
Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA

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Abstract Sustainable use of groundwater must ensure not only that the future resource is not threatened by overuse, but also that natural environments that depend on the resource, such as stream baseflows, riparian vegetation, aquatic ecosystems, and wetlands are protected. To properly manage groundwater resources, accurate information about the inputs (recharge) and outputs (pumpage and natural discharge) within each groundwater basin is needed so that the long-term behavior of the aquifer and its sustainable yield can be estimated or reassessed. As a first step towards this effort, this work highlights some key groundwater recharge studies in the Kansas High Plains at different scales, such as regional soil-water budget and groundwater modeling studies, county-scale groundwater recharge studies, as well as field-experimental local studies, including some original new findings, with an emphasis on assumptions and limitations as well as on environmental factors affecting recharge processes. The general impact of irrigation and cultivation on recharge is to appreciably increase the amount of recharge, and in many cases to exceed precipitation as the predominant source of recharge. The imbalance between the water input (recharge) to the High Plains aquifer and the output (pumpage and stream baseflows primarily) is shown to be severe, and responses to stabilize the system by reducing water use, increasing irrigation efficiency, adopting water-saving land-use practices, and other measures are outlined. Finally, the basic steps necessary to move towards sustainable use of groundwater in the High Plains are delineated, such as improving the knowledge base, reporting and providing access to information, furthering public education, as well as promoting better understanding of the public's attitudinal motivations; adopting the ecosystem and adaptive management approaches to managing groundwater; further

improving water efficiency; exploiting the full potential of dryland and biosaline agriculture; and adopting a goal of long-term sustainable use.

Résumé L'utilisation durable de l'eau souterraine doit permettre non seulement que la pérennité de l'eau ne soit pas menacée, mais aussi que les environnements naturels qui dépendent de cette ressource, tels que la végétation riveraine, les écosystèmes aquatiques et les milieux humides, soient protégés. Afin d'assurer une gestion appropriée des ressources en eau souterraine, une information précise concernant les entrées (recharge) et les sorties (décharge naturelle et pompage) d'eau dans chacun des bassins est nécessaire afin que le comportement à long terme de l'aquifère et le taux de pompage durable puissent être estimés. En guise d'initiative, ce travail illustre certaines études clé concernant la recharge de l'eau souterraine à plusieurs échelles dans les hautes plaines du Kansas. Ces études comprennent le bilan sol-eau et la modélisation numérique à l'échelle régionale, l'étude de la recharge des nappes souterraines à l'échelle du comté, des études expérimentales à petite échelle et certaines découvertes originales. Lors de la présentation de ces études, l'emphase est portée sur les hypothèses et limitations ainsi que sur les facteurs environnementaux qui affectent les processus de recharge. En général, les effets de l'irrigation et de l'agriculture sur la recharge sont d'augmenter considérablement le taux de recharge, et dans plusieurs cas, d'excéder les précipitations comme principale source de recharge. Le déséquilibre entre les intrants d'eau (recharge) et entrants (pompage et écoulement de base dans les rivières) dans l'aquifère des hautes plaines est très important. Les résultats des efforts de stabilisation du système aquifère en diminuant l'utilisation d'eau, en améliorant l'efficacité des techniques d'irrigation, en adoptant des pratiques d'utilisation du territoire qui réduisent l'utilisation d'eau et en adoptant certaines autres mesures sont présentés. Enfin, les étapes de base nécessaires afin d'atteindre une utilisation durable de l'eau souterraine dans les hautes plaines sont exposées. Elles comprennent l'amélioration des connaissances de base, la promotion d'une meilleure compréhension de la motivation et de l'attitude du public, l'adoption d'une approche de gestion de l'eau souterraine adaptable et basée sur les écosystèmes, l'amélioration de l'efficacité d'utilisation de l'eau, l'exploitation du plein potentiel de

Received: 19 March 2003 / Accepted: 3 August 2004
Published online: 14 January 2005

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l'agriculture biosaline et en milieu aride, et l'adoption d'un objectif pour l'utilisation durable à long terme.

Resumen El uso sostenible de aguas subterráneas debe garantizar tanto que el recurso futuro no esté amenazado por sobreutilización como que los ambientes naturales dependientes del recurso sean protegidos (ie el flujo base de los arroyos, la vegetación ripariana, los ecosistemas acuáticos y los pantanos). El manejo adecuado de los recursos de aguas subterráneas requiere información precisa con respecto a los inlfujos (recarga) y descargas (bombeo y descarga natural) en cada cuenca de aguas subterráneas de tal manera que se pueda estimar o reevaluar el comportamiento de largo plazo del acuífero y su tasa de sostenibilidad. En un primer paso hacia esta meta, este trabajo destaca algunos estudios claves de recarga de aguas subterráneas en las llanuras altas de Kansas. Dichos estudios se concentran en diferentes escalas: estudios regionales del presupuesto para aguas del suelo y modelos de aguas subterráneas, estudios de recarga de aguas subterráneas a nivel provincial y estudios locales experimentales de terrenos que incluyen algunos interesantes descubrimientos nuevos. Estas investigaciones comparten el énfasis en los presupuestos de partida y las limitaciones así como en los factores ambientales que afectan los procesos de recarga. El impacto general de las irrigaciones y cultivos sobre la recarga es un obvio incremento en el monto de recarga y en muchos casos excede a la precipitación como la fuente principal de recarga. Se puede observar que el desequilibrio entre el inlfujo de agua (recarga) del acuífero de las llanuras altas y la descarga (bombeo y flujos base de los arroyos principalmente) es severo. Asimismo, se describen las respuestas para estabilizar el sistema a través de la reducción del uso de agua por medio del incremento de la eficiencia de las irrigaciones y de la adopción de las prácticas de ahorro de agua y del uso de tierras así como otras medidas adicionales. Finalmente se describen los pasos básicos necesarios para evolucionar hacia el uso sostenible de las aguas subterráneas en las llanuras altas de Kansas. Estos pasos están constituidos por una mejora del conocimiento base, comunicar y proporcionar fácil acceso a la información, mejorar el conocimiento público general así como promover un mejor entendimiento de las motivaciones para las actitudes de la comunidad, adoptar los enfoques administrativos de ecosistemas y administración adaptable en el manejo de las aguas subterráneas, continuar las mejoras del uso eficiente del agua, explotar el potencial de la agricultura de terrenos áridos y biosalina y adoptar como meta el uso sostenible a largo plazo.

Keywords Soil-water budgets · Groundwater modeling · Irrigation return flow · Time lag · Ecosystem and adaptive management · Dryland and biosaline agriculture

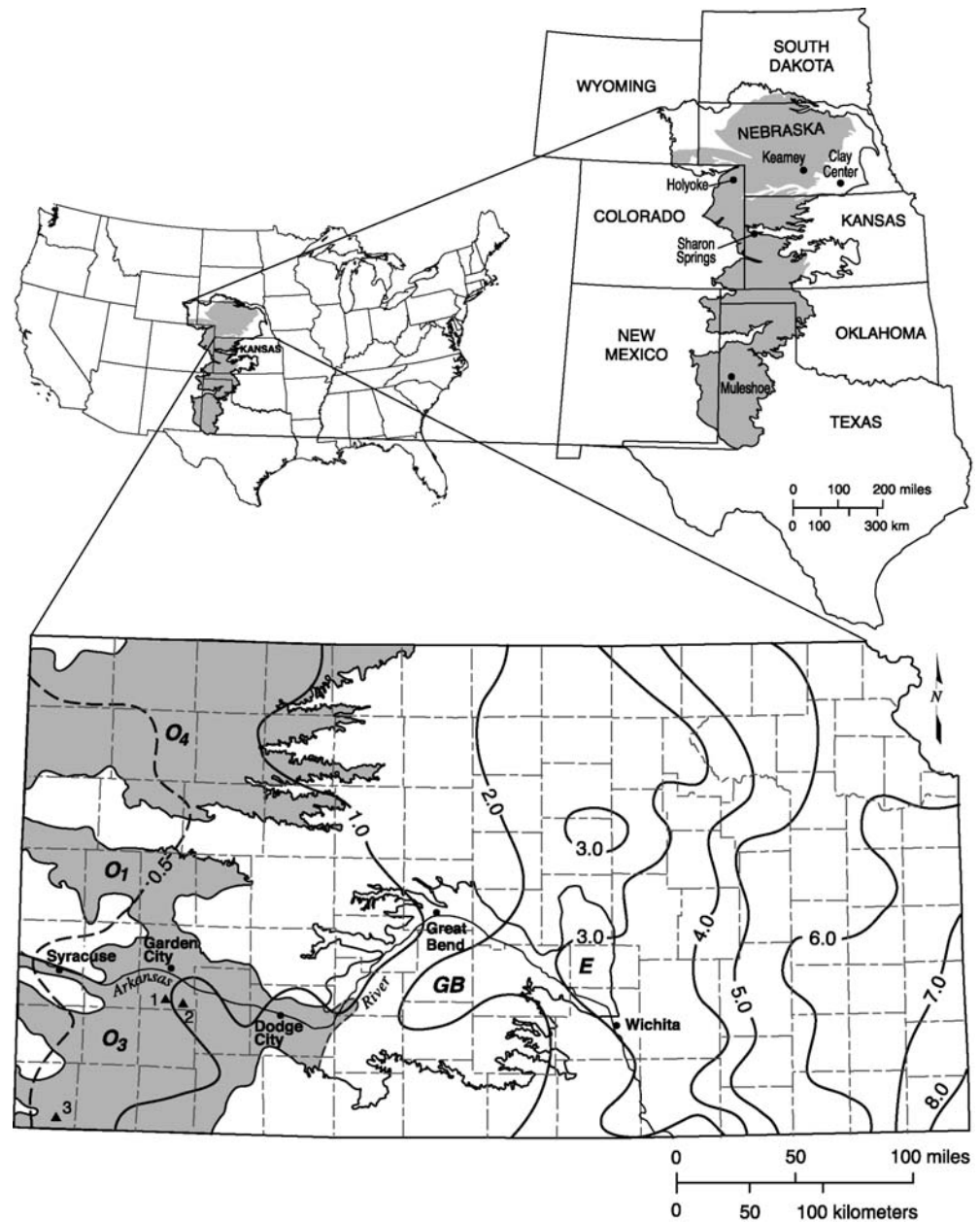
Introduction: the importance of groundwater recharge and the High Plains Aquifer

As Kansas water resources become fully allocated and demand for groundwater increases, groundwater managers are faced with the difficult task of ensuring the future viability of the resource. With the rise in public environmental awareness, groundwater managers are also concerned with protecting natural environments that dependent upon the groundwater, such as stream baseflows, riparian vegetation, aquatic ecosystems, and wetlands. Sustainable use of groundwater must ensure not only that the future resource is not threatened by overuse and depletion, but also that natural environments that depend on the resource are protected. There will always be trade-offs between groundwater use and potential environmental impacts, and therefore a balanced approach to water use between developmental and environmental requirements needs to be advocated. However, to properly manage groundwater resources, managers need accurate information about the inputs (recharge) and outputs (pumpage and natural discharge) within each groundwater basin, so that the long-term behavior of the aquifer and its sustainable yield can be estimated or reassessed.

Estimating recharge is essential in any analysis of groundwater systems and the impacts of withdrawing native water from them. In water resource investigations, groundwater models are often used to simulate the flow of water in aquifers, and, when calibrated, may be used to simulate the long-term behavior of an aquifer under various management schemes. Without a good estimate of recharge and its spatiotemporal distribution, these models become unreliable. Thus, without a good estimate of recharge, the impacts of withdrawing groundwater from an aquifer cannot be properly assessed, and the long-term behavior of an aquifer under various management schemes cannot be reliably estimated. Accurate estimates of recharge and recharge mechanisms are also necessary to assess the risk of groundwater contamination, particularly diffuse agricultural contamination (such as nitrates and pesticides). If water and contaminants move rapidly through fractures, for example, then dilution, attenuation, and degradation will be minimized and the contaminant is likely to arrive at relatively high concentrations soon after application at the soil surface. However, if transport is through the matrix, then the much slower travel time will allow for dispersion, dilution, and potential degradation that will influence the final concentration that reaches the groundwater. Clearly, understanding recharge is essential to managing most groundwater systems.

The High Plains aquifer is a regional aquifer system, the largest freshwater aquifer in the USA, underlying parts of eight states in the USA Great Plains from South Dakota to Texas (Fig. 1). The most extensive unit of the High Plains aquifer system is the Miocene–Pliocene Ogallala Formation (Gutentag et al. 1984), popularly known as the Ogallala aquifer (Fig. 1). Approximately 30% of the groundwater used for irrigation in the USA comes from the High Plains aquifer, and approximately

Fig. 1 Extent of the High Plains aquifer (Ogallala aquifer portion shaded). In addition, the lower panel displays the following items: Mean annual potential natural recharge in Kansas (in inches per year, modified from Hansen 1991; to convert inches per year to mm/year multiply by 25.4). The *italic-letter* designations stand for the following portions of the High Plains aquifer in Kansas: *E* Equus Beds aquifer; *GB* Great Bend Prairie aquifer; *O* Ogallala aquifer, with the numerical subscript representing the corresponding Groundwater Management District (GMD) number in western Kansas (*GMD4*, *GMD1*, and *GMD3* from north to south, respectively). *Solid triangles* with numbers 1, 2, and 3 represent experimental recharge sites described in the text subsection titled: Field-based experimental recharge studies at the local level



20% of the irrigated land in the USA is in the High Plains region. The Ogallala aquifer in western Kansas supports the regional agricultural and associated agribusiness economy. However, western Kansas is a generally semi-arid region with high evapotranspiration (Sophocleous 1998a); estimated recharge (although plagued with uncertainties) is much less than the water extracted from the Ogallala aquifer, resulting in significant water table declines (exceeding 50% of the aquifer saturated thickness in parts of western Kansas) as well as streamflow declines (Kromm and White 1992; Sophocleous 1998a, 1998b, 2000a, 2000b, 2002; Schloss et al. 2000), and making sustainable management of such an aquifer a particularly difficult problem.

Because of the semi-arid climate of western Kansas, recharge rates are generally low, and policies to balance

groundwater withdrawals with average recharge rates and environmental requirements have been viewed as being too harmful to the region's economy to be adopted (Sophocleous 2000a, 2000b, 2002). However, the people of the region recognize that they need to reduce the depletion of the aquifer and prolong its life if they are to assure future economic stability in the region. To assist in this effort, Sophocleous (2004) undertook a study to compile and reassess the various recharge estimates for the High Plains aquifer in Kansas. This paper provides some highlights from that study and attempts to elucidate the path towards sustainable use of groundwater in the High Plains. Although the focus in this paper is on the High Plains aquifer in Kansas, the results and analysis presented are believed to be characteristic of the entire multi-state High Plains aquifer in the USA, and are also

typical of intensively used aquifers in semiarid to sub-humid plains regions.

The groundwater balance and sustainability

Under natural or virgin conditions and over long periods of time (before any development), groundwater recharge is balanced by groundwater discharge, i.e., $Recharge = Discharge$. As groundwater is nearly always moving, it will naturally flow from the recharge areas to the discharge areas. The discharge from the aquifers may occur in a variety of ways such as flow to streams, lakes, and springs; water use (transpiration) by phreatophytic vegetation that draws its water from the water table or its capillary fringe; evaporation from playas and areas of very shallow water table; leakage to adjacent aquifers; or flow to the sea.

Pumping groundwater constitutes an additional withdrawal from the system that was in a natural state of balance under virgin conditions. For the system to reach a new equilibrium (a state of *sustainability*), pumping must either cause the recharge to increase, and/or it must cause the discharge to decrease. Groundwater pumping usually has little impact on the recharge, in cases of fairly flat potentiometric surfaces away from rivers or groundwater divides; these conditions are normally prevalent under arid and semiarid conditions with deep water tables, as recharge is determined mostly by climatic conditions, although in areas of intense irrigation, return flows to the underlying aquifer could be significant. Pumping, however, can decrease groundwater discharge by lowering shallow water tables, thus reducing groundwater evapotranspiration and seepage to streams, springs, lakes, or wetlands. In hydrogeologic terms, pumping can *capture* groundwater discharge. The position of the water table, which normally reflects the distribution of the recharge and discharge areas, as well as the geometry of the aquifer and its hydrogeologic properties, will change as the system adjusts to the change in discharge. Thus, declines in groundwater levels are not necessarily an indication that the sustainable yield of an aquifer is being exceeded, but simply that the water balance has been altered (Cook et al. 2001), and may reflect a temporary decrease in aquifer storage that occurs before a new equilibrium is established.

In order for a groundwater system to be *sustainable*, pumping must be balanced by an equal capture of discharge and/or recharge. If pumping persistently exceeds the total amount of natural recharge or discharge from the system, groundwater *mining* occurs, and the system is no longer sustainable. However, even without regard to the environment, it is not always possible to extract all of the natural aquifer recharge or discharge. In some cases, wells will run dry before natural groundwater discharges are reduced to zero. The fraction of recharge that can theoretically be extracted from an aquifer under steady-state conditions will depend on the geometry of the aquifer system, and, in particular, on the location of the pumping

wells relative to the natural recharge and discharge zones (Bredehoeft et al. 1982; Sophocleous 1998b, 2000a; Bredehoeft 2002). Therefore, the sustainable yield of aquifers, and thus the environmental impact of groundwater extraction, depends not only upon the volume extracted, but also on the location of pumping wells relative to recharge and discharge areas, and sometimes also on the timing of the extraction. Prediction of environmental impacts of groundwater extraction always requires detailed investigation of natural groundwater recharge and discharge processes.

It is important to note that all levels of groundwater extraction will, in the long run, result in declines of natural discharges, with consequent environmental impacts. Sometimes such impacts will be small and not readily identifiable, while in other cases, they may be much more dramatic, such as in the drying up of springs and streams in western Kansas. However, there is always a *time lag* between groundwater extraction and reduction in natural discharge, and therefore the current apparent health of an exploited aquifer and the ecosystems that depend upon it does not necessarily indicate that the situation will be sustainable in the longer term (Cook et al. 2001). The task of groundwater managers is to determine what limits of environmental impact are acceptable to the community and to manage extraction to maintain impacts within those limits.

Once the groundwater system is sufficiently perturbed, even cessation of pumping may not stop the adverse impacts. The impact of pumping persists for a variable time after pumping is stopped. The time lag between groundwater extraction and reduction in natural groundwater discharge will depend on the extraction rate of groundwater relative to the natural recharge and discharge rates. For an aquifer discharging to a stream, this time lag is proportional to the square of the distance of groundwater pumping from the stream and inversely proportional to the hydraulic diffusivity of the aquifer (usually expressed as the ratio of aquifer transmissivity to storativity). For relatively large groundwater basins with low recharge fluxes, this time lag can be many hundreds of years (Sophocleous 1998b, 2000a). In some cases, this allows groundwater extraction at rates well in excess of recharge rates to continue for a number of years before the impact of this policy can be recognized.

Changes in land use, such as intensive irrigation, oftentimes result in increased deep drainage, which creates a pressure front that moves down through the soil towards the water table (Jolly et al. 1989). Until the pressure front reaches the water table, aquifer recharge continues at the same rate as it did before irrigation development. When the pressure front reaches the water table, aquifer recharge increases, causing the water table to rise. The time lag between the increase in deep drainage and the increase in aquifer recharge is related to the deep drainage rate, the initial water table depth, and the soil water content within the unsaturated zone. Assuming purely diffuse flow, a uniform profile, and a constant velocity of the pressure

front, this time lag, t_L can be approximated as (Jolly et al. 1989; Cook et al. 1989)

$$t_L = D(\theta_w - \theta_d)/\Delta R, \quad (1)$$

where D is the depth to the water table, ΔR is the change in deep drainage rate, θ_d is the soil water content of the soil before irrigation development, and θ_w is the mean soil water content above the pressure front after irrigation development. Usually, θ_w and θ_d are approximated by the water contents below and above the pressure front, respectively. For example, if the water table is 45 m below land surface (typical of southwestern Kansas) and the deep drainage rate increases 25 mm/yr (due to irrigation development), resulting in an average subsurface moisture increase of approximately 8%, the time lag between the increase in drainage and the increase in recharge is estimated to be 144 years under the idealized conditions governing Eq. (1). Thus, the impacts of land use changes vis-à-vis groundwater recharge and discharge can take many years to manifest.

Groundwater recharge in the Kansas High Plains Aquifer

As mentioned earlier, the groundwater recharge rate and its spatio-temporal variability is a critical component of the water balance with respect to sustainability. Recharge, however, is difficult to estimate, especially in dry areas. A recent study funded by the Kansas Water Resources Institute (Sophocleous 2004) compiles, analyzes, and synthesizes most groundwater recharge studies in the Kansas High Plains and related aquifers that have quantified groundwater recharge. These recharge studies can be divided into the following four categories: (1) regional climatic soil-water balance studies, (2) regional groundwater modeling or analysis studies, (3) Kansas basin- to county-scale groundwater studies, and (4) field-based experimental studies at the local level. The following discussion will highlight only one (or two) studies from each category, including some original new findings as well (Sophocleous 2004). As previously mentioned, the results of these recharge studies are believed to be characteristic of the entire High Plains aquifer in the USA.

Climatic soil-water balance studies on regional scales

Two major regional climatic soil-water balance studies have been conducted by the USGS, one for the state of Kansas as a whole (Hansen 1991), and the other for the entire High Plains aquifer (Dugan and Zelt 2000). Because of their importance and the adoption of the Hansen (1991) study by the Division of Water Resources of the Kansas Department of Agriculture in the cases where more specific recharge data were not available, those studies are briefly analyzed here.

USGS study on natural recharge for principal aquifers in Kansas

Hansen (1991) estimated “potential natural recharge” for the entire state of Kansas by extending the results of the soil-water budget model and methodology employed by Dugan and Peckenbaugh (1985) for the Central Midwest Regional Aquifer Systems Analysis (CMRASA) in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, South Dakota, and Texas, to the High Plains aquifer of Kansas. Potential natural recharge refers to the deep drainage rate of soil water (made available from precipitation) below the root zone, where the water is presumed to be below the zone of influence of evapotranspiration processes, and thus potentially available to move downwards towards the water table and eventually recharge the aquifer.

The soil-water balance approach accounts for soil water entering, leaving, and remaining within the root zone, and can be summarized in the following simple equation:

$$R = ASW + P - SRO - AET - SC, \quad (2)$$

where R = potential recharge (deep percolation), ASW = antecedent soil water within the root zone, P = precipitation, SRO = surface runoff, AET = actual evapotranspiration, and SC = total available soil water storage capacity of the root zone. All the above components are expressed in length units per month.

The soil-water balance approach emphasizes the physical factors (climate, soils, and vegetation) that determine the availability of water for recharge and consumptive water use. Observed monthly climatic data from numerous weather stations in Kansas were compiled for the period of study (1951–1980). Land use data, by county, which provided vegetation patterns, were derived from 1978 statistics collected for the Census of Agriculture (U.S. Dept. of Commerce 1980). Changes in vegetation over the period of study were considered small and thus neglected. The soils information was derived from Natural Resources Conservation Service (NRCS) reports and other soil-compilation studies. The resultant distribution of potential natural recharge is shown in Fig. 1.

Numerous simplifications and approximations were used in estimating potential natural recharge, producing relatively large uncertainties in the results. Equating deep drainage to aquifer recharge assumes that the immediate underlying aquifer is unconfined and true water table conditions exist, and that all water that passes through the root zone into the unsaturated zone below ultimately reaches the underlying aquifer. In addition, aquifer properties were not taken into account in determining potential recharge, nor were return flow from irrigation and underflow from areas outside Kansas considered in the Hansen (1991) study. Finally, the results of that study were not calibrated or compared to actual measurements or more detailed estimates. Because of the general nature of that study (generalized vegetation, land use, and soil characteristics, as well as generalized relationships between consumptive water requirements and potential

Table 1 Comparison of deep percolation for irrigated conditions (DPI) with deep percolation for non-irrigated conditions (DPD) for selected soils and crop types at Kearney, NE, and Holyoke, CO, 1951–1980. (All values rounded to the nearest mm/yr; adapted from data in Dugan and Zelt 2000)

| Crop Type | Clay-Silty Clay Loam soil; flat to undulating topography | | | Silty Loam to Loam soil; flat to undulating topography | | |
|--|---|-----------------|-----|---|-----------------|-----|
| | DPI | % irrig. return | DPD | DPI | % irrig. return | DPD |
| Kearney (mean annual precipitation = 623 mm) | | | | | | |
| Corn | 75 | 7.4 | 70 | 111 | 4.4 | 106 |
| Sorghum/Soybeans | 119 | 6.4 | 112 | 160 | 4.4 | 153 |
| Alfalfa | 25 | 25.5 | 19 | 31 | 17.5 | 25 |
| Holyoke (mean annual precipitation = 448 mm) | | | | | | |
| Corn | 21 | 12.3 | 18 | 36 | 8.5 | 33 |
| Sorghum/Soybeans | 45 | 9.0 | 41 | 70 | 5.8 | 66 |
| Alfalfa | 2 | 42.9 | 1 | 3 | 30.8 | 2 |

evapotranspiration), caution should be exercised in directly applying the results to specific areas.

Nonetheless, such an analysis provides valuable insights into the hydrologic system in an area. The spatial patterns of potential recharge and consumptive water use, systematically derived from measurable climatic, soil, and vegetation characteristics, are of great use to water resources managers and planners. The overall patterns of resultant recharge (Fig. 1), which are similar to the spatial distribution of mean annual precipitation in Kansas, indicate that the controlling elements are the climatic factors themselves, particularly precipitation. One can generalize that as precipitation declines, both the magnitude and proportion of precipitation contributed to recharge decline and that areas of high, cool-season precipitation tend to receive higher amounts of recharge (Dugan and Peckenbaugh 1985). Smaller variations within local areas, however, are related to differences in soils and vegetation. The effect of soils, for example, is apparent in the westward extension of potential recharge isopleths in the Equus and Great Bend Prairie aquifer components of the High Plains aquifer in south-central Kansas as well as in the Arkansas River sand dune areas in southwestern Kansas that coincide with sandy soils (Fig. 1). The role of vegetation is less apparent because regional vegetation changes are usually gradual (Dugan and Zelt 2000). However, in areas where precipitation and soils are similar, potential recharge tends to be larger for cropland than for natural vegetation.

USGS study of soil-water conditions in the Great Plains

Dugan and Zelt (2000) expanded the CMRSA study (Dugan and Peckenbaugh 1985) to the Great Plains and adjacent areas, including the entire Kansas High Plains aquifer. A major difference of this study to the previous regional climatic soil-water balance studies of Dugan and Peckenbaugh (1985) and Hansen (1991) was that the impacts of irrigation on recharge were considered. Thus, the soil-water balance, computed monthly over the period 1951–1980, is summarized by the following simplified equation—compare to Eq. (2):

$$R = ASW + P + I - SRO - AET - SC \quad (3)$$

where I = irrigation water required in length units per month, and all other terms are identical to the ones shown

for Eq. (2). With the exception of incorporating irrigation return flow to recharge estimation, this study is subject to the same assumptions and limitations as in the previously mentioned USGS soil-water balance studies (Dugan and Peckenbaugh 1985; Hansen 1991), plus additional ones related to the introduction of the irrigation term (Zelt and Dugan 1993).

The Dugan and Zelt (2000) study is one of few that provides some insight into the impact of irrigation on deep drainage and recharge on a regional scale, although Sophocleous and McAllister (1987; 1990) clearly demonstrated such impacts on a basin scale. As expected, deep drainage under irrigated conditions is higher than under non-irrigated conditions. This increase does not result from excess irrigation but from an increased available water capacity in the root zone at the end of the irrigation season (Dugan and Zelt 2000) that maintains the soil profile wetter than otherwise possible, thus making infiltrating precipitation more effective in creating soil-water surpluses available for deep drainage. A comparison of deep drainage under irrigated and non-irrigated conditions for similar soils and crop types at two selected sites is shown in Table 1.

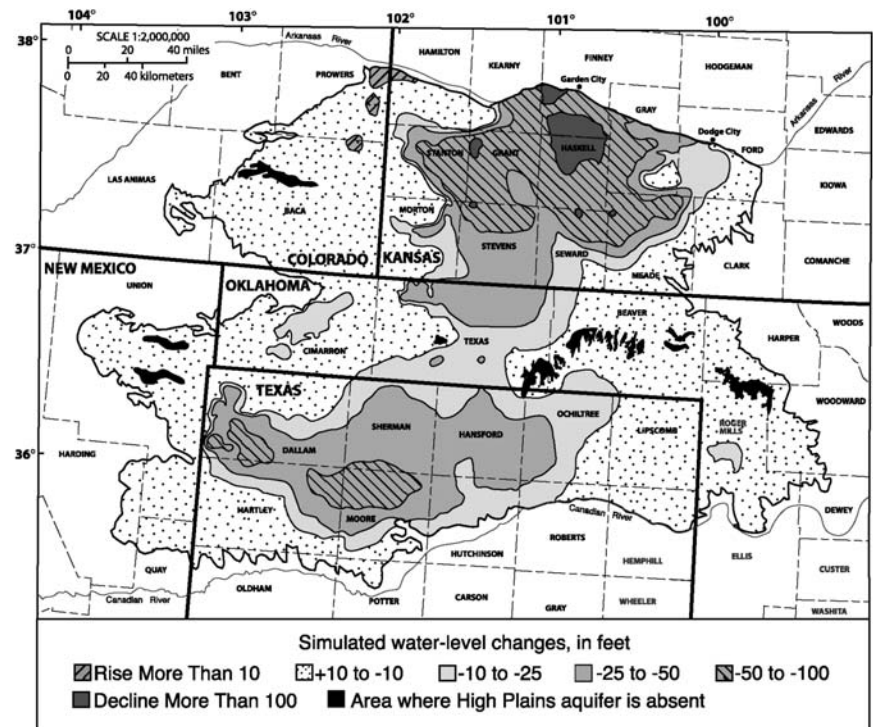
Although the absolute variations between deep drainage under non-irrigated and irrigated conditions are relatively small, the percentage differences can be considerable, particularly when deep drainage is small. The average percentage difference between deep drainage under irrigated and non-irrigated conditions for all soil- and crop-type combinations considered (Dugan and Zelt 2000) was 13% at Kearney, Nebraska and 24% at Holyoke, northeastern Colorado (Fig. 1). Generally, in areas where cultivated crops are prevalent, the potential recharge is larger than in grassland areas with similar climatic and soil conditions. It should be noted, however, that the potential recharge increase under irrigated conditions does not necessarily coincide with a net gain by the underlying aquifer under groundwater-irrigated conditions (Dugan and Zelt 2000). This gain, derived from an increase of water in the root zone, is at the expense of groundwater in aquifer storage. Finally, one needs to be aware that the results presented here are from simulations of generalized climatic, soil, vegetation, and land use conditions, and that actual measurements are needed to determine the irrigation return flows under various environmental conditions.

Table 2 Comparison of mean annual deep drainage (potential recharge) in combined non-irrigated and irrigated conditions for actual vegetation with deep drainage under non-irrigated conditions in grassland for clay-silty clay loam soil at selected sites, 1951–1980

| Site | Land Use | Predominant vegetation types | Mean annual precipitation (mm) | Mean annual potential evapotranspiration (mm) | Potential recharge for combined irrigated and nonirrigated conditions (mm) | Grassland potential recharge (mm) |
|---------------------------|------------------------|------------------------------|--------------------------------|---|--|-----------------------------------|
| Grand Forks, North Dakota | non-irrigated cropland | Fallow, SG | 464 | 711 | 102 | 40 |
| Clay Center, Nebraska | irrigated cropland | Grassland, HRC | 668 | 1143 | 109 | 92 |
| Sharon Springs, Kansas | non-irrigated cropland | Fallow, SG | 465 | 1473 | 15 | 8 |
| Muleshoe, Texas | irrigated cropland | Fallow, HRC | 408 | 1727 | 7 | 0 |

(all values rounded to the nearest mm; adapted from Dugan and Zelt 2000) *SG* = small grain; *HRC* = high-water-demand row crops (corn, cotton)

Fig. 2 Simulated water-level changes in the central High Plains for 1998–2020 using mean 1996–1997 pumpage. To convert feet to meters multiply by 0.3048 (adapted from Luckey and Becker 1999)



The Dugan and Zelt (2000) study also compared simulated deep drainage for actual crops at four sites in North Dakota, Nebraska, Kansas, and Texas, which are predominantly in cultivation, with deep percolation for natural grassland only at those sites for clay-silty clay loam soil (Table 2). All sites showed that recharge was considerably greater under actual cultivated conditions than under grassland conditions alone (Table 2). Fallow conditions tend to increase the difference between potential recharge under irrigated and non-irrigated conditions (Table 2; Dugan and Zelt 2000). The low potential recharge for both conditions at Sharon Springs, Kansas, and Muleshoe, Texas (Fig. 1), as compared to those at Grand Forks, North Dakota, and Clay Center, Nebraska, was a result of the larger potential evapotranspiration at those sites (Dugan and Zelt 2000).

Large-area groundwater modeling

Among regional groundwater modeling studies, one relatively recent USGS study (Luckey and Becker 1999) focuses on the High Plains aquifer in Oklahoma and adjacent areas, and includes the High Plains aquifer of southwestern Kansas. Luckey and Becker (1999) applied and calibrated a more spatially detailed finite-difference numerical model for the central High Plains (exclusive of the High Plains area south of the Canadian River, Fig. 2) than the one used in an earlier USGS Regional Aquifer Systems Analysis (RASA) study (Luckey et al. 1986). They employed a single-layer, two-dimensional MODFLOW model (McDonald and Harbaugh 1988) using a uniform grid-cell size of 1.83-km \times 1.83-km (3.35-km 2). The flow model had an active cell area of 70,479 km 2 , including all of southwestern Kansas south of the Ar-

Kansas River (Fig. 2). They calibrated the model for both predevelopment (pre-1946) or steady-state conditions, and development (1946–1997) or transient conditions.

Predevelopment period simulation

To estimate recharge from precipitation, the model area was divided into zones of greater or lesser recharge. The zones of greater recharge represented either sand dunes or areas of extremely sandy soils, whereas the zones of lesser recharge represented the remainder of the area (Luckey and Becker 1999). The calibrated mean recharge value for the zones of higher recharge was almost 18 mm/yr, which represents 4% of the mean 1961–1990 precipitation in the area (419 mm/yr). The mean recharge for the areas of lesser recharge was almost 2 mm/yr, which represents about 0.37% of the mean precipitation in the area. The predevelopment, overall mean simulated recharge from precipitation was almost 4 mm/yr.

Development-period (1946–1997) simulation

The development period was simulated using five stress periods of 10 years each from 1946 to 1995, and one stress period of two years (1995–1997). Pumpage was assumed constant within each stress period and was the average of estimated pumpage for all years within the period. Water use for irrigation was estimated based on Census of Agriculture data (U.S. Dept. of Commerce, 1949–1992) for the period 1946–1997 using the method outlined by Heimes and Luckey (1982) that consists of estimating irrigation use as the product of calculated irrigation demand (based on a modified Blaney-Criddle method—Blaney and Criddle 1962), reported irrigation acreage, and assumed irrigation efficiency. The estimated pumpage was based on mean 1961–1990 monthly precipitation and temperature. Time steps used in the simulation were 36.5 days. Pumpage was also assumed to occur throughout the year, although most pumpage actually occurred during the summer.

Simulated recharge due to irrigation averaged 24% of pumpage for the 1940's and 1950's; 14% for the 1960's; 7% for the 1970's; 4% for the 1980's; and 2% for the 1990's (Luckey and Becker 1999), apparently reflecting improvements in irrigation efficiency with time. Recharge due to irrigation was subtracted from total pumpage before the simulation was made, so only net pumpage was input into the model. This operation means that recharge due to irrigation was assumed to occur within the same stress period as the pumpage. Given the relatively deep water table depths in western Kansas and the resulting approximate estimated time lags (Eq. (1), this assumption may be of questionable validity.

Recharge due to dryland cultivation was estimated to be 3.9% of the mean 1961–1990 precipitation of 419 mm/yr or 16 mm/yr over the area in dryland cultivation (which also included irrigated wheat). Over the entire study area, dryland cultivation recharge amounted to 6 mm/yr. Thus, total simulated recharge in the development-period model consists of almost 4 mm/yr background recharge from precipitation, 6 mm/yr due to dryland cultivation, and

about 0.5 mm/yr due to irrigation, totaling approximately 10 mm/yr recharge from all sources.

Simulated water-level changes in southwestern Kansas for 1998–2020, using mean 1996–1997 pumpage, indicate more than 30-m declines in Finney and Haskell Counties (Fig. 2). A summary of simulated water budgets indicated that groundwater storage over the Central High Plains study area is projected to decrease by 60.4 km³ (or 858 mm) from the end of 1997 to the beginning of 2020 (Luckey and Becker 1999).

Basin-scale to county-scale groundwater studies

A significant county-scale groundwater study is the Finney County groundwater study in southwestern Kansas by Meyer et al. (1970). Meyer et al. (1970) conducted a detailed study of recharge from streams, precipitation, return flow from irrigation, and inflow through the aquifers (Arkansas River valley alluvium and Ogallala aquifers) in Finney County, Kansas (Fig. 2). They developed a detailed water budget for all of Finney County minus the panhandle area (a total of 24 townships or 223,777 ha) using the following equation: *Total Recharge = Change in Storage + Total Discharge*, where all elements of the right-hand side of the equation were observed or estimated, and *Total Discharge = well pumpage + (lateral groundwater outflow – inflow) + streamflow seepage* (positive for baseflow, negative for streamflow losses). Data from the 24-year period (1940–1964) were used in the calculations. Observed values of the components on the right-hand side of the equation are summarized in Table 3.

Thus, the average recharge indicated by the water-balance equation for the 24-year period (1940–1964) was 152,952 megaliters per year (ML/yr) or approximately 68 mm/yr over the area. If the groundwater system were considered to be under near-equilibrium conditions before pumping began, the components in the water balance equation would be as shown under column (3) “Predevelopment conditions” of Table 3. However, historic streamflow records for the period 1922–1930 indicate a seepage loss from the Arkansas River between Syracuse and Garden City (Fig. 1) of 25,903 ML/yr or almost 12 mm/yr over the study area. The long-term average predevelopment recharge to the aquifer was approximately 11 mm/yr (based on 1922–1930 conditions) or even two orders of magnitude less (based on the 1940–1964 conditions).

Thus, according to Meyer et al. (1970), the estimated development-conditions recharge rate of approximately 68 mm/yr probably reflects an additional recharge resulting from recycled groundwater from irrigation and an accompanying increase in effective recharge from precipitation on the irrigated land. Note that the Meyer et al. (1970) study lumps together the Arkansas River alluvial aquifer, characterized by sandy sediments and a shallow water table, and thus high recharge, with the deeper but hydraulically connected Ogallala Formation aquifer proper, characterized by a deep water table and much less recharge. The change in land use from native grassland to

Table 3 Water-balance components for the Finney County study area (223,777 ha), based on data for 1940–1964. (Values in rounded mm/yr; data from Meyer et al. 1970)

| Budget item | Development conditions | Predevelopment conditions ¹ | 1922–1930 Predevelopment conditions |
|---|------------------------|--|-------------------------------------|
| (1) | (2) | (3) | (4) |
| Change in storage | -13 | 0 | 0 |
| Well pumpage | 81 | 0 | 0 |
| Lateral groundwater outflow – inflow | 1 | 1 | 1 |
| Net seepage loss from Arkansas River | -1 ² | -1 ² | -12 ³ |
| Recharge (from precip. and irrigation return) | 68 | 0.2 | 11 |

¹ Predevelopment conditions (1940–64 period) assuming zero pumpage and zero change in storage

² Corresponding to 2,097 megaliters/yr

³ Corresponding to 25,903 megaliters/yr

cropland is a factor contributing to increased recharge. As the water table is lowered by pumping, the groundwater evapotranspiration losses are also reduced and the effective recharge to the aquifer is increased.

In addition to county-scale studies, integrated watershed and groundwater models on basin scales have been applied successfully in Kansas. These involved combining the groundwater flow model MODFLOW with the agricultural watershed models SWAT [in the case of the Rattlesnake Creek basin in south-central Kansas (Sophocleous et al. 1999), a part of the Great Bend Prairie aquifer unit (GB in Fig. 1) of the High Plains aquifer, resulting in an average area-weighted total recharge of 53 mm/yr over the 1955–1994 period but with high variability], and POTYLDR [in the case of the Wet Walnut Creek basin in west-central Kansas (Ramireddy-gari et al. 2000), an associated aquifer to the Great Bend Prairie aquifer unit, resulting in an average total recharge of 48 mm/yr over the 1960–1996 period, but also with high variability]; the reader is referred to the publications already mentioned, plus Sophocleous and Perkins (2000), for more information on these developments.

Field-based experimental recharge studies at the local scale

A recent study falls under the fourth category of field-based experimental studies at the local level. This is a deep vadose zone study of groundwater recharge in the High Plains aquifer of southwest Kansas (Sophocleous et al. 2002), although additional field-based experimental studies have been conducted by Prill (1968, 1977) in southwestern Kansas, and by Sophocleous (1992, 2000c) in south-central Kansas. Recent improvements in technology have made it possible to study the deep vadose zone, well below the rooting depths of plants. Such technology has been employed to monitor, on a continuous basis, the deep pore-water fluxes en route to the Ogallala aquifer. The proof-of-concept pilot study by Sophocleous et al. (2002) provided, for the first time, information on the quantity and pattern of water fluxes in the deep vadose zone that impact the management of both the quantity and quality of the Ogallala aquifer in Kansas. That pilot investigation evaluated the use of heat-dissi-

pation sensors and advanced tensiometers for measuring pore-water pressures in deep boreholes at two irrigated land-use sites, located in southern Finney County (Sites 1 and 2, Fig. 1) and one natural grassland site, located in the Cimarron National Grassland in Morton County (Site 3, Fig. 1). Continuous time-series data obtained from the heat-dissipation sensors (installed at a depth of 35.4 m at the irrigated sites and at 41.8 m at the grassland site) revealed constant pore-water pressures with time over the May 2000–September 2001 monitoring period, as exemplified in Fig. 3 from one of the monitored sites in an irrigated land-use setting in southwestern Kansas (see also Table 4).

The observed time-series patterns of pore-water pressure head in the deep vadose zone of the High Plains imply homogenization at depth of near-surface, temporally varying water fluxes. This results in much lower-intensity, but nearly constant recharging fluxes to the High Plains aquifer.

The measured average hydraulic-head gradients for all sites, together with the estimated recharge fluxes based on Darcy's law, are shown in Table 4. It is interesting to note that the hydraulic-head gradients between the deepest heat-dissipation sensor and the groundwater level at each site were approximately 0.75 for Sites 1 and 2, but was nearly zero for Site 3.

Darcian methodology was used to obtain estimates of recharge at all three investigation sites. As Table 4 shows, estimated recharge rates for the irrigated land-use sites (1, 2) were appreciably higher (3 mm/yr and 0.5–1.0 mm/yr, respectively) than the estimated recharge rate for the natural grassland site (Site 3), which was less than 0.25 mm/yr. In all cases, the estimated annual recharge values were less than 1% of annual precipitation. These results indicate that water for irrigated agriculture exceeded natural precipitation as the predominant source of recharge to the Ogallala aquifer. Although the large uncertainty associated with these estimates and the small number of study sites precludes using these flux estimates alone to draw firm conclusions regarding present-day recharge in the region, the irrigated and natural grassland sites selected are representative of irrigated and grassland

Fig. 3 Time series of pore-water pressure head data from heat-dissipation sensors (HDS) at the indicated depths for irrigated land-use (Site 1) in southern Finney County, southwestern Kansas. The heat dissipation (HD) sensors took appreciable time to equilibrate with the surrounding soil (Sophocleous et al. 2002)

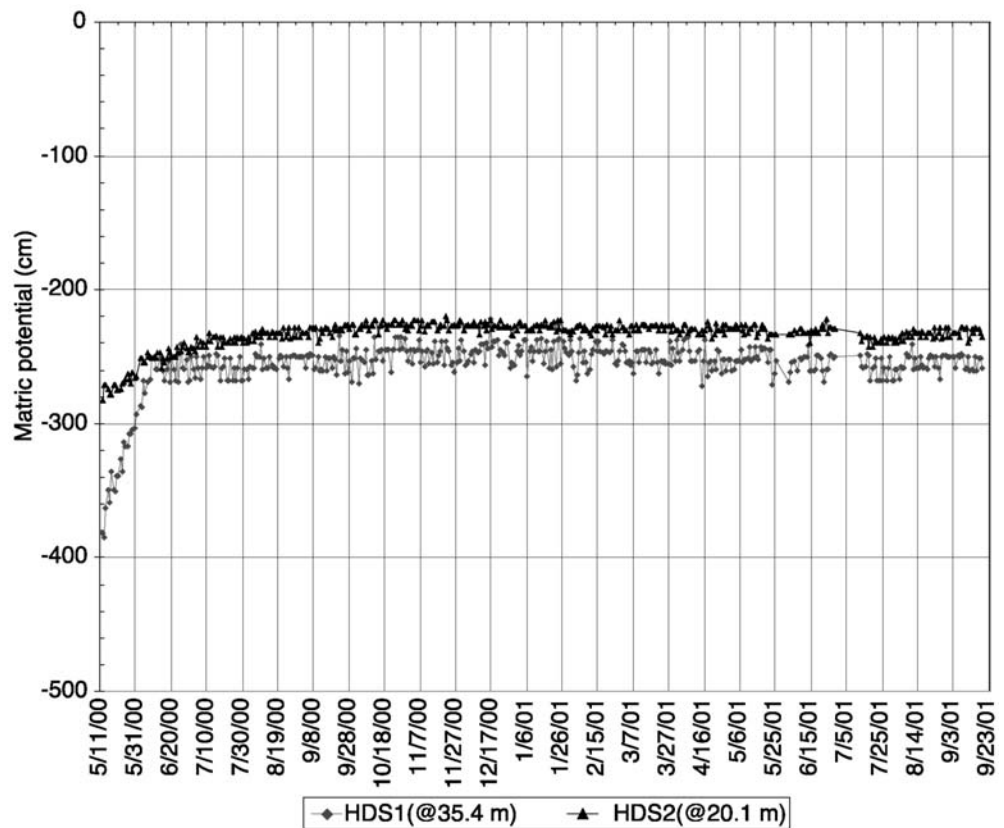


Table 4 Measured hydraulic-head gradients and estimated water fluxes in deep, unsaturated High Plains sediments based on heat-dissipation (HD) sensors. Site locations are shown in Fig. 1. (Adapted from Sophocleous et al. 2002)

| Site ID | County and legal location description | Land use | HD sensor depth locations (m) | Avg depth to water level (m) | Hydraulic head gradient ¹ (dimension-less) | Direction of flow | Estimated Darcian water fluxes ² (mm/yr) |
|---------|---------------------------------------|-----------------------|-------------------------------|------------------------------|---|-------------------|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 1 | Finney 26S-32W-21adc | irrigated cropland | 20.1; 35.4 | 45.3 | 1.01 | downwards | 3 |
| 2 | Finney 26S-31W-31ccd | irrigated cropland | 9.5; 35.4 | 45.6 | 0.86 | downwards | 0.5–1 |
| 3 | Morton 34S-41W-25ada | native grassland | 23.5; 41.8 | 50.0 | 0.47 | downwards | 0.1–0.25 |

¹ Gradient taken between the two HD sensor depth levels indicated in column 4.

² Assuming arithmetic average of the two unsaturated hydraulic conductivities at the HD sensor depth levels shown in column 4. The hydraulic conductivities are based on laboratory-measured saturated hydraulic conductivity values and water retention curves, all determined from undisturbed cores collected by the U.S. Geological Survey laboratory in Sacramento, CA. The RETC fitting program (van Genuchten et al. 1998) was used to quantify the hydraulic properties of the collected cores. The relative water-flux error was estimated by Sophocleous et al. (2002) to be at least 102%.

areas overlying the High Plains aquifer in southwestern Kansas.

The U.S. Geological Survey conducted several chemical and tracer analyses at the aforementioned sites. Chloride profile analysis of the grassland site indicated that the recharge flux below the root zone ranged from less than 2.5 to almost 10 mm/yr, with an average of approximately 5 mm/yr, and that estimate is considered to be a long-term (on the order of hundreds of years) estimate of recharge at the grassland site (McMahon et al.

2003). At both irrigated sites bomb tritium and pesticides were detected in both the unsaturated and saturated zones (McMahon et al. 2003), which implies a much higher recharge rate at those sites than at the grassland site where neither were detected. These results apparently contradict the idealized conceptual model presented in Eq. (1), and imply that preferential flow, downward leakage through the annular space of improperly sealed wells, and/or focused recharge played a possible role in rapidly transmitting these substances to deeper depths.

Overall recharge assessment

A compilation and analysis of data from all western Kansas counties overlying the Ogallala aquifer (Fig. 1) that have quantified recharge estimates based on Kansas Geological Survey Bulletin publications (Sophocleous 2004) resulted in a mean recharge estimate of almost 8 mm/yr and a standard deviation of less than 4 mm/yr (sample number: 18 counties). A similar analysis based on county-recharge estimates compiled by the Kansas Water Resources Board (KWRB 1967) resulted in a mean recharge estimate for the Ogallala aquifer of almost 7 mm/yr with a standard deviation of approximately 3 mm/yr (sample number: 28 counties). The regional climatic soil-water budget studies as well as the regional groundwater modeling studies resulted in similar recharge values for the central (and Kansas) High Plains aquifer on the order of 10 mm/yr or less. The basin- to county-scale studies in Kansas resulted in higher recharge values than the regional studies mainly because the former studies covered river-alluvial valleys (with a generally shallow water table), which are associated with the High Plains aquifer. Finally, the field-based studies at the local scale resulted in variable recharge values depending on the climatic-soil-vegetation system of the study area. However, the small number of study sites located in the Ogallala aquifer proper resulted in similarly small recharge values as those for the regional recharge studies. It is difficult to say which recharge method of those employed results in the most accurate values because all methodologies have associated variable uncertainties and simplifications. Therefore, a combination of methodologies is the preferred way to deal with the recharge issue. Although knowledge of recharge in the Kansas part of the Ogallala aquifer is still appreciably limited, the overall consensus from the combination of existing analyses at both regional and local scales (selectively highlighted here and comprehensively reviewed in Sophocleous 2004) is that the estimated average recharge to the Ogallala aquifer in Kansas is of the order of less than 10 mm/yr, not enough to sustainably support the irrigation pumping taking place in the area.

The reported water use for 1990 and 2000 (www.kwo.org) in the three western Kansas Groundwater Management Districts (corresponding to O_1 , O_3 , and O_4 in Fig. 1), which practically encompass the entire Ogallala aquifer portion of the High Plains aquifer system in Kansas, are 4.27 million megaliters and 3.55 million megaliters, respectively, which correspond to approximately 475 mm/yr and 396 mm/yr, respectively over the total irrigated area in those Districts (totaling 0.89 million ha), or approximately 109 mm/yr and 91 mm/yr, respectively over the total area of the three western Groundwater Management Districts (totaling 3.91 million ha). Although the recent values of reported water use have been decreasing relative to reported values in earlier years, nevertheless it is obvious that the difference between water extraction and recharge water input is significant.

Forces of change and responses in the High Plains region

According to the report of the Committee on the Future of Irrigation (NRC, 1996), on which much of this section is based, and as the previously outlined western Kansas recharge assessment also indicated, farmers have been pumping water from the Ogallala aquifer at a rate that exceeds recharge by 12 to 40 times. With recharge shown to be miniscule in most areas, persistent mining of the aquifer will continue to reduce water availability, reduce well yields, and increase pumping lifts and associated costs. Thus, as water supplies become more scarce, higher water costs threaten the continued expansion of irrigation as well as the continued production and profitability of current irrigators. Irrigated acreage from the Ogallala is projected to decline in all states except Nebraska (which has the largest aquifer saturated thickness among all USA High Plains states) after 2020 (NRC 1996). The long-term result of aquifer mining will be a continuing shift to dryland farming and/or supplemental irrigation. The transition to dryland farming will increase vulnerability to soil erosion from the wind (NRC 1996). As a result of the above factors, the depletion of the Ogallala is likely to have serious socioeconomic implications, especially for small towns in the region.

Conventional farming in the High Plains region with abundant water use cannot succeed over a long period of time, and adjustments toward more self-sufficient systems are needed. What can farmers do to make the most of limited water supplies and increase the stability of their farming systems? Researchers at the University of California, Sustainable Agriculture Research and Education Program (Sustainable Agriculture newsletter, vol. 3, no. 3, Spring 1991), made the following recommendations:

- Improve the receptivity of rainfall catchment areas.
- Enhance soil water infiltration and soil-water holding capacity by increasing soil organic matter.
- Match water applications closely to crop needs.
- Improve the efficiency of irrigation systems.
- Reduce evapotranspiration with windbreaks.
- Try to begin the season with a full soil-water profile.
- Control weeds that could compete with the crop for valuable soil moisture.
- Plan ahead; determine what your water supply will be and then decide the acres that can be effectively irrigated with that amount of water.
- Select crops and growing seasons that use less water. Winter grains, for example, use significantly less water than summer field and vegetable crops.
- Know the critical stress periods of your crops and avoid drought stress during those developmental stages.

Perhaps the least controversial course of action for the High Plains region is to conserve water primarily by increasing irrigation efficiency (NRC 1996). As water costs rise, technologies and management practices that con-

serve both energy and water become more cost-effective and often essential to the continued profitability of irrigated farming.

In general, farmers in the High Plains have a range of choices for responding to high energy and water costs before abandoning irrigation (NRC 1996). These opportunities include improving pumping efficiency, installing tailwater reuse systems, reducing a sprinkler's operating pressure, irrigation scheduling, improving conveyance efficiency, monitoring soil moisture, shaping and leveling the land, irrigating alternate furrows, growing crops with lower water requirements or higher returns to water, and reducing the quantity of water delivered to a given crop. Other adjustments to increase irrigation efficiency include shortening row lengths for gravity-flow systems, converting to low-pressure sprinklers, and replacing worn sprinkler nozzles (Ellis et al. 1985, cited in NRC 1996), and converting to drip irrigation systems.

Improved farming systems also contribute to High Plains water conservation (NRC 1996). Minimum tillage, rotating a row crop such as sorghum with wheat or other small grains, and careful use of herbicides for weed control to reduce the number of implement trips across the fields can cut costs and maximize the use of water. Another improved-management practice is the limited irrigation-dryland system, in which the upper half of a field is fully irrigated, the next one-fourth is a tailwater runoff section using runoff from the fully irrigated section, and the lower one-fourth is managed as a dryland section solely dependent on rainfall. Throughout the High Plains, this system offers a higher water use efficiency than full or conventional irrigation (Gilley and Fereres-Castiel 1983, cited in NRC 1996).

New technologies have improved the efficiency of water use in irrigation in recent years (CAST 1988). For example, sprinkler systems now reduce the pressure to deliver water, include drop tubes to place the water in a furrow, and add appliances to apply chemicals (multi-function systems). Future technological innovations (in equipment, biotechnology, computer-based management systems) will further help farmers offset the impacts of higher water and energy prices. However, it is important to note that improved efficiency of water use and lower energy use often increases the desire for farmers to expand production to new acreage, thus eliminating any net benefit in water conservation. Thus the emphasis on irrigation efficiencies should be on net water savings to the aquifer system. Economic development assistance and incentives to help farming communities to move into dryland production will be required, and such programs need to be in place as soon as possible.

Technological developments for increasing water supplies in the High Plains aquifer are far less promising (NRC 1996). Experiments with artificial recharge to restore the aquifer have not resulted in any significant large-scale replenishment of the aquifer, with the central Kansas Equus Beds recharge enhancement pilot project being a significant exception. The High Plains Underground Water Conservation District No. 1 in the southern High

Plains of Texas has experimented with air injection, which sought to release water bound to sand particles in the desaturated zone. Although technically successful, the procedure is prohibitively expensive for the amount of water recovered (Opie 2000). Cloud seeding is equally unpromising in terms of cost (Opie 2000). Even if a cost-effective weather modification technology existed, there would be major institutional obstacles to its adoption (NRC 1996). Although cloud seeding has not been cost effective for increasing precipitation, it has apparently been effective in reducing crop damage by hail (Eklund et al. 1999).

Key steps necessary to move towards sustainable use of groundwater

The people of Kansas, through their citizen committees, their local and state agencies, and their Governor, are unanimous in their desire to extend and conserve the life of the Ogallala aquifer. The Kansas Water Plan objectives (<http://www.kwo.org>) call for a reduction in water-level decline rates within the Ogallala aquifer by 2010 and implementation of enhanced water management in targeted areas. The plan also calls for achievement of sustainable management of Kansas surface and groundwater sources outside of the Ogallala aquifer by 2015 (in central and eastern Kansas, where precipitation and aquifer recharge are generally greater than in the Ogallala region) and for meeting minimum desirable streamflow standards (established at 33 locations statewide) at a frequency no less than the historical achievement at time of enactment by 2015. In the long term, it is impossible to extract more water from an aquifer than is recharged to it by seepage from precipitation or surface water bodies. Sooner or later, the pumping rate will automatically have to adjust to the availability of water. Clearly, it is wiser to strike this balance when groundwater levels are high than at low levels, to provide leeway for temporal overdraft and, therefore, supply safety, and also because the cost of pumping increases as water levels decline.

The key steps to move toward sustainable use of groundwater are basic and commonsensical, but a sustainable groundwater management strategy can only be as good as its potential for implementation. Several of the following steps were outlined at the January 2002 "Expert Workshop on Freshwater in North America" at the University of Toronto, Canada (organized by the Commission for Environmental Cooperation of North America, www.cec.org/calendar), but they can be extended and applied to the High Plains conditions:

- Improve the knowledge base.
- Improve reporting and access to information.
- Improve public education and better understand the public's attitudinal motivations.
- Use the ecosystem approach to manage groundwater.
- Embrace adaptive management.
- Further improve water efficiency and crop productivity.

- Exploit the full potential of dryland and biosaline agriculture.
- Adopt a goal of sustainable use.

Improve the knowledge base: Our ability to effectively manage groundwater is hampered by gaps in our knowledge of the groundwater resource, including recharge rates and mechanisms, and the linkages between groundwater and surface water systems (Sophocleous 2002, among others). The Committee on USGS Water Resources Research has recently identified several key areas of research priorities, many of them directly applicable to the High Plains aquifer, such as— and in addition to the areas already identified above— aquifer management, aquifer storage and recovery, groundwater quality and movement in surficial materials, and characterization of aquifer heterogeneity at large and small scales (NRC 2000). Although obtaining additional and refined data and filling-in our knowledge gaps will always be an ongoing process, uncertainties will always remain, and therefore lack of complete knowledge should not be used as a reason for delaying action on needed changes. Being wise before it is too late is not easy, especially when the environmental or health impacts may be far into the future, and the costs of averting them are large and immediate. The precautionary principle (“better safe than sorry”) should be the overarching framework of thinking that governs the use of foresight in situations characterized by uncertainty and lack of knowledge, and where there are potentially large costs to both action and inaction (Harmoës et al. 2002).

Improve reporting and access to information: Our ability to assess the state of groundwater is limited not only by the knowledge gaps mentioned previously, but also because the information that does exist is scattered among many organizations, is often stored in different formats, is oftentimes incomplete, and is difficult to access. Easy and timely public access to data and information is key to achieving a participatory and inclusive approach to water management, and to building trust among the planners, regulators, and users.

Improve public education and better understand the public’s attitudinal motivations: Increasing education of the public on water issues and promoting awareness of water-efficient technologies should be a permanent goal of water management. The need for education cannot be overstated: sustainable groundwater use cannot be achieved without an aware and involved citizenry. That is why improvements in reporting and public access to information are so important. In addition, consideration of societal perceptions, attitudes, and values are extremely important in bringing about the necessary attitudinal and behavioral changes needed to embrace the ethic of sustainable development. Groundwater is a vital part of our life support system on this planet.

Use the ecosystem approach to manage groundwater: Groundwater, surface water, and aquatic systems are closely interrelated and thus cannot be managed and regulated independently (Sophocleous 2003). Although

the current emphasis in Kansas is in the “local” approach to management, groundwater resources also need to be planned and managed for maximum basin-level efficiency. Even though groundwater supplies are local in nature, their use, overuse, and contamination can have regional and national impacts. Thus the High Plains states need to come together to develop consistent and coordinated regulatory and management plans so that individual local and state conservation efforts are optimized.

Embrace adaptive management: As an alternative to a prescriptive or “blueprint” approach to resource management, adaptive management is characterized by feedback loops and a willingness to adjust assumptions, objectives, management actions, and outputs. In this regard, the most important element of adaptive management is the capacity to initiate and maintain long-term monitoring programs. The capacity to adjust management actions in response to monitoring is essential to achieving sustainability of the resource (Jenkins and Edwards 2000). Adaptive management provides a means to manage dynamic, variable, and complex systems that are characterized by chance and randomness, as is often the case with nature-human interactive systems (Sophocleous 1997; 2000a).

Further improve water efficiency and crop productivity: Achieving sustainable groundwater use requires that everyone uses water as efficiently as possible. This means removing the incentives to waste water, and providing incentives to conserve it. It also means adopting a system of water pricing that aligns the incentives for groundwater use with the goal of sustainability, mandating the use of water-efficient technologies in homes, businesses, and industries, and removing subsidies for growing water-intensive crops and tax exemptions for exhausting supplies. It is also important to achieve high value out of the use of water and not expend large volumes of water in low-value production.

Exploit the full potential of dryland and biosaline agriculture: Worldwide, dryland agriculture still produces approximately 60% of total cereals (Rosegrant et al. 2002). In Kansas, during 2000, dryland agriculture produced approximately 84% of the harvested wheat (Kansas Farm Facts; <http://www.nass.usda.gov/ks/ffacts/2002/ffacts.htm>). There is a need for exploiting the full potential of dryland agriculture through research and technology to relieve considerable pressure on irrigated agriculture and on water resources (Rosegrant et al. 2002). Such research and technology should focus on water harvesting technologies, crop breeding targeted to rainfed environments, agricultural extension services, and access to markets, credit, and input supplies in rainfed areas (Rosegrant et al. 2002). In addition, Kansas is endowed with appreciable quantities of brackish and saline water resources (Hargedine et al. 1978). Biosaline agriculture can be part of the solution to integrated water resources management by making use of salty water and salt-affected land (Al-Attar 2002). Promoting the use of saline water and salt-tolerant species to increase food and feed production has the potential of freeing up scarce

freshwater resources and bringing into production marginal areas where agriculture is currently not viable because soils are saline or water is brackish.

Adopt a goal of sustainable use: In order to avoid or reduce the severe ecological, social, and economic impacts of groundwater mining, we need to adopt as a management goal the long-term sustainability of groundwater resources. In other words, what is taken out of the aquifer should not be more than what goes in, with provisions made for ecosystem requirements (which means identifying threshold levels for streamflows, aquatic-riparian-terrestrial habitat changes, groundwater levels, water quality, and other thresholds, like land subsidence), thus ensuring that future generations have access to adequate amounts of clean groundwater. Fostering a long-term perspective to the management of groundwater resources is perhaps the most important attribute to the concept of sustainability as there may be circumstances that warrant temporary overpumping of an aquifer that could be balanced, for example, by intervening additions to groundwater storage. Fostering the long-term perspective also allows time for transition and readjustment to diminished groundwater availability for agriculture and to more effective use of rainfall in crop production.

Acknowledgments Funding support for this study by the Kansas Water Resources Institute is gratefully acknowledged. The author is indebted to the reviewers of the *Hydrogeology Journal* Thomas Burbey, Richard Luckey, and Assoc. Editor Ken Belitz, and the following individuals who read and commented on this paper: Susan Stover (Kansas Water Office), Allen Macfarlane, Rex Buchanan, Liz Brozius, Brownie Wilson (Kansas Geological Survey), and Rick Devlin (Dept. of Geology, The University of Kansas).

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