
Review: groundwater management practices, challenges, and innovations in the High Plains aquifer, USA—lessons and recommended actions

Marios Sophocleous

Abstract The US High Plains aquifer, one of the largest freshwater aquifer systems in the world, continues to decline, threatening the long-term viability of the region's irrigation-based economy. The eight High Plains States take different approaches to the development and management of the aquifer based on each state's body of water laws that abide by different legal doctrines, on which Federal laws are superposed, thus creating difficulties in integrated regional water-management efforts. Although accumulating hydrologic stresses and competing demands on groundwater resources are making groundwater management increasingly complex, they are also leading to innovative management approaches, which are highlighted in this paper as good examples for emulation in managing groundwater resources. It is concluded that the fragmented and piecemeal institutional arrangements for managing the supplies and quality of water are inadequate to meet the water challenges of the future. A number of recommendations for enhancing the sustainability of the aquifer are presented, including the formation of an interstate groundwater commission for the High Plains aquifer along the lines of the Delaware and Susquehanna River Basins Commissions in the US. Finally, some lessons on groundwater management that other countries can learn from the US experience are outlined.

Keywords Groundwater over-abstraction · Tragedy of the commons · Groundwater management · Water-resources conservation · USA

Introduction to the High Plains region: physical, cultural, and other characteristics

The High Plains aquifer is one of the largest freshwater aquifer systems in the world, covering more than 450,000 km² in area in parts of eight US states from Texas to South Dakota (Fig. 1) and is the most intensively used aquifer in the United States, providing 30% of the total withdrawals from all aquifers for irrigation (Maupin and Barber 2005; Waskom et al. 2006). The aquifer also provides drinking water to 82% of the people who live within its boundaries, totaling 2.3 million according to both the 1990 census (Dennehy et al. 2002) and the 2000 census (USGS 2009).

The majority of the High Plains has a mid-latitude dry continental climate, with annual precipitation ranging from 406 mm/yr in the west to 711 mm/yr in the east (Dennehy et al. 2002). Evaporation rates measured from class A pans in the High Plains range from 1,520 mm in the north to 2,670 mm in the south, among the highest in the United States because of high summer temperatures and persistent winds (Gutentag et al. 1984; Dennehy et al. 2002).

The High Plains agricultural economy literally runs on water from the High Plains aquifer. The crop, livestock, and meat processing sectors, as well as oil and gas production, are the backbone of the regional economy (Waskom et al. 2006). Irrigated crops provide feed for livestock, which are part of a large meat-packing industry in the region. An estimated 15 million cattle and 4.25 million hogs are raised annually over the aquifer (Waskom et al. 2006). Approximately 23% of the cropland overlying the High Plains aquifer is irrigated, accounting for 94% of the total groundwater use on the High Plains (McMahon 2000).

As the Ogallala Formation underlies 80% of the High Plains region and is the principal geologic unit of the High Plains aquifer, the aquifer is oftentimes popularly called the Ogallala aquifer. (Both terminologies will be used interchangeably in the rest of this paper.) The saturated thickness averages about 60 m but reaches a maximum of more than 379 m in Nebraska (Gurdak and Qi 2006). An estimated 23.5 km³ of groundwater was withdrawn for irrigation in 2000 (Maupin and Barber 2005), which was

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M. Sophocleous (✉)
Kansas Geological Survey,
University of Kansas,
1930 Constant Ave., Lawrence, KS 66047, USA
e-mail: marios@kgs.ku.edu

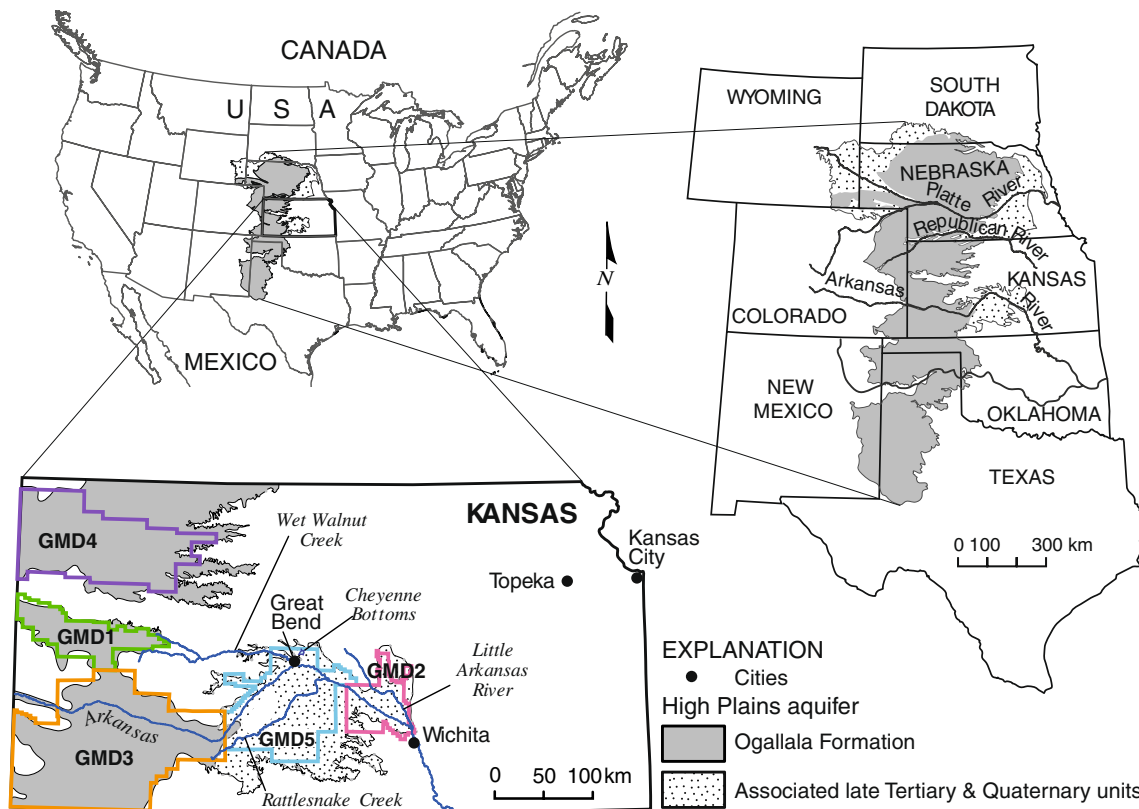


Fig. 1 Extent of the High Plains aquifer and Kansas Groundwater Management Districts (GMDs) 1–5. Groundwater Management District No. 2 (GMD2) covers the Equus Beds aquifer extension of the High Plains aquifer (modified from Sophocleous 2005)

used to irrigate more than 5 million ha (McGuire 2009). Potential annual recharge for a weighted combination of irrigated and non-irrigated conditions (1951–1980) in the High Plains area has been estimated to range from less than 6 mm along the western boundary of the aquifer to as much as 152 mm in the northeastern part of the aquifer (Dugan and Zelt 2000).

Substantial pumping over at least the past 50 years caused water-level declines of up to 60 m locally (Fig. 2) and saturated thickness declines greater than 50% in parts of the aquifer. As a result, streamflows in many streams in the High Plains have declined and riparian and aquatic systems deteriorated, prompting the establishment of minimum desirable streamflows in Kansas and instream-flow requirements in Texas (Sophocleous 2000a, 2003, 2007; NRC 2005). While the rate of decline appears to have slowed in the past two decades, the downward trend continues in many areas, threatening the long-term viability of an irrigation-based economy (McGuire 2009).

The High Plains States take different approaches to the development and management of the aquifer. However, they all recognize that the aquifer is being depleted at rates in excess of recharge. Because recharge is generally very low, in most cases management in the High Plains focuses on “planned depletion” rather than sustainability of the groundwater base, which is perceived as destructive to the current economy of the region. However, several states such as Kansas, Nebraska, and Colorado, are taking steps designed to reduce the rates of water-level declines by

regulating both groundwater withdrawals and further development of the aquifer. Although such measures have slowed the rate of declines, they have not halted the declines.

Historically, the US government has deferred to the states in matters of water allocation, use, and management. Although the US Constitution makes clear that when state law conflicts with federal, the federal law preempts the state law, in practice federal authorities have rarely interfered with state systems of water rights and allocation, leaving water allocation in the US generally in the hands of state governments, not the federal government.

Each state has a body of water law that derives from its constitution, legislative acts, and court decisions. The eastern and western States abide by different legal doctrines, which reflect in part their dissimilar climatic, historical, and economic circumstances (Postel and Richter 2003). Federal laws take place within the context of these state legal systems, and oftentimes the overlapping of and, at times, competition between, federal and state authorities create difficulties in integrated regional water-management efforts.

This paper deals with the scientific, legal, and constitutional underpinnings of policies and management practices of several US states sharing a common groundwater resource. It first examines some basic tenets of hydrologic science on which groundwater management is based and sketches the common-pool resource nature of the High

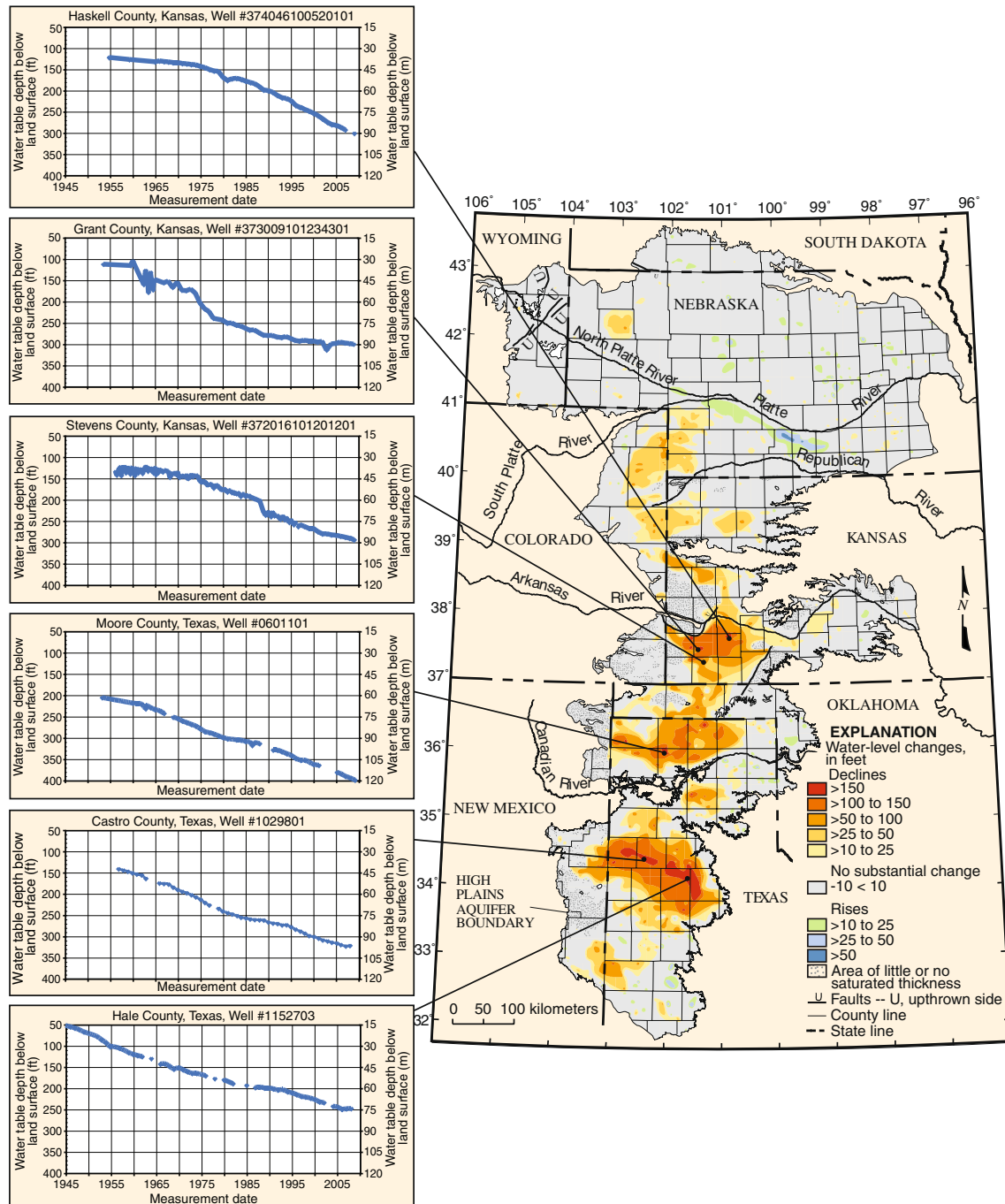


Fig. 2 Water-level change map of the High Plains aquifer from predevelopment to 2007 (to convert feet to meters multiply by 0.3048; adapted from McGuire 2009) and selected water-level hydrographs from predevelopment to 2008–2009 showing significant declines in Texas and Kansas

Plains aquifer to show why groundwater might be prone to commons problems. Some major legal and regulatory aspects of water governance and management in the states forming the High Plains aquifer from Texas to Nebraska will be outlined and recent interstate conflicts among Kansas, Colorado, and Nebraska, resulting from increasing water demands and a failure to incorporate hydrologic-science principles into the interstate compacts, will also be briefly reviewed. Groundwater management innovations

from a number of the High Plains States will then be highlighted, followed by a discussion of conservation policies in place. This paper will conclude with comments on challenges facing the High Plains and needed actions for enhancing its water management. Additional details on the High Plains States' legal, policy, and regulatory aspects are presented in Sophocleous (2010). It is hoped that societies both within and outside the High Plains can learn from the Ogallala experience and avoid potential failures.

Scientific basis of groundwater management

The framework of hydrologic science is the hydrologic cycle, which is the pathway of water as it moves in its various phases through the atmosphere, to the Earth, over and through the land, to the ocean, and back to the atmosphere (NRC 1991). In so moving, water plays a central role in many physical, chemical, and biological processes regulating the Earth system. Contemporary views of hydrology accept that human activity has become an integral and inseparable part of the hydrologic cycle, that the quality of water is no less a concern than the quantity, and that water dynamically interacts with the components of the Earth system (atmosphere, oceans, lithosphere, and biosphere; Eagleson 1991). Because water “does not hold still for labeling or fencing,” and the amount of water varies greatly from place to place and time to time in uncertain ways (Lord and Kenney 1993), water conflicts are often difficult to resolve.

Groundwater is a component of the hydrologic cycle, subject to well-established physical laws. Groundwater is recharged by seasonal precipitation and discharged throughout the year through sustaining baseflow of streams, transpiration by phreatophytes, and evaporation via the vadose zone. Because of these interactions, groundwater storage is continuously changing, diurnally, seasonally, and progressively, over longer time scales (Narasimhan 2009).

Surface water and groundwater have been historically thought of as separate resources and often are managed separately. However, as the hydrologic sciences have matured, the details of how surface water and groundwater interact as a single resource are better understood (Winter et al. 1998; Sophocleous 2000a). A “systems approach” to groundwater management is increasingly advocated because it focuses attention on the interactions and feedbacks that occur among the elements of the water-resource system (Galloway et al. 2003).

The primary goals of agencies involved in groundwater management are to manage aquifer development according to a designated plan that treats aquifers as either renewable resources (“safe-yield” management) or exhaustible resources (planned-depletion management) and to protect property rights in groundwater (Emel and Maddock 1986). In doing so, the management agencies follow the political and economic mandates of the legislature, court, or district board of directors. Both types of groundwater management plans are followed by different regions of the High Plains depending on the degree of aquifer renewability based on estimated recharge in a given area (Sophocleous 2000a, b; Emel and Maddock 1986). For example, South Dakota and two of the five Kansas Groundwater Management Districts (GMD 1 and 5, Fig. 1) follow “safe yield” policies (see section [Kansas groundwater management districts’ “safe yield” policies](#), which also describes how the “safe yield” policies changed over time in Kansas), whereas the three western Kansas GMDs (1, 3, and 4; Fig. 1), Oklahoma and other High Plains regions follow “planned depletion”

policies. Decisions over the traditional alternatives for achieving the groundwater management agencies’ mandated goals are based on the quantity of pumpage for existing wells and the location, number, and quantity of pumpage of new wells. Political and economic goals are thus translated into hydrologic response objectives (Emel and Maddock 1986). The science of hydrology is pivotal in the administrative implementation of groundwater-management objectives because natural resource policy cannot be credible without science. An improved scientific understanding of the groundwater system can also reduce management uncertainties and enhance the beneficial use of the resource (Galloway et al. 2003).

The common-pool nature of the aquifer

The rapid depletion rates in parts of the High Plains aquifer confirmed by numerous monitoring assessments (Fig. 2) have alarmed many observers. They feared such potentially tragic environmental consequences could occur akin to the situation described by Hardin (1968) in his classic *The Tragedy of the Commons*, which predicts excessive rates of depletion under common property situations. The theory of the commons maintains that users of a common resource are “unlikely to restrain their own behavior when the immediate benefits of their actions are their own but the costs are passed on to society as a whole (or other specific groups), and any longer-term or external benefits that might accrue from an individual’s self-instigated” moral restraint are indiscernible in effect (McCay and Acheson 1987).

This theory can be applied to a groundwater setting where users have no incentive to limit pumping to a socially desirable level (Roberts 1992). Groundwater is a common-pool resource, one for which the right to use (typically without charge) is shared with others. Because the resource is accessible to the “water-rights” holders (more in section [Legal and institutional framework for water management in the High Plains](#)) and is not priced, no private incentive exists for any user to reduce current consumption so that more will be available for the future. Any user who does so runs the risk that other users will take the resource for their own use. As groundwater users continue to deplete the aquifer water without any concern for bordering neighbors, tragedy could result (Longo 2002). In the following passage from Hardin’s *The Tragedy of the Commons* (Hardin 1968), draw the analogy to citizens removing water from the High Plains:

Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons...As a rational being, each herdsman, seeks to maximize his gain...Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another, and another...But this is a conclusion reached by each and every herdsman sharing a commons.

Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit—in a world that is limited.

Hardin's tragedy of the commons is a model, and as such is abstract and simplified (McCay and Acheson 1987). Refuters of Hardin's gloomy syllogism frequently draw a distinction between an open-access resource that anyone can exploit and a limited-access commons such as the High Plains aquifer that is closed to all but lawful users (Ciriacy-Wantrup and Bishop 1975; Fennell 2009). As outlined in the next section, the High Plains States have put in place a variety of laws and regulations, differing in each state, limiting access to and use of the water resource. However the mere fact that the aquifer is not open to the entire world does not protect it from tragedy because too many pumpers are still pumping too much water.

Because the High Plains aquifer is highly heterogeneous and groundwater flow rates are relatively very slow, the entire aquifer is not a pure common-pool resource because depletion from pumping in one part, say Nebraska, will have no discernible effect on water levels in a distant part, say Texas. However, at smaller levels of scale within the aquifer such as farms, counties, and locations immediately across jurisdictional lines from each other, the common-pool resource characteristic is apparent as exploitation of the resource at one point decreases water availability at other points (Cash 2001).

The empirical and theoretical research stimulated over the past 40-plus years by Garret Hardin's (1968) article has shown that tragedies of the commons are real but not inevitable (Ostrom et al. 1999). Ostrom (1990) and others have shown that communities throughout the world have been able to avoid the tragedy through development of local management institutions. Both conservative and liberal solutions to the tragedy of the commons exist (Roberts 1992). Common property may be made private, or the use of common property may be regulated by the larger public. However, property schemes that provide complete protection to those who are willing to "save" water in the ground for future use in resources such as the High Plains aquifer have not yet been developed (Roberts 1992).

Although Hardin's model has been criticized as oversimplified and one that cannot be properly generalized without incorporating contextual factors (McCay and Acheson 1987; Dietz et al. 2003), the situation described by Hardin has real and meaningful messages for High Plains jurisdictions. No private incentive exists to save for tomorrow, even if there is general agreement that the future value of the resource is greater than the present value. Two major social consequences of unregulated or loosely regulated development of common-pool resources are that (1) the resource is likely to be consumed at a rate faster than the optimum rate, and (2) local and regional economies dependent on the resource use will contract as depletion occurs (Aiken 1982).

Legal and institutional framework for water management in the High Plains

In American law, a water right is considered a real property right, "appurtenant to and severable from the land on or in connection with which the water is used" (Kansas Statutes Annotated, KSA82a-701 g). A "water right" is a right to use a certain annual quantity of water at a certain place, diverted from a specific point of diversion at a certain rate, and in perpetuity—as long as the water-right holder follows the law and the prescribed conditions of the water right (Peck 2007). But water rights are not exactly like land rights; the fluid nature of the resource precludes a right holder from physical possession of the water in the ground. A groundwater right is thus a right to use the water, not ownership of the water. Some types of water rights may also be lost by non-use (Peck 2007).

The legal concept of "beneficial use" plays an important role in the evolution of water-right law. Beneficial use refers to a reasonable quantity of water applied to a non-wasteful use such as irrigation, domestic water supply, industry, and power generation. The beneficial-use concept was developed to encourage economic efficiency (Ashley and Smith 2001). Although uses such as water for domestic purposes, irrigation, manufacturing, and stock watering have always been considered beneficial, conflict and controversy sometimes arise over what constitutes a beneficial use beyond these traditional uses. For example, some state legislatures and courts have found water needed for the protection and propagation of fish in streams to be a beneficial use, while others have not. Also, disagreements have arisen over whether water for recreation, aesthetic, or scenic uses is a beneficial use. Beneficial use issues become problematic for groundwater regulation in cases where groundwater permits are increasingly denied because of the impact withdrawals would have on stream flow. While such an approach is environmentally sound, it is not necessarily politically popular (Ashley and Smith 2001).

As previously alluded to, the laws and legal institutions regulating the water resources vary among the US states. In spite of these different laws and management programs, the High Plains States are attempting to sustain the economic life of the available groundwater resources and are moving at different rates towards more rigorous management and control of groundwater. Four basic doctrines or rules form the basis for groundwater allocation in the High Plains: (1) absolute ownership, (2) reasonable use, (3) correlative rights, and (4) prior appropriation (Aiken 1980). The absolute ownership, reasonable use, and correlative rights doctrines all share the major premise that the right to use groundwater is based on owning land overlying the aquifer and are collectively referred to as overlying-rights theories (Aiken 1980). Under prior appropriation, rights to use groundwater are based not on land ownership, but on the act of physically withdrawing groundwater, using it beneficially, and complying with state appropriation procedures.

Under the absolute ownership doctrine, a landowner is virtually unrestricted in the use of groundwater and is not liable if such use interferes with the groundwater use of another unless he/she acts maliciously or negligently. The doctrine is essentially the *Rule of capture*: every landowner has the right to pump as much groundwater as he/she can capture without regard to the rights of others. Of the High Plains States, only Texas still follows the absolute ownership doctrine, although it has modified it for some areas.

As the “reasonable use” name implies, the reasonable-use doctrine entitles a landowner to the reasonable use of groundwater. However, what is reasonable is judged solely in relation to the purpose of such use on overlying land only; it is not judged in relationship to the needs of others (Harnsberger et al. 1973). Nebraska and Oklahoma still follow “reasonable use” as a partial basis for groundwater allocation.

The rule of correlative rights differs from the reasonable-use rule mainly in two ways. First, although correlative rights are based on owning land overlying the groundwater reservoir, groundwater can be appropriated for non-overlying use if local overlying users are not harmed. Second, where the ground water supply is inadequate to meet the needs of all users, each user could be judicially required to proportionally reduce water use until the overdraft ends. The correlative rights doctrine is part of the jurisprudence of Nebraska and South Dakota (Aiken 1980).

The doctrine of prior appropriation is based on two fundamental principles: (1) water rights are acquired, not as an incident of land ownership, but by diverting water from a stream or aquifer for beneficial use, and (2) conflicts are generally resolved on the basis of priority, so that the earliest (“senior”) appropriator has a better right over subsequent (“junior”) appropriators. Examples of states with long traditions in prior-appropriation rights are New Mexico, Colorado, and Kansas.

Experiences from the High Plains States indicate that one or a combination of the four allocation doctrines outlined above cannot resolve all groundwater problems (Kaiser and Skillern 2001). As a result, states experiencing overdrafting, mining, or subsidence problems have adopted “critical area” legislation to supplement state allocation rules. Legislation of this type typically allows states to designate areas for study. When the amount of water available has been established and a determination has been made that withdrawals exceed the estimated recharge rate, pumping can be controlled, limited, or suspended (Kaiser and Skillern 2001). New pumping can be prohibited in prior appropriation states. Colorado, Kansas, Nebraska, New Mexico, and Texas, all have legislation allowing for critical area designation and regulation (Kaiser and Skillern 2001). Designation, degree of control, and local input patterns vary extensively among the states. Table 1 lists the groundwater allocation rules or doctrines followed by the High Plains States and the extent to which each uses state or local districts to deal with the problems.

States following the prior-appropriation system vest most of the supervisory authority for critical groundwater areas in a state water official, usually a state engineer. Local input into district creation and a local governing board may be authorized, but these local boards generally act as an advisor to the state water official. Colorado and Kansas exemplify this approach. In states that do not follow the prior-appropriation system for groundwater such as Nebraska and Texas, local officials have greater autonomy in aquifer control, regulation, and management (Kaiser and Skillern 2001). Typically, these districts address specific problems that are not adequately handled under the general-allocation rules. Within a district, the rules adopted by the district’s board apply to allocation and use of groundwater.

Critical area legislation offers the advantage of faster response to problems. The legislature can set forth specific objectives to be attained and specific problems to be addressed by district management. This degree of specificity is not possible under the four allocation doctrines mentioned earlier (Kaiser and Skillern 2001).

The relative merits and demerits of state versus local control are often debated. Severe overdraft requires severe measures, which local residents are reluctant to impose upon themselves or each other (Peterson 1991). However, local control enjoys strong citizen support and is firmly established in Texas, Nebraska, and Kansas. Texas represents the extreme, with all powers to regulate groundwater being vested in districts formed at the discretion of local voters who control those districts (Roberts 1992). As Cash (2003) also pointed out, in weighing the tradeoffs between more centralized control (efficiencies and providing public goods) and more local control (gaining local political legitimacy and place-specific solutions), Nebraska, to a larger extent—see section [Nebraska’s Natural Resources Districts \(NRDs\)](#)—and Kansas attempted to avoid the dichotomy by creating a hybrid system with the positive qualities of both extremes while avoiding the pitfalls of either.

Recent interstate conflicts over water and state versus federal controls

Disputes among US states over interstate rivers have been common (Longo 2002). In time of conflict, it is unlikely that a state legislator would argue for giving more water to a neighboring state than to local constituents. Fortunately, political human nature is balanced by the judicial objective for face-saving water allocation. As the cases have revealed, the courts have provided an avenue for water-sharing deals to take shape (Longo 2002). Thus by default, the courts are the depositories of border conflicts over water. If not for the guidance of the courts, water issues would be an even more divisive force in and between state governments on the High Plains. The overriding message from the various courts is simple—water must be shared (Longo 2002). As Clark (1978) pointed out, the United States has learned most of its

Table 1 Groundwater allocation rules or doctrines and control systems for selected states (modified from Kaiser and Skillern 2001)

State	Groundwater rules or doctrines			Critical-area programs	
	Capture	Reasonable use	Prior appropriation	State control	Local control
Colorado			X	X	X
Kansas			X	X	X
Nebraska		X			X
New Mexico			X	X	
Texas	X				X
Oklahoma		X		X	

lessons about natural resource uses and conservation through a process that can be described as “education by disaster,” a process that is continuing with respect to groundwater mining. As a result of this experience, the US has institutionalized a system of “equitable apportionment” (Fischer 1974), according to which the litigant states enter the Court on equal footing, with the Court showing no preference for one state’s water allocation doctrine over another.

Kansas versus Colorado

Kansas viewed Colorado’s use of the Arkansas River (Fig. 1) as threatening the flow of the river through Kansas. Naturally, Colorado viewed the Arkansas River as belonging to the citizens of Colorado. In 1949, the two states reached agreement and signed the Arkansas River Compact. The John Martin Reservoir in Colorado, with a total capacity of more than 863,400 million L (700,000 acre-ft), has been completed in 1948, and the development of operating criteria for the dam was a principal purpose of the compact negotiations (MacDonnell 1999).

In 1985, Kansas filed an action against Colorado arguing that water users in Colorado, primarily those groundwater pumpers who had installed wells after the compact had been signed, had materially depleted Arkansas River water that should have been available for users in Kansas (MacDonnell 1999). Trial before the US Supreme Court’s Special Master commenced in 1990 and the first phase ended in late 1992. In February 1994 the Special Master issued his first report, concluding that groundwater pumping in Colorado from wells installed between 1948 and 1969 violated the provision of the Arkansas River Compact regarding material depletion of Arkansas River water (Longo 2002). The US Supreme Court affirmed this finding in 1995. As a direct result of this decision, all large-scale groundwater pumpers in the lower Arkansas in Colorado now are required to account for and replace their depletions of Arkansas River water—a requirement that forced at least some of the pumping to cease (MacDonnell 1999).

Kansas versus Nebraska

Draining an approximately 64,500 km² watershed, the Republican River (Fig. 1) begins in Colorado, runs

eastward into Kansas, turns northward into Nebraska and then southeast back into Kansas. Because of the interstate nature of the river and the potential for conflict, Kansas, Colorado, and Nebraska signed the Republican River Compact in 1942 with a view of equitably dividing the waters of the river and its tributaries and of avoiding future conflict (Peck 2007). The Compact provided the name and location of each basin and subbasin, defined the “virgin annual water supply” as “the water supply within the Basin undepleted by the activities of man” (Kansas Statutes Annotated, 2005, Art. II), and allocated to each state a portion of the virgin annual water supply (Peck 2007). The Compact runs in perpetuity.

In the 1990s Kansas claimed that Nebraska was using more than its share of water by allowing unregulated pumping of alluvial groundwater. After unsuccessful facilitation talks, Kansas sued Nebraska and Colorado in the US Supreme Court in 1999 (Peck 2007). A pivotal issue involved alluvial groundwater. Nebraska denied that the Compact covered groundwater pumping, in that the language of the Compact did not expressly address groundwater in its allocation scheme. The Supreme Court ruled against Nebraska on that issue, holding that “[t]he... [c]ompact restricts a compacting state’s consumption of groundwater to the extent the consumption depletes stream flow in the Republican River Basin” (*State of Kansas v. State of Nebraska and State of Colorado*, 2002, Special Master’s First Report and Case Management Order).

In 2003, the states settled the other issues in the case such as treatment of groundwater pumping (including the use of computer modeling of the groundwater system as a means of accounting for the consumption of groundwater), dispute resolution, a moratorium on the construction of new groundwater wells, formulas for determining future compact compliance, use of 5-year running averages for accounting and compliance, and a framework for working together to improve operational efficiencies and the usable water supply in the lower Republican River basin (Peck 2007). The negotiated settlement included recognition of the impact of groundwater withdrawal on surface-water flows in the basin, resulting in a moratorium on new large-capacity well drilling in most of the basin in Nebraska and increased regulation on existing wells (Waskom et al. 2006).

US federal versus state control over water

As mentioned in section [Introduction to the High Plains region: physical, cultural, and other characteristics](#), although the federal laws under the US Constitution preempt state laws, in practice the US government has deferred to the states in matters of water allocation, use, and management. In matters of water quality protection, however, the federal law prevails. In 1982, the US Supreme Court decided in *Sporhase v. Nebraska* that groundwater came under the aegis of interstate commerce and therefore was subject to the Commerce Clause of the US Constitution intended to guarantee

the benefit of free competition among all regions of the country and equal access to all markets (Kerr 1983). The Court found that because the Ogallala aquifer extends through parts of eight states and supports agricultural production of food for national and worldwide markets, a significant federal interest exists in conservation as well as in fair allocation of this diminishing resource. This ruling has caused states to become concerned that in times of drought their interests will be superseded by those determined by the federal government (Heritage Foundation 2009).

In 1983, a federal district court struck down New Mexico's statutory prohibition on the export of groundwater as an unconstitutional restriction on interstate commerce. Subsequently, the New Mexico Legislature passed a new law establishing a permit system for the appropriation of groundwater to be transported out of the state (Templer 1992). The law includes a requirement that the permit not be contrary to the conservation of water within the state and not be otherwise detrimental to the public welfare of New Mexico's citizens (Templer 1992). In 1984, a New Mexico federal district court upheld the transportation-permit requirement, finding that "if applied in a manner which does not burden interstate commerce, the regulation of groundwater appropriation for the purpose of promoting conservation is constitutionally permissible" (Smith 1989).

Groundwater-management innovations

Accumulating hydrologic stresses and competing demands on groundwater resources are making groundwater management increasingly complex. Yet, they are also leading to many innovative approaches to the management of groundwater supplies. A selection of such innovative approaches is presented in the following as good examples to emulate in managing groundwater resources.

Texas Groundwater Availability Modeling (GAM) program

Aquifer systems are complex due to the difficult-to-estimate flows into and out of the aquifer, the interaction between surface water and groundwater, and the uncertainty of aquifer properties. Because of this complexity, computer models are excellent tools for assessing the effect of pumping and droughts on groundwater availability. Groundwater-availability modeling (GAM) is the process of developing and using computer programs to estimate future trends in the amount of water available in an aquifer. It is based on hydrogeologic principles, actual aquifer measurements, and stakeholder guidance.

In 2001, the Texas Legislature, recognizing the importance of accurate groundwater-availability estimates, approved initial funding for the GAM program. The Texas Legislature passed legislation to enable the Texas Water Development Board (TWDB), the state water planning agency, to develop and implement the GAM program as

part of the 1997 Senate Bill 1 (SB1) planning activities. (SB1 is a major water planning and management bill in Texas.) The Legislature required TWDB to complete GAM modeling for the nine major aquifers of Texas by October 2004, and that task was accomplished. In addition, SB1 mandated that groundwater-conservation districts must use GAM data to develop groundwater-management plans.

The goal was to provide timely and reliable data about groundwater quantity in specific aquifers that could be used to accurately estimate aquifer storage and the effects of long-term pumping on water yields. GAM methods could also help evaluate the merits of proposed groundwater-management strategies. Steps involved in creating a GAM included developing the concept of flow for the aquifer; collecting and inputting data on aquifer characteristics, pumping, and water levels; and testing the model to see that results could be accurately calibrated and verified. The model could then be applied to assess current conditions and to examine how future water use could affect aquifer levels.

Unlike previous modeling efforts, new models developed under the GAM program have had substantial stakeholder involvement. In some cases, the GAM represented the first modeling work for the area. All of the models, reports, and support data are available electronically (TWDB 2009).

The nine major aquifers required 17 different models to provide full coverage, including two covering the northern and southern parts of the Ogallala aquifer, respectively. Although the models for the major aquifers have been completed, the TWDB's work is not completed. Models are "living tools" that are updated with new data and refined to better meet stakeholders' needs. In addition, the Texas Legislature required the TWDB to develop and obtain GAMs for the minor aquifers of the state, a task that is in progress. Finally, the TWDB supports the models by assisting groundwater conservation districts, regional water-planning groups, and other political subdivisions with requests for additional model simulations and interpretation of model results.

The total amount spent on the nine major aquifers and 10 minor aquifers completed to date (of the total of 30 TWDB-recognized aquifers in Texas) is US \$8,218,682 from fiscal year 2001 to fiscal year 2007. An additional US \$1,780,000 is currently being spent on contracts either in progress or proposed (R. Mace, Groundwater Resources Division, TWDB, personal communication, 2009).

Overall, the Texas GAM program has proven to be highly successful in providing appropriate, publicly available tools for regional water planning; for raising stakeholder awareness of the fundamentals of hydrogeology and groundwater modeling; and for promoting the importance of groundwater management (Kelley et al. 2008).

Colorado's water-augmentation program

The state of Colorado has made significant progress in integrating the competing uses of surface water and

groundwater (MacDonnell 1988). Indeed, Colorado has vigorously attempted to reconcile the protection of senior surface appropriations with the maximum utilization of groundwater by junior appropriators.

Under conventional priority administration, the junior groundwater appropriators could simply be issued closing orders and stopped from pumping until the senior surface appropriators uses are satisfied. However, Colorado provides numerous options for junior groundwater appropriators to avoid the threat of being issued a closing order altogether (Aiken 2002).

The 1969 Water Right Determination and Administration Act set forth procedures for implementing “plans for augmentation.” Augmentation plans provide that if a junior water user can provide replacement water to other senior users, the junior water user can divert out of priority so long as the replacement water is of suitable quantity and quality.

A plan of augmentation for a well, or series of wells, involves first determining the depletions of stream flows, or injury to the river, caused by out-of-priority well pumping. Then a source of water is identified that will be made available to the river at the time and place of injury. Augmentation plans ordinarily must be approved and decreed by water courts; temporary plans of augmentation, renewed on an annual basis, are administered by the State Engineer’s office (MacDonnell 1988; Blomquist et al. 2004). Augmentation plans are highly flexible tools that enable new uses of water without strict regard for the priority system, so long as existing rights are not seriously affected (MacDonnell 1988).

Kansas’ Intensive Groundwater Use Control Area (IGUCA) policy: the Wet Walnut case

In Kansas, the Chief Engineer has statutory mandate to “enforce and administer” the provisions of the Kansas Water Appropriation Act (which in 1945 established the prior-appropriation doctrine for both surface water and groundwater) and to initiate public proceedings designating an Intensive Groundwater Use Control Area (IGUCA) if certain statutory criteria are met. Those criteria include groundwater levels in the area that are declining or have already declined excessively, a rate of withdrawal that exceeds the rate of recharge, the occurrence of preventable waste, and other conditions that require regulation in the public interest (Rolf 2006). An IGUCA can be used to address local or regional groundwater issues and even situations where groundwater use is adversely affecting streamflow. It is a powerful tool that allows the use of a variety of remedies to solve groundwater problems, including (1) closing an area to new permits, (2) apportioning the permissible withdrawal in an area among the valid groundwater-right holders in the area, (3) reducing the permissible withdrawal of groundwater-right holders, (4) requiring rotation of use within the area, and (5) other measures that would protect the public interest (Rolf 2006). In short, the IGUCA process provides the only explicit authority for mandated water-rights reduc-

tions. There are currently five IGUCAs in Kansas (Rolf 2006). The only one in the area overlying the Ogallala consists of a strip 6.5 km wide along a 240-km stretch of the Arkansas River in southwest Kansas.

In 1992 the Chief Engineer established the Walnut Creek IGUCA in west-central Kansas, after extensive hearings held in Great Bend, Kansas, in 1990 and 1991. The problem lay in the inability of the Kansas Department of Wildlife and Parks to satisfy its senior rights to surface water from the Arkansas River and its tributary Walnut Creek (Peck 2006). These rights provided water for the Cheyenne Bottoms (Fig. 1), an important wildlife area and stopover for migratory birds. These rights could not be satisfied, allegedly due to pumping by irrigators of alluvial groundwater from Walnut Creek, upstream from the Cheyenne Bottoms (Peck 2006).

Information contained in the files of the office of the Chief Engineer and presented at the IGUCA proceedings indicated that groundwater levels in the area in question were declining or had declined excessively, the rate of withdrawals of groundwater within the area in question equaled or exceeded the rate of recharge in such area, and conditions existed within the area in question that required regulation in the public interest.

The Walnut Creek IGUCA Order determined that basinwide “safe yield” was 28 million m³ (22,700 acre-ft) per year and that pumping was double that amount. The Order then established two broad categories of water rights, with 1 October 1965, as the date of demarcation (Peck 2006). With a goal of achieving safe yield in the basin, the Order reduced both the senior rights with priorities before that date between 22 and 33%, depending on their location within the IGUCA, and the junior rights from 64 to 71%. Vested rights (i.e., water rights existing prior to the 1945 Kansas Water Appropriation Act mentioned earlier) were not affected. The Order reduced senior water-right pumping on the basis that irrigators could efficiently irrigate in this region with smaller annual quantities of water. In contrast, the Order reduced junior rights both to promote efficiency and to achieve safe yield in the basin (Peck 2006). Although the irrigators affected protested the Order and gloomy economic repercussions were forecast, the Order stimulated sales of irrigation-system upgrades and conservation practices, such as no-till, which resulted in increased efficiency and reduced pumping costs; however, the Order also forced some reduction in irrigated hectares (S. Falk, GMD5 Manager, personal communication, 2009).

The IGUCA policy is the single most powerful tool that the Chief Engineer of the state of Kansas has to cut down annual pumping of any water right holder, regardless of priority date of the water right. This is a necessary tool to protect the public interest.

Kansas Groundwater Management Districts’ “safe yield” policies

Since passage of the 1972 Kansas Groundwater Act, which established local Groundwater Management Districts

(GMDs) in Kansas, five GMDs have been formed (Fig. 1). Each district developed its own distinct management plan with goals to conserve and prolong the life of the aquifer and protect its water quality.

The various management programs of the GMDs aimed to limit new development in areas that already had significant development and declines in water levels. The area of influence of a well was considered to be a circular area of 3.2-km (2-mile) radius covering an area of 32.5 km². Drawdown analysis for typical well and aquifer parameters indicated that drawdown was limited beyond a radius of 3.2 km from a pumping well (Sophocleous 2000b). In addition, an area of 3.2-km radius was considered representative of local conditions, given aquifer variability, location of existing water rights, and other factors.

The different hydrologic conditions in the various GMDs were reflected in the management policies adopted. The central Kansas GMDs (2 and 5; Fig. 1) have more precipitation (ranging from west to east from 580 to 810 mm/yr on average) and thus more groundwater recharge and smaller water-table declines than in the western GMDs (1, 3, and 4; Fig. 1). As a result, GMD2 and GMD5 have good prospects for balanced groundwater management in their districts rather than the depletion situation found in western Kansas. Whereas the western GMDs concentrated their efforts on slowing the rate of water-table declines, the central Kansas GMDs concentrated primarily on maintaining steady-state water-table conditions, as well as on monitoring saltwater intrusion from underlying brine formations or man-made sources (Sophocleous 2000b).

The central Kansas GMDs (2 and 5) initially adopted a “safe-yield” management plan during the late 1970s and early 1980s, attempting to balance groundwater withdrawals with aquifer recharge. According to this policy, the total appropriation in a 3.2-km (2-mile) radius circle around the proposed diversion was limited to the long-term average annual recharge calculated for the circle. Thus, the quantity already appropriated within that 3.2-km radius circle plus the quantity proposed under the new application had to be less than the long-term average annual recharge. However, the central Kansas GMDs, in particular GMD5, initially over-estimated recharge (originally estimated at 229 mm/yr or 9 in/yr), resulting in over-appropriations and groundwater depletion in some areas. Following an intensive recharge-estimation program (Sophocleous and Perry 1985, 1987; Sophocleous and McAllister 1987, 1990; Sophocleous 1991, 1992, 1993; Hansen 1991; Sophocleous et al. 1996), GMD5 reduced its recharge estimate (Sophocleous 2000b; Falk 2006) initially by one-half in November 1984 to 114 mm/yr (4.5 in/yr), and then again by another one-half in 1996 to 57 mm/yr (2.25 in/yr). Although a number of farmers voiced concerns about the negative economic impacts of the reductions, those reductions dealt with future allowable appropriations of groundwater and did not affect existing water right holders. In December 1998, the district recommended to the Chief Engineer that the remainder of

the district be closed to further appropriations, and the whole district was closed to large-scale development (Falk 2006).

Although the previously mentioned recharge-estimation program provided temporal and spatial distribution of recharge, spatially zoning the region with regard to recharge is the more difficult problem politically. However, GMD2 divided the district into two zones; a northern low-recharge region that receives half the amount of recharge (76 mm/yr or 3 in/yr) received by the rest of the district, and the rest of the district. Thus, its safe-yield program was modified accordingly (Sophocleous 2000b).

Although the adoption of those safe-yield policies in Kansas has slowed the rate of water-table declines, declines have continued throughout most of the High Plains aquifer and in all the GMDs. This has resulted in steadily decreasing streamflows in western and central Kansas streams (Sophocleous 2000a, b). In 1980, in response to these streamflow declines, the Kansas Legislature passed the minimum instream flow law, which required that minimum desirable streamflows (MDS) be maintained in different streams in Kansas. (The MDS standards were passed into law in 1984.)

The concept of safe yield as originally adopted by the GMDs was used to balance groundwater withdrawals with groundwater recharge but ignored the naturally occurring groundwater discharge (Sophocleous 1997, 1998, 2000a). Under natural or equilibrium conditions, recharge to an aquifer ultimately results in an equal amount of discharge from the aquifer into streams, springs, and seeps. Consequently, if pumping equals or exceeds recharge, the streams, marshes, and springs eventually dry up (Sophocleous 2000a). Continued pumping in excess of recharge would eventually deplete the aquifer. In all the GMDs, the non-accounting of natural groundwater discharge, in combination with the previously mentioned over-estimation of recharge and the consequent over-appropriations, resulted in the declines in groundwater levels and streamflow just described. Recognizing that streams and their alluvial aquifers are closely linked in terms of water supply and water quality, and that neither can be properly understood or managed by itself, both GMD2 and GMD5 have recently reevaluated their safe-yield policies to account for natural groundwater discharge and stream-aquifer interactions, which are so predominant in the baseflow-dominated streams in their regions.

Starting in the early 1990s, GMD2 and GMD5 have moved toward conjunctive stream-aquifer management by amending their safe-yield regulations to include baseflow (i.e., the natural groundwater discharge to a stream), represented as a groundwater withdrawal, along with regular water-permit appropriations when evaluating a groundwater-permit application. In other words, baseflow is viewed as groundwater that already has been appropriated. (Baseflow is estimated as the streamflow that is exceeded 90% of the time on a monthly basis from the streamflow-duration curve.) The concept is to prorate the baseflow to a series of artificial wells, known as “baseflow nodes” located on the stream centerline at intervals

according to the district's well-spacing requirements. Each node is assigned an annual quantity of water equal to its prorated share of the estimated baseflow, which is considered its appropriation in "2-mile (3.2-km) circle" computations. If there are such nodes in a 3.2-km radius circle, they are each treated as prior appropriations for purposes of determining whether a new application should be approved (Sophocleous 2000b). It is hoped that this new measure, together with the establishment of minimum-desirable streamflow standards, will provide additional needed protection to the riverine-riparian ecosystem.

Although the central Kansas GMDs (2 and 5) followed safe yield policies since their establishment in the mid-1970s, many areas within the GMD boundaries were already over-appropriated when those policies first became applicable. However, the safe yield policies reduced the rate in the numbers of new permits granted (the districts were closed to further development by 1990) and slowed down the depletion of the aquifer, as can be seen from the annual water-level change maps of those districts (S. Falk, GMD5 Manager, personal communication, 2009). As a result of GMD actions, annual pumping of groundwater in Kansas leveled off after decades of increases (Sophocleous 1998).

Water-use reporting in Kansas

One of the keys to good water regulation and management depends on having accurate information about water use on which to base regulatory and management decisions. In 1988, the Kansas Legislature made water-use reporting mandatory (Rolfs 2006). (Failure to timely file a complete and accurate report could result in a civil fine up to US \$250 per water right). The reported water-use data are reviewed, follow-ups are made, and a statewide annual water-use report is jointly published for municipal use by the Division of Water Resources (DWR; the water rights regulatory agency in Kansas), the Kansas Water Office (KWO; the water planning agency in Kansas), and the US Geological Survey. All five of the GMDs have regulations requiring water flowmeters on almost all non-domestic groundwater points of diversion within their districts (Rolfs 2006). Tax incentives to groundwater users are provided for installing those well meters, and the GMDs provide assistance with testing and maintaining the water flowmeters. Each year over 99.9% of all water-use reports are filed (Rolfs 2006). This water use-reporting program is indeed a highly successful one that needs to be emulated elsewhere as well. Figure 3 shows reported water-use for two wells included in Fig. 2. It indicates that water use, although variable depending on local climatic conditions, generally decreased with time as irrigation systems became more efficient. The water-use information, together with the data obtained from the Kansas annual groundwater-level monitoring network that are made publicly available in a timely manner (KGS 2009) and other gathered knowledge, provides reliable information on which to base management decisions in Kansas.

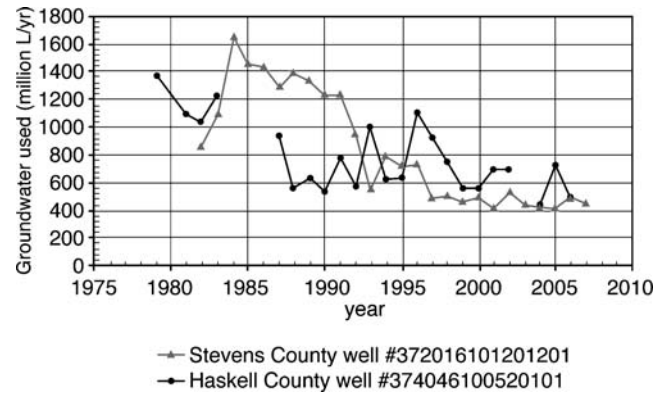


Fig. 3 Reported groundwater use for two Kansas irrigation wells shown in Fig. 2

Wichita's Aquifer Storage and Recovery (ASR) program

Wichita, the largest city in Kansas, is located just south of the easternmost extension of the High Plains aquifer system, known as the Equus Beds aquifer, which is locally managed by Groundwater Management District No. 2 (GMD2; Fig. 1). In the 1930s Wichita established wells in the Equus Beds and began pumping groundwater for municipal use. Running through the Equus Beds area southeastward is the Little Arkansas River, which joins the Arkansas River at Wichita (Fig. 1).

Until the early 1990s Wichita drew heavily from the Equus Beds aquifer. Extensive groundwater use by Wichita and irrigating farmers drew down the aquifer approximately 13 m in some locations, with a total loss of approximately 24.6 million m³ of water from aquifer storage since the time heavy pumping began in the 1940s (City of Wichita 2009; Peck 2007). Irrigators with water rights junior to the City of Wichita's water rights may have to shut down their wells if the water table keeps dropping. In addition to the lowering of the water table, another problem in the region is a large, underground saltwater plume located northwest of the Wichita wells and migrating towards the city's well field (Sophocleous 1984).

After studying various options to enhance its long-term water supplies, including diverting water from the Kansas River basin, the City of Wichita embarked on a pilot project in the late 1990s on aquifer storage and recovery (ASR). This project involved diverting water during above-normal flows from the Little Arkansas River and its streambanks and recharging it (following treatment to meet State water quality standards) back into the Equus Beds aquifer via basin, trench, or injection wells. Ultimately, Wichita wants to pump this water back out of the Equus Beds for municipal use. The project will provide water for the benefit of Wichita and area irrigators. At the same time it will form a hydraulic barrier to impede the migration of the saltwater plume moving toward the Wichita well field (City of Wichita 2009).

A demonstration project from 1995 to 2004 showed that engineering aspects of the ASR project were feasible, but legal problems arose because of inadequate statutes and regulations (Peck 2007). In response, the DWR

worked with Wichita and promulgated a new set of regulations designed explicitly for “aquifer storage and recovery permitting” (Peck 2007). Each applicant for an ASR project must file applications for two types of appropriation permits: one that allows diversion of water either directly from the river or from bank storage and the other that allows diversion of water from the Equus Beds aquifer for its ultimate use. The applicant must also comply with relevant regulations of the Kansas Department of Health and Environment regarding the quality of the injected or artificially stored water.

Wichita’s ASR project covers four phases to be completed in 2015, with a goal of 378.5 million L/day capacity. Phase 1 was completed in 2007, with a capacity of 37.85 million L/day. Water quality, being a concern, is carefully monitored. The pilot project Phase 1 was highly successful, prompting initiation of Phase 2 (with a capacity of 113.56 million L/day), which started in 2009.

Nebraska’s Natural Resources Districts (NRDs)

While Texas, Kansas, and other High Plains States were experimenting with management districts that focused on specific issues, Nebraska sought to experiment with a different structure of governance. By the 1960s, Nebraska had established watershed-planning boards, rural water districts, and flood-control districts in addition to the existing soil and water conservation and irrigation districts. With overlapping functions, authorities, and boundaries, there often was confusion about who had responsibility for what issues, and coordination from the state to the local level was extremely difficult (Cash 2003). In 1969, legislation was passed consolidating the 154 existing resource-related districts into 23 natural resources districts (NRDs).

The NRDs are local management agencies based on watershed boundaries with broad authority to research and regulate natural-resource use and to provide environmental protection. NRD legislation established a suite of innovative institutional structures, which created a new system of natural-resource management and assessment with broad-reaching abilities to coordinate and integrate science and decision making (Cash 2003). NRDs, with their authority over all resource-related issues, allow integrated resource analysis, planning, and management in which linked issues can be addressed in a coordinated and efficient manner.

As Cash (2003) pointed out, the way in which NRD boundaries were created—by using watershed boundaries that cover the state—has a critical effect on how resources are managed in Nebraska. The idea was to match institutional boundaries to boundaries of consequence for resources, avoiding problems of poor institutional fit. Second, they were created to be large enough to capture efficiencies of scale and minimize transboundary problems yet small enough to manage effectively. Third, because perceptions of what is efficient and effective might change from issue to issue or over time, boundary drawing was somewhat flexible (Cash 2003). By law, NRDs can

formally merge or split apart (this was done once in 1989 when two NRDs merged), and they can formally collaborate with neighboring NRDs to address transboundary issues (this is the case, for example, for the Platte River, because the Platte [Fig. 1] cuts through several NRDs).

Locally elected NRD board members are given a broad range of authority to manage in the context of state laws. This includes powers to tax (to help generate revenue to buy out water rights), regulate, educate, perform monitoring and research, provide financial incentives, and enforce regulations. Such a suite of functions provides a flexible toolbox from which to manage. Thus, for groundwater management, the state ultimately controls the resource (all underground water is owned by the state), but the NRDs have broad leeway when devising regulations tailored to the needs, interests, and environment of their particular place (Cash 2003).

The effectiveness of the NRDs in managing groundwater resources depends critically on institutions at the state and federal levels because the NRDs are subject to intense pressure from local entitlement holders. Tensions often arise between local control of groundwater and state control of surface water and water compacts. Recent initiatives by three NRDs to establish water-allocation rules that will eventually limit the amounts farmers can use for irrigation would have been ineffective were it not for the existence of the state judicial system. For example, one NRD had to obtain a ruling in county court to force a farmer who had exceeded his water allocation to cease irrigating (Peterson et al. 1993).

Groundwater-conservation policies in the High Plains with Kansas as an example

Agricultural prosperity in large portions of the High Plains region depends on mining water from the Ogallala aquifer. Although the amount of water in the aquifer is enormous, it is a practically nonrenewable resource because current pumping for irrigation exceeds by far the recharge rate. It can be argued that this is no different than the mining of other nonrenewable resources and the resulting ghost towns that also were once bustling prosperous communities of several thousand people. However, one can see some important differences (Bittinger 1981). First of all, the area affected is large—the Ogallala covers an area about the size of California. Decisions about groundwater mining affect not only the overlying landowners but also surface-water users and regional economies benefiting from irrigated agricultural production. The impact of the depletion will not only be on those deriving their water from the Ogallala but on consumers across the country because of the food and fibre production attributable to Ogallala water. An estimated 40% of the US beef production comes from the High Plains area—beef fattened on grain irrigated with Ogallala water (Bittinger 1981).

The value of groundwater supplies to regional survival, much less prosperity, is rarely understated. Typically, only three solutions are discussed with reference to Ogallala groundwater depletion (Somma 1997): (1) voluntary conservation, (2) mandatory regulation, and (3) water importation. Surface-water importation from other regions represents huge costs and politically sensitive environmental considerations. It is the least discussed solution at the present time. Because everyone agrees on the need for conservation, the real policy battle is over the institutional design and practices of the groundwater-conservation agency (Somma 1997). Some voluntary measures can be coupled with incentives, like the CREP program (discussed in the following), so that they are a mix of public/private responses.

In order to address the numerous groundwater problems, increasing collaboration between states on research on the High Plains, prompted by federal funding efforts, has been taking place. An example is the Ogallala Aquifer Program, a federally funded effort between the US Department of Agriculture and the land grant universities in Texas and Kansas. And collaboration is likely to occur between states for federal programs to help provide relief for over-appropriated areas of the aquifer in the various states (S. Stover, Kansas Water Office, High Plains Unit, personal communication, 2009).

The development of irrigated agriculture in western Kansas created an environment that has led to extensive growth in crop production, livestock, meatpacking, and other related industries. Even over the past decade, the number of irrigated hectares in western Kansas has significantly increased (Perry 2006; Golden 2006). Additionally, an increase in the hectares of water-intensive crops such as corn, has been observed (Golden 2006). Increasing corn hectarage implies increasing water use from the aquifer and consequently, the depletion rate of the aquifer. On the other hand, a steady reduction in the per hectare water use for all irrigated crops has been observed, attributed to improved irrigation efficiency and other factors (Golden 2006).

In Kansas, past trends in water consumption and crop mix, as well as recent economic research, suggests that efficiency gains might have had an unintended consequence (Golden 2006). The adoption of more efficient irrigation technology may actually be accelerating water use and increasing the pace at which the aquifer is depleted. If society's goal is either to "conserve and extend" the life of the Ogallala aquifer, or achieve "sustainable yields" from the aquifer, then future technological advancements without policy/regulation could have an adverse effect (Golden 2006).

Current Kansas water policy calls for achieving an absolute reduction in water consumption from the Ogallala aquifer and slowing aquifer-decline rates. At the same time, political forces require that the economic viability of agriculture in western Kansas be maintained, and if possible enhanced, through policy implementation (Golden 2006). In order to maintain the profitability of irrigated agriculture, technological innovations need to

continually be developed through the research and development process and adopted by the agricultural community. The general consensus is that the solution will require policy alternatives that combine incentive-based programs coupled with voluntary participation (Golden 2006). However, mandated reductions are also needed in critical areas.

Since the early 1980s, both research and policy have focused on improving irrigation efficiency as the primary means of extending the economic life of the Ogallala aquifer. One policy aimed at increasing irrigation efficiency is the current cost-share program administered by the Kansas State Conservation Commission (SCC). Under this program, irrigators within the Ogallala aquifer region of western Kansas are reimbursed a portion of the cost of adopting modern irrigation technologies. Western Kansas has seen a shift to more efficient irrigation technology (Perry 2006; Golden 2006). The majority of cost-share funds have been expended on the adoption of "low pressure with drops" technology (Golden 2006). The rapid adoption of technological improvements has led to significant economic benefits to production agriculture in western Kansas.

However, Golden and Peterson (2006) point out that an analysis of the SCC cost-share program suggests that there has been little to no annual reduction in gross water pumped from the aquifer, and in many cases, water use increased as producers expanded irrigated acreage and shifted cropping practices to more water-intensive crops. The study also suggested that the estimated cost efficiency of the SCC investments did not appear to compare favorably to alternative policies such as a water-right buyout program.

Another recent conservation program is the Conservation Reserve Enhancement program (CREP), which is a US Department of Agriculture program with state partnership. It is a voluntary and incentive-based program that allows owners of irrigated land in western Kansas (along the Arkansas River corridor) and other High Plains regions such as Nebraska and Colorado, to retire their irrigated hectarage and receive program payments for that hectarage. This program in Nebraska and Colorado was in response to interstate compact compliance lawsuits (see section [Legal and institutional framework for water management in the High Plains](#)), whereas in Kansas, it was a pro-active water conservation move. The CREP economic analysis suggested that, in fact, the policy would reduce water consumption and extend the economic life of the aquifer (Leatherman et al. 2006; Golden 2006). Although there may be short-term adverse economic impacts resulting from the CREP program, the long-term benefits of reduced aquifer stress along river corridors will particularly benefit the drying streams and associated ecosystems of western and central Kansas (Sophocleous 2000a, 2003).

Concern over the dwindling supplies in the Ogallala aquifer due to mining of the aquifer led to various proposals for conserving the aquifer (Peck 2003). One such proposal was the "two pool" concept proposed by the Kansas Water Office in 2001. That proposal would have

created an upper “useable pool,” which would be available for current water-right holders until exhausted, and a lower “conservation pool,” which would be more heavily regulated because it had to satisfy safe-yield criteria and would have been available for drinking water and other basic needs. Even though the “two pool” approach was discarded due to political opposition (mainly stemming from uncertainty about how that system would work), it seems prudent to reserve a certain amount of water for some future use and/or development when groundwater is the only source of water instead of waking up some day to discover that we have bequeathed to ourselves and our descendants a future of water use that we did not want.

Concluding comments and recommendations

The institutions devised to manage water resources in the nineteenth and twentieth centuries are not well suited to address the challenges of managing water resources in the twenty-first century. The water rights in the High Plains and the western United States in general were developed when water was plentiful and existing supplies were not fully allocated (NRC 2001, 2004). Texas stands out among all High Plains States as an anomaly with respect to laws that govern access to and use of groundwater. It relies on the doctrine of absolute ownership (i.e., the “Rule of Capture”) that was developed when groundwater was considered “secret, occult, and concealed” (*Frazier v. Brown*, 12 Ohio St. 294 [1861]), that is, before the science of hydrology advanced to its modern-day level of development. Absolute-ownership concepts and granting water rights in perpetuity seem anachronistic, reflecting an American mindset of the nineteenth century when seemingly limitless land was thrown in the laps of the settlers, so to speak. Today, from a science perspective, this is unrealistic. There is a need to replace “rights” with “permits” for beneficial water use over specified periods of time. These permits would have to be constrained by the availability of water and the preservation of the resource base for future generations.

Today most rivers and aquifers are fully allocated, and the High Plains resources require more flexible allocations to respond to changing demands. In many cases, instream flows and ecological values are not adequately protected (Sophocleous 2007), and new laws may be needed if such protection is to be provided (NRC 2001, 2004). Legal systems that treat surface water and groundwater similarly such as those of New Mexico, Colorado, and Kansas (all of which follow the prior-appropriation doctrine for both surface water and groundwater), are better equipped to deal with surface water/groundwater interaction problems than the legal systems that treat surface water differently from groundwater such as those in Texas, Oklahoma, and Nebraska (which follow the prior-appropriation doctrine for surface water but not groundwater as shown in Table 1). In addition to increasing water demands, a common thread underlining both compact disputes outlined previously (see section [Interstate conflicts over water](#)

and State versus Federal controls) was the neglect to take into account the surface water—groundwater interrelationship. The National Research Council (2001, 2004) concluded that the existing institutions are inadequate for managing water as a common pool resource or as a public good. The fragmented and piecemeal institutional arrangements for managing the supplies and quality of water are unlikely to be sufficient to meet the water challenges of the future (NRC 2001, 2004). Yet, the NRC (2001, 2004) also concluded that knowledge about how such institutions might be modified and improved is scarce, and research on institutions occupies only “a very small portion of the current water research agenda.”

It is apparent that dealing with groundwater depletion issues forces politically difficult choices. Aiken (1984) pointed out that the most difficult choice was whether existing groundwater users would be forced to share groundwater deficit through reduced withdrawals, or whether that cost will be borne primarily by those denied groundwater access through development restrictions or prohibitions. Most western states, including the High Plains States, have exempted existing users from restrictions on groundwater use and are restricting only future groundwater development. This is probably the most important shortcoming of western groundwater depletion policies (Aiken 1984). It is clear that the failure to regulate existing groundwater users reflects not only the strong opposition of existing groundwater users who have lobbied accordingly but also an apparent limitation inherent in appropriation law—that the quantity of an appropriative water right is not subject to reduction so long as the water is used beneficially. As pointed out by Aiken (1984), this fixed-quantity principle, followed in the High Plains States of Colorado, Kansas, and New Mexico, should yield logically to the physical reality of permanent supply reduction from groundwater depletion, such that withdrawal limitations should be legally tolerated to extend the life of the aquifer. Because the states of Texas, New Mexico, Kansas, Colorado, and Nebraska have critical area legislation (see section [Legal and institutional framework for water management in the High Plains](#)), groundwater development may be restricted or prohibited in those areas.

The economic impact of reduced irrigation is probably the biggest challenge in achieving reductions in water use—when saving for tomorrow at the cost of today. The more the economy can be shifted away from irrigation and diversified, the easier it will be to implement and improve voluntary programs and regulations to conserve the water resource far into the future. To succeed, there must be some personal stake to conserve the resource (S. Stover, Kansas Water Office, High Plains Unit, personal communication, 2009).

As the National Research Council Committee on the Future of Irrigation recommended, states need to establish improved systems to facilitate the voluntary transfer of water among the different users (NRC 1996). These systems, to be managed at the local or regional levels, should provide clear rules and well-defined processes by

which transfer can occur and should incorporate measures for protecting other existing uses of water (NRC 1996). Innovation and flexibility will be required, especially as direct federal support continues to diminish.

An additional approach to the problems of the aquifer that is clearly needed is political and legal consensus on a coherent groundwater policy and management among all states that share the water resources of the aquifer, instead of the currently existing patchwork of laws, regulations, and policies that varies from state to state (outlined in Sophocleous 2010). The system of “equitable apportionment” (see section [Interstate conflicts over water and state versus federal controls](#)) offers promising opportunities in the management of large groundwater aquifers that traverse state lines such as the High Plains aquifer.

The Delaware and Susquehanna River Basins Compacts of 1961 and 1970, respectively, have gone furthest in providing a legal framework for management of surface waters and groundwaters across state lines and have developed the unique feature of having the US Government as a partner with the states in the interstate effort (Clark 1978; Muys 1973). A similar interstate groundwater commission that regulates the entire High Plains aquifer may be the key to preserving the resource. Such commission, made up of representatives from the eight High Plains States and the federal government, would have complete authority over the aquifer, including the power to allocate the waters of the High Plains among the signatory states in accordance with the doctrine of equitable apportionment, and could override any state laws that conflict with its programs. Other international models of similar arrangements include the Murray Darling Basin Commission in Australia and the European Union Groundwater Directive.

However, the realities of US politics indicate that the emergence of a political consensus on a coherent groundwater policy in the High Plains aquifer by all constituent states does not seem likely at the present time. The states would likely fight mightily to prevent any federal management of the groundwater. While water policy in the US is extremely resistant to wide-ranging change, water policy challenges (such as persistently declining groundwater levels, growing conflicts between users of surface and ground waters, declines in aquatic ecosystem health, and aging water infrastructure) and fears that climate change could undermine the reliability of existing water supply systems and pose major challenges to water users and managers have intensified. As Leshy (2009) pointed out, such circumstances are creating a more favorable political climate for adopting long-needed reforms than has existed for decades.

Although the United States and the rest of the world are facing common problems of groundwater depletion and contamination, the great variety of groundwater management approaches in use in different US states makes it challenging for anyone to glean lessons from the American experience that would be particularly useful in other parts of the world. As Deason et al. (2001) also pointed out, however, there are many lessons from the US

experience in water resource policy formulation that may be applicable in other regions of the world; these are mainly related to institutional reforms, conflict resolution mechanisms, and modern-planning and decision-making procedures. The local Groundwater Management Districts, present in four High Plains states (Colorado, Kansas, Nebraska, and Texas), are the most common institutional arrangement to deal with a wide spectrum of issues related to water management. Designation of “critical areas” is very important in regulating further over-exploitation. Promotion of incentive-based programs to reduce groundwater pumping in sensitive areas and increase water productivity also is needed to affect desirable change. Water-management innovations, especially those less embedded in law, continuously move across international borders. Incorporating the innovative aspects of groundwater management from the different states previously identified (see section [Groundwater-management innovations](#)) into a regional groundwater-management approach would appreciably enhance the sustainability of this precious groundwater resource.

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