver a somber message: using existing management practices, groundwater resources cannot be sustained (Famiglietti 2014; Currell et al. 2012; Molden and de Fraiture 2010; Scanlon et al. 2012). Figure 1 illustrates locations of current (and suggest impending) water challenges that exist in many parts of the world. Areas most water challenged are also areas relying heavily on irrigation for food production. Because irrigated lands are the most productive and most productively stable agricultural lands in the world, loss of irrigated land contributions to food security, especially in the face of climate change, greatly impedes progress towards food security (Haddeland et al. 2014; Elliot et al. 2013). Famiglietti (2014) explicitly states in a commentary for *Nature Climate Change*, “Vanishing groundwater will translate into major declines in agricultural productivity and energy production, with the potential for skyrocketing food prices and profound economic and political ramifications.

The roadway to future global food security is not yet mapped. We are essentially certain that irrigation water availability will influence what is produced, where it is produced, and in what quantities. However, water is not the only stressor of concern. Water issues coupled with multiple other stressors including population growth (FAO 2009), sealing of agricultural lands by urban expansion (Seto et al. 2012), degrading soil resources (den Biggelaar et al. 2004), and climate change (Lobell 2014) amplify the impact of any single component of the food-water nexus. A variety of potentially negative interactions with cascading effects may exist as implied by Famiglietti (2014); these are less well understood and often ignored. The implications of selected interactions may be greater than the main effects themselves. Not only may the interacting effects be substantial, addressing these increasingly complex challenges—which include social and economic reaction to developing stresses—may be more cumbersome and of much greater challenge than those of direct effects alone. Uncertainty related to global food security brings with it potentially serious implications we have not encountered on a global scale.

This leads to the question addressed in this paper: What goals drive irrigation management of aquifers used to support irrigation in the Great Plains and the Western US? Do existing short-term economic interests dominate management approaches of these water resources, or is longer term sustainability the primary driving factor? Examples of existing approaches will be given from the Great Plains and Western US, one of the more water stressed areas in the world (Fig. 1). From these examples, a synthesis statement will be developed relating irrigation aquifer water management in an educationally and technologically advanced culture (Great Plains and Western US) to challenges of managing irrigation water for sustained global food security.

Understanding and sustaining the Ogallala aquifer (Great Plains)

The Ogallala Aquifer is a vast underground aquifer located in the Great Plains and underlies 450,660 km² in parts of eight states (Fig. 2)—eastern Colorado, western Kansas, Nebraska, eastern New Mexico, southeast Wyoming, southern South Dakota, and the panhandle areas of Texas and Oklahoma (Thelin and Heimes 1987). The three states with the largest areas underlain by the aquifer are Kansas, Nebraska, and Texas with 79,000, 165,000, and 91,815 km², respectively (Thelin and Heimes 1987). The Ogallala is the largest aquifer in North America and contains enough fresh water to fill Lake Huron with enough leftover to fill 1/5 of Lake Ontario. The water formation of the Ogallala was deposited 10,000 to 25,000 years ago and is considered to be “fossil water,” meaning that current recharge to most of the aquifer is minimal, ranging from 0.06 cm annually in parts of Texas up 15 cm

per year in south central Kansas (Gutentag et al. 1984; Luckey and Becker 1999). Average recharge is low due to minimal rainfall, high evaporation, and low water infiltration. The saturated thickness of the aquifer, which represents the interval between the water table of the aquifer and the base of the aquifer, ranges from 0 to 360 m and averages 60 m (Lowry et al. 1967; Luckey et al. 1981). The thickest portions of the aquifer are located in Nebraska and in the panhandle areas of Texas and Oklahoma and into southwest Kansas. The depth of water below the surface ranges from almost 120 m in the northern part of the aquifer to between 30 and 200 m throughout much of the southern portion of the aquifer.

The regions overlying the Ogallala Aquifer are some of the most productive in the USA for growing alfalfa, cotton, corn, wheat, sorghum, and soybeans. These crops provide cattle operations with feed for 40 % of the feedlot cattle output in the USA. The success of large-scale agriculture in areas of inadequate precipitation and lack of perennial surface water for diversion has depended upon pumping groundwater for irrigation. About 27 % of the irrigated land in the USA overlies this aquifer system (Buchanan et al. 2009). Eighty-two percent of the people who live within the aquifer boundary depend upon the aquifer for drinking water. Farmers and ranchers began intensive use of groundwater for irrigation in the 1930s and 1940s. Estimated irrigated acreage in the area overlying the aquifer increased from 5.0 million hectares in 1949 to 33 million hectares by 1980 but has stayed relatively constant since then (36.1 million hectares in 2005) (Gutentag et al. 1984; McGuire 2012). In 2005, irrigated hectares overlaid 14 % of the aquifer area.

Irrigation use accounts for nearly 90 % of the groundwater withdrawals from the Ogallala Aquifer (Maupin and Barber 2005). In many areas of the aquifer, especially the southern portion of the Texas High Plains and in northwestern Kansas, the saturated thickness has been reduced by as much as 40 % of pre-development levels (McGuire

2009). Withdrawals greatly exceeding recharge rates have resulted in deeper water tables, reduced saturated thickness, and lower well yields. By 1980, water levels in the aquifer in parts of Texas, Oklahoma, and southwestern Kansas had declined more than 30 m, and by the late 1990s, in vulnerable areas of Texas and Kansas, farmers have already abandoned irrigation due to inadequate water supply. Groundwater withdrawals from the aquifer for irrigation were 26 km³ in 2000 and 23 km³ in 2005 (Maupin and Barber 2005). By 2005, the total depletion since pre-development was estimated to be 311 km³. Lowering of the water table has an important impact on stream base flow (Stanton et al. 2010). In contrast, due to greater saturated thickness and higher rainfall, the northern parts of the aquifer, particularly in Nebraska, have seen much less aquifer depletion and in some areas increased saturated thickness. Steward et al. (2013) estimated in 2013 that in the Kansas portion of the aquifer, 30 % of the water was already depleted; by 2060, 70 % would be depleted, and by 2100, it would be almost completely depleted. His estimates did not take into account the impacts of predicted climate change. Most areas within the central and southern high plains have been impacted by the depletion. It is common today to have well yields of 1/4 to 1/3 of historic well yields. In Kansas Groundwater Management District #1 in west central Kansas, useful lifetime of the aquifer is estimated at 10 to 30 years.

Water level declines began in portions of the aquifer after extensive irrigation began using groundwater (U.S. Geological Survey 2014). Average water level changes in the Ogallala Aquifer over the period from pre-development to 2007 by state are as follows: Colorado −3.8 m, Kansas −6.8 m, Nebraska −0.30 m, New Mexico −4.7 m, Oklahoma −3.9 m, South Dakota 0 m, Texas −11.1 m, and Wyoming −0.14 m (Burbach 2007; Clark and Brauer 2010). Water level

Fig. 1 Water scarcity index, ratio of freshwater use to recirculating freshwater availability. Values greater than 0.40 are considered unsustainable. Note areas of concern (*circled*) related to areas that rely heavily on irrigation for agricultural production. Adapted from Oki and

Kanae (2006). From Oki and Kanae (2006) Global hydrological cycles and world water resources. Science. 313:1068–1072.. Reprinted with permission from AAAS

Fig. 2 Ogallala aquifer groundwater surface elevation change, 1950–2007

declines increase pumping costs and decrease well yields. Water level declines also negatively affect surface water flow.

Potential climate change impacts on the central Great Plains managed ecosystems and society are profound. These changes will likely include increasing temperatures, larger daily rainfall amounts in extreme events, longer and more frequent heat waves, and related impacts on plant production, water supply, and human health (Kunkel et al. 2013). Annual precipitation is predicted to decline slightly while annual temperatures will likely increase by 1–3 °C. However, the major impact will be greater variability and extremes in temperature and precipitation. Extreme weather events will become more

common, e.g., high rainfall events, more sustained droughts. This will have very significant impacts on the regional economy and rural communities as crop and livestock production will be adversely impacted. Higher temperatures will increase crop water demand and likely increase irrigation demand from the Ogallala Aquifer (Elliot et al. 2013). Analyses show that the Ogallala region will experience 4–6 °C increase in the maximum temperature for the month of July and August. In addition, rainfall distribution will be highly variable with some regions receiving high rainfall during the month of May and very low rainfall during the month of August (Kunkel et al. 2013). As an example of the potential impact,

simulation results show a drastic decrease in the yield of grain sorghum and more than 30 % yield reduction is predicted in response to future climate without targeted adaptation strategies. The central Great Plains region is heavily dependent upon agriculture, and therefore its climate, for its economic well-being (\$11 billion market value, 2007). When one combines the projections of climate change with the certain reduction of irrigation availability (Steward et al. 2013), potential exists for irreparable economic, environmental, and community impacts. As the nation's and, in many ways, the world's breadbasket, agricultural disruptions in this region have the potential to severely disrupt national and global food supply. Thus, long-term strategies are needed to cope with the impacts of climate change and variability on water use, crop production, and the economic sustainability of this region.

The development of irrigation has had a tremendous economic impact on communities overlying the aquifer. The Ogallala has enabled many industries, such as cattle feeding, irrigated crops, meat processing, and energy industries to develop in areas that would not be possible otherwise. Land values increased immediately after irrigation development, relative to non-irrigated counties in the Ogallala region. The difference in land values between irrigated and non-irrigated crop land peaked in the 1960s with an increase in value due to groundwater access estimated at \$29 billion (in 2002 dollars) (Yates et al. 2010). That value has decreased in recent years as declines in groundwater have forced some farmers to switch from irrigation back to dryland or much-reduced well capacity has reduced crop yield potential. In Kansas, the use of the Ogallala has made the economy particularly dependent on water and irrigated crops, with more than 3 million head of feeder cattle and irrigated crop revenues exceeding \$600 million annually (Leatherman and Cader 2003). It is estimated that the Kansas economy would lose 1800 jobs without irrigation from the Ogallala. Texas and other states would suffer similarly without irrigation to sustain their economies.

Irrigation and aquifer depletion is also an important factor shaping rural demographics (FAO 1994) and affects changes in this region. The feedlot and packing plant industries have attracted a substantial number of Latino and Asian immigrants. In comparison, the non-irrigated areas have experienced continual population decline and aging of their populations. In many areas, the economic depletion of the aquifer is complete or rapidly approaching. The future of many communities overlying the Ogallala Aquifer may hinge on planning for long-term depletion of the aquifer.

Governance and management

Groundwater withdrawals from the Ogallala Aquifer are in general regulated by state governments with little or no federal government oversight; selected exceptions exist in which groundwater management districts or national

resource districts play a role. Each state manages its groundwater differently depending upon history, culture, and political considerations. Some states do not allow future drilling of new irrigation wells, while other states still allow drilling of new wells subject to local regulations of regional groundwater conservation districts. For example, Texas uses the "Rule of Capture" which gives complete ownership to a landowner to withdraw as much groundwater as wanted at any rate even if it harms adjoining landowners. Texas is the only western state that still uses that policy. The rule of capture is ingrained in the Texas state constitution and adds an additional hindrance to regulatory control. Kansas and Colorado use the policy known as the "Prior Appropriation Doctrine." Under this doctrine, groundwater belongs to the state but landowners can put the water to beneficial use. Water is allocated in chronological order, or what is referred to as first in time, first in right. In Kansas, individuals are allocated a set annual quantity of water based on historical use and other factors. Each individual point of diversion requires a state permit and a water meter. Each permit requires the landowner to file a water use permit with the state.

The rapid depletion of the southern portion of the Ogallala Aquifer has been recognized by both state and local governmental organizations, groundwater management districts, and local citizens. In Kansas, significant regulatory and legislative changes have occurred in recent years in an attempt to extend the life of the Ogallala Aquifer. For example, Kansas enacted legislation that allows local groups of farmers to voluntarily develop their own "local enhanced management areas (LEMAs)." The first LEMA developed in northwest Kansas requires all irrigators to reduce their water withdrawals by 25 % over a 5-year period. Other LEMAs are currently being developed across western Kansas. Kansas has enacted a 5-year flex program where irrigators can enroll and then are able to use their water over a 5-year period which allows more flexibility and possibly reduction in their overall water use. In 2014 and 2015, Kansas developed a 50-year vision for water. This plan identified research and management needs as well as suggested needed updates in legislation. Texas has also developed a 50-year plan for water and is currently undergoing legislative action in an attempt to cope with rapidly declining groundwater availability in the Ogallala Aquifer Region. Groundwater management districts are also proposing and implementing new policies.

Past efforts, through state water planning and programs (e.g., Agricultural Water Conservation Demonstration Initiative), and federal programs have been funded and implemented but, in general, have not had a significant impact on the problem. Most funding programs have concentrated on improving irrigation efficiency and maintaining the regional

economy and in limited areas using the Federal farm program subsidized component, Conservation Reserve Program, or other programs that encourage irrigators to convert to dryland production. More advanced technologies and management practices have been widely adopted. These include center pivot irrigation (and enhanced nozzle and technology improvements), subsurface drip irrigation, irrigation scheduling, reduced and no tillage, and other techniques. These have significantly improved irrigation efficiency but have not had a major impact on water withdrawals. In many cases, even though efficiency has improved, as well capacity has decreased, many irrigators have compensated by extending the irrigation season through implementing off season irrigation (irrigating in the fall and winter). However, in many cases, as well capacity gets so low that it is not economically feasible to continue irrigation, irrigators may be required to revert to dryland production. In all states located in the southern Ogallala Region, technology development and implementation along with enhanced education is a major priority.

Colorado groundwater sustainability issues

Groundwater aquifers in the State of Colorado are annually tapped for approximately 1540 MGD or 2.14 km³/year of water, providing nearly 14 % of all water used for irrigation and domestic needs in the state (Maupin et al. 2014). Certain regions of Colorado are wholly dependent upon groundwater to satisfy human needs due to the arid nature of the landscape and paucity of surface streams. Management of Colorado groundwater has progressed from unregulated pumping (prior to 1957) to regulated pumping based upon a principle of maximum utilization (1957–1969), to integration within the system of the prior appropriation doctrine (1969), and to a more recently introduced notion of groundwater sustainability (2004).

Currently, Colorado faces groundwater stress in the eastern plains that are served by the declining Ogallala Aquifer; in the Denver Basin, where municipal and industrial extractions exceed the recharge rate; and in the Rio Grande basin where groundwater levels have declined significantly in the past decade due to drought conditions coupled with unsustainable pumping rates. In contrast, the South Platte alluvial aquifer has been the scene of intense institutional change and upheaval over the past decade as surface water users contested the pumping practices of tributary aquifer diverters under the doctrine of prior appropriation. The conflict and subsequent resolution in the S. Platte Basin has resulted in a reversal of previous water level declines, bringing the system closer to a steady state condition, where recharge and withdrawal rates are nearing equilibrium. Below, we contrast the institutional setting and resolution of groundwater declines in two Colorado basins—the Rio Grande Basin in the San Luis

Valley of south central Colorado and the S. Platte alluvial aquifer in northeast Colorado.

Rio Grande basin

Precipitation in the San Luis Valley of Colorado ranges from only 18–25 cm annually, yet the Rio Grande River and the underlying aquifer system support nearly 242,800 irrigated hectares of potatoes, barley, vegetables, and alfalfa, thanks in large part to a highly productive groundwater system which underlays the valley. An average of 2.47 km³ of water is used annually in the basin, of which 0.99 km³ are pumped from 3500 high-capacity groundwater wells (Colorado Water Conservation Board 2002). Most of these wells are completed in the so-called unconfined aquifer, which occurs in the upper 12 m to approximately 55 m of unconsolidated alluvial sands and gravels. Below the unconfined aquifer and separated by a layer of volcanic-derived clay lies the vast confined aquifer, thought to range from 152 to 4270 m thick (Topper et al. 2003). Following the severe drought of the early 2000s, precipitous drops in groundwater levels were recorded, with depletions exceeding recharge by some 1.2 km³, resulting in the first groundwater legislation in Colorado specifically calling for sustainable utilization of groundwater in the Basin, without prescribing or defining exactly what that meant. Colorado Senate Bill 04-222 stated that “Use of the confined and unconfined aquifers shall be regulated so as to *maintain a sustainable water supply* in each aquifer system, with due regard for the daily, seasonal, and long-term demand for underground water” (emphasis added) (Colorado Senate Bill 04-222. 2004).

The quest to define and implement sustainable management in the aquifer went into motion, with all of the attendant modeling, stakeholder input, proposals, rules, and inevitable litigation. Special Improvement District No. 1 (Subdistrict #1) in the “closed basin” portion of the San Luis Valley was recognized as a legal entity in 2006 and formed in order to take action and help restore a balance between available water supplies and current levels of water use so that the San Luis Valley can continue to remain a sustainable agricultural community. The subdistrict encompasses 64,750 irrigated hectares, and modeling results indicate that as many as 16,187 of these hectares may have to be temporarily fallowed or permanently retired to achieve sustainable groundwater levels. Rules promulgated for the subdistrict by the state engineer require all wells to be metered and pumping amounts to be reported, and an annual replacement plan must be filed which documents how injurious stream depletions will be remedied (Wolf 2015). The second groundwater subdistrict has recently been initiated with several more yet to come as water users in the San Luis Valley of Colorado seek to find sustainability while maintaining the principal economic engine of the region. The jury is out—both in terms of reaching equilibrium in

groundwater levels and what cost that will have on the local economy.

South Platte alluvial aquifer

In 2002–2003, Colorado entered into a prolonged drought that resulted in the curtailment of many groundwater wells that were arguably over-pumping the South Platte River tributary groundwater. In *Simpson v. Bijou*, the Colorado Supreme Court held that the General Assembly through the 1969 Water Rights Determination and Administration Act had required the wells to be integrated into the prior appropriation system. Because groundwater wells were developed decades later than most surface water rights, they were deemed junior and therefore out-of-priority. Four decades after the 1969 Act that brought tributary groundwater into the Colorado system of prior appropriation, the desire to integrate surface and groundwater management has proven a formidable task in virtually every water basin in the state.

The South Platte basin is one of the most complex water use and administration basins in Colorado, with a long management history and some 18,600 decreed points of surface and groundwater diversion. The state estimates that approximately 335,890 ha are irrigated within the S. Platte basin using approximately 0.62 km³ of alluvial groundwater annually (Colorado Water Conservation Board 2002, 2002–2013). A century and a half of irrigation development in the basin has resulted in an extensive network of diversion ditches, canals, and reservoirs, all of which seep large amounts of water into the alluvial aquifer, recharging and thereby replacing water depleted by pumping. More recently, particularly in the last 20 years, there has been extensive development of dedicated groundwater recharge projects that are used to augment out-of-priority groundwater diversions or withdrawals. While at one time there were over 10,000 high-capacity irrigation wells in the basin, today, an estimated 6000 wells utilize groundwater, and their depletions are monitored and must be repaid through a system of augmentation to keep senior surface water users whole. The process leading to changed administration in the basin included expensive litigation, uncertainty, and loss of wealth for many farmers, but eventually resulted in a system that approaches equilibrium although localized high groundwater levels plague some landowners in the basin (Waskom 2014).

The planned conjunctive use of groundwater and surface water has been touted to offer benefits in terms of economic, environmental, and social outcomes through increased water use efficiency and the control of shallow groundwater levels and consequently soil salinity. However, retrofitting conjunctive use into a prior appropriation system that heavily favors surface water users is made difficult by the many layers of management and local interests that have evolved over time. The South Platte alluvial aquifer provides a huge storage

vessel, far surpassing anything that could feasibly be built in the modern era. Conjunctive use of surface and groundwater has been shown to increase the economic output of a basin and to provide a buffer against drought. However, to avoid over-appropriation of the groundwater resource, the measure of sustainable development must be the balance of long-term recharge and diversion by pumping. It is critically important to the long-term sustainability of crop production in the basin to acknowledge that water table control and drainage is the key to salinity management in any river basin system in an arid region. High water tables inevitably lead to non-beneficial evaporative upflux and salinization, a slow but sure death for soil productivity. Bredehoeft (2011) stressed that strict administration by prior appropriation and conjunctive use are not compatible; integration of surface and groundwater management into a single administrative framework is needed to achieve sustainable conjunctive management. There are few examples of how to retrofit a basin such as the South Platte without harming existing water rights or economic output.

The problems of groundwater management are complex and controversial from a number of viewpoints. The challenge of sustainably using groundwater without impairing the senior rights of surface water diverters is made more difficult by the lack of comprehensive and readily available data, models that accurately simulate actual conditions, and a common technical platform used by all water managers. Due to the time lags involved with detecting groundwater movement and change, it is difficult to react in real time to excess depletions or accretions, sometimes resulting in undesirable impacts such as high groundwater levels causing waterlogging of agricultural fields. In Colorado, concerns have arisen in recent years from conflicting viewpoints about over-pumping, as well as loss of the ability by some to utilize groundwater, excess augmentation leading to high water tables, and augmentation water not adequately replacing depletions. Often times, the problems observed are localized, and care must be exercised not to over-reach when applying solutions.

California groundwater supplies, use and management

Groundwater supplied 38 % of California's annual average total water supply from 2005–2010 or almost 20.4 km³ per year (the 16.5 million acre-feet in Fig. 3) (California Natural Resources Agency: Department of Water Resources 2015a). While an important source of water for cities and residences, the majority of groundwater is used for agricultural production. In drought years, groundwater use for agriculture increases significantly. In 2015, the fourth year of the most severe drought on record, California groundwater use soared to almost 60 % of water supplies or 28.6 km³. Groundwater is

CASGEM Basin Prioritization – June 2014

Fig. 3 California groundwater management basins. Sourced from State of California's Groundwater Update 2013, chapter 2

a significant source of water for the 4.05 million hectares of irrigated cropland under production each year in California.

California's agricultural industry produces approximately \$46 billion in value each year. In terms of agricultural receipts,

California is the largest agricultural state in the USA and the supplier of approximately 50 % of its fruits and vegetables. Yet, California agriculture is a relatively small part of the state's overall GDP, just over 2 %. While small by statewide

standards, California agriculture is the major economic and job engine in many rural areas of the state.

It is estimated that California has about 53 km³ of surface water storage, 18.5 km³ of storage as annual snowpack, and over 185 km³ of usable groundwater storage (California Natural Resources Agency: Department of Water Resources 2014). While groundwater is obviously an important source of water and economic wealth for California, groundwater management and the information needed for management of groundwater usage is severely lacking. It is estimated that there are at between 1 and 2 million groundwater wells in California (California Natural Resources Agency: Department of Water Resources 2015b). There are no statewide databases on groundwater well construction or on groundwater use. In an average year, it is estimated that California groundwater basins are overdrafted (measured as a reduction in groundwater storage) by between 1.2 and 2.4 km³ with state agencies suggesting that these numbers may be increasing over a long-term average (California Natural Resources Agency: Department of Water Resources 2015a). In drought years, California landowners overdraft groundwater aquifers by nearly three times this amount.

In 1992, California passed groundwater legislation known as AB 3030. This legislation allowed local agencies to draft groundwater management plans. While a positive step, the groundwater management plans enabled by this legislation were completely voluntary in nature. Thus, while at least 149 groundwater management plans were written, they did not have the enforcement mechanisms necessary for implementation and, thus, groundwater management rarely took place.

The current California drought has brought increased attention to California's poor groundwater management. Prior to the current drought, California had no required statewide groundwater management process and no regulation of groundwater use. Groundwater well drilling permits were controlled by the counties and did not deal with groundwater use or groundwater rights but only with the physical construction of the well. In all, California has 22 adjudicated groundwater basins with varying degrees of court ordered groundwater management and control. In all other areas of the state, California landowners face no legal constraints on groundwater use. This lack of control over groundwater use has led to many basins being pumped unsustainably with some areas having critical levels of groundwater overdraft (California Natural Resources Agency: Department of Water Resources 2015c).

Thus, as California entered its third year of extreme drought in 2014, the Governor and Legislature, along with water management agencies and other stakeholders, saw the need for a new era in groundwater management. Due to the

drought, groundwater drilling was at an all-time high with many drilling operators running 24 h a day, 7 days a week, and waitlists of greater than 1 year. This rush to pump groundwater, combined with little or no recharge, has led to over 2500 groundwater wells going dry (California Natural Resources Agency: Department of Water Resources 2015d). Groundwater levels in some basins were dropping nearly 15 cm per month, and land subsidence in some basins was nearly 2.5–5.0 cm per month (Farr et al. 2015).

The Sustainable Groundwater Management Act (SGMA) of 2014 seeks to put California's overdrafted groundwater basins on the path to long-term sustainability. The SGMA defines sustainable groundwater management as "the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results." To do this, the SGMA supports local control over groundwater basins. It sets to reach its goals through a four-step process: (1) the California Department of Water Resources designates high, medium, low, and very low priority basins by January 31, 2015; (2) local agencies in high and medium groundwater basins form locally controlled groundwater sustainability agencies (GSAs) by June 30, 2017; (3) the GSAs produce groundwater sustainability plans (GSPs) with measurable objectives and milestones in 5-year increments by June 30, 2020, for "critically overdrafted" high and medium basins, and by June 30, 2022, for all other high and medium basins; and (4) each GSA has 20 years from its GSP adoption to fully implement the GSP. The State Water Resources Control Board has the authority to place nonperforming agencies on probation and implement state controls should the GSAs fail to perform.

The California Department of Water Resources designated the groundwater basin boundaries by referencing Bulletin-118, 2003 Update on groundwater (California Natural Resources Agency: Department of Water Resources 2003). This report designates 431 groundwater basins, of which 24 are subdivided into 108 sub basins. Thus, there are 515 unique groundwater basins in California. Of these, 43 are identified as high priority and 84 as medium priority. Thus, 127 basins must create GSAs and write GSPs. These basins represent 96 % of California's groundwater use and an overlying population of 80 % of California's population.

In response to the failure of the 1992 voluntary legislation, the SGMA empowers the state and the GSAs to implement the GSPs. It specifically grants the GSAs the authority to conduct investigations, determine the sustainable yield of groundwater basins, measure and limit extractions, impose fees for groundwater management, and enforce the GSP. It is far too early to know whether the California SGMA will reach its goals. State agencies have been working hard to gather information and inform local agencies of their tasks. Water districts and city and county governments have begun conversations on

forming GSAs, and several agencies across the state have indicated that they intend to fulfill the GSA role. Stakeholder groups, universities, and nonprofit educational organizations have put together materials to educate the public as well as the local government agencies (Fig. 3).

The SGMA recognizes the immense institutional tasks and challenges necessary to create new local government agencies and write and implement sustainable groundwater management plans. The more-than-25-year timeline gives these agencies time to reach these sustainable groundwater management goals, but there is concern over the state's ability to succeed. What happens if local agencies delay actions or get embroiled in conflict over control of groundwater management plans? What if agencies lack the political will to fully implement the plans? And, of particular concern, does California have enough aquifer capacity to continue to overdraft groundwater basins, and potentially continue to increase that overdraft because of the drought, while implementing the many stages of the SGMA to reach its sustainability goals?

Synopsis

Large sections of major groundwater aquifers in the Great Plains and Western US are being depleted and losing capacity to supply water, especially for irrigation, at rates historically observed and required to sustain current economies. Stakeholders recognize the serious aquifer depletion challenge and immediate need to adjust aquifer management appropriately, yet policy development and actions to sustain aquifer water resources are slow to evolve and in significant areas seem to be absent. Efforts to sustain groundwater resources in isolated regions, while having a favorable impact, are hydrologically, socially, and economically challenging. Current economic interests seem to be overshadowing the long-term focus of sustaining irrigation aquifer resources over most of the area. These observations are particularly disconcerting given that the US agricultural industry being supported by this groundwater resource is arguably the most technologically advanced and educated in the world. Many less developed countries are also relying on dwindling groundwater resources but have an agriculture with less technology available, weaker economic structure, and limited education compared to the USA. It is unlikely they will experience outcomes that contrast from those that seem to be developing in the Great Plains and Western US.

If current water use patterns continue, especially if the existing record drought is prolonged, depleted irrigation aquifers virtually guarantee agricultural production in these areas will decline, employment opportunities will be reduced, local community economic vigor will diminish, and property values will be marginalized. Serious regional, national, and global implications associated with

declining food and feed production from historically irrigated areas is capturing little attention at this time. However, the critical role irrigated agriculture plays in global food security dictates the lesson we are learning from these case examples become increasingly recognized. The nexus of water resource limitation, rising global food demand, and climate change less favorable for food production should be taken very seriously. These case examples do little to refute Famiglietti's (2014) statement, "Vanishing groundwater will translate into major declines in agricultural productivity and energy production, with the potential for skyrocketing food prices and profound economic and political ramifications."

The potential for elevated food prices brings with it elevated commodity prices at the farm gate and seldom considered environmental impacts in the dryland agricultural areas of the USA. Rapid rise of commodity prices in the previous decade brought with it rapid conversion of environmentally sensitive lands to row crop production and potential for elevated environmental damage (Wright and Wimberly 2013; Secchi et al. 2009). This evidence suggests price rise of commodities from decreased irrigation production would trigger a new round of profit-driven management decisions threatening environmental stewardship in non-irrigated agricultural areas. In addition, linking increased row crop production pressure on sensitive lands with increased frequency of extreme precipitation events further increases resource degradation potential. The risks associated with loss of irrigation production capacity brings the immediate need to implement policies and practices favoring resilience across both irrigated and dryland agricultural areas.

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