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From safe yield to sustainable development of water resources—the Kansas experience

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Abstract

This paper presents a synthesis of water sustainability issues from the hydrologic perspective. It shows that safe yield is a flawed concept and that sustainability is an idea that is broadly used but perhaps not well understood. In general, the sustainable yield of an aquifer must be considerably less than recharge if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and ground-water-dependent ecosystems. To ensure sustainability, it is imperative that water limits be established based on hydrologic principles of mass balance. To establish water-use policies and planning horizons, the transition curves of aquifer systems from ground-water storage depletion to induced recharge of surface water need to be developed. Present-day numerical models are capable of generating such transition curves. Several idealized examples of aquifer systems show how this could be done. Because of the complexity of natural systems and the uncertainties in characterizing them, the current philosophy underlying sustainable management of water resources is based on the interconnected systems approach and on adaptive management. Examples of water-resources management from Kansas illustrate some of these concepts in a real-world setting. Some of the hallmarks of Kansas water management are the formation of local ground-water management districts, the adoption of minimum streamflow standards, the use of modified safe-yield policies in some districts, the implementation of integrated resource planning by the City of Wichita, and the subbasin water-resources management program in potential problem areas. These are all appropriate steps toward sustainable development. The Kansas examples show that local decision-making is the best way to fully account for local variability in water management. However, it is imperative that public education and involvement be encouraged, so that system complexities and constraints are better understood and overly simplistic solutions avoided.

Keywords: Water sustainability; Safe yield; Transition curve; Stream-aquifer systems; Integrated resource planning; Kansas water management

1. Introduction

In general, the time has passed when abundant supplies of water were readily available for development at low economic, social, and environmental costs. Now we are in what Hufschmidt (1993) called the period of the "maturing water economy," with increasing competition for access to fixed supplies, a growing risk of water pollution, and sharply higher economic, social, and environmental costs of development. Few areas of public policy are as contentious as the management of our water resources.

Around the world, most of the easily developable water has been developed, and future water management will depend on obtaining more out of existing

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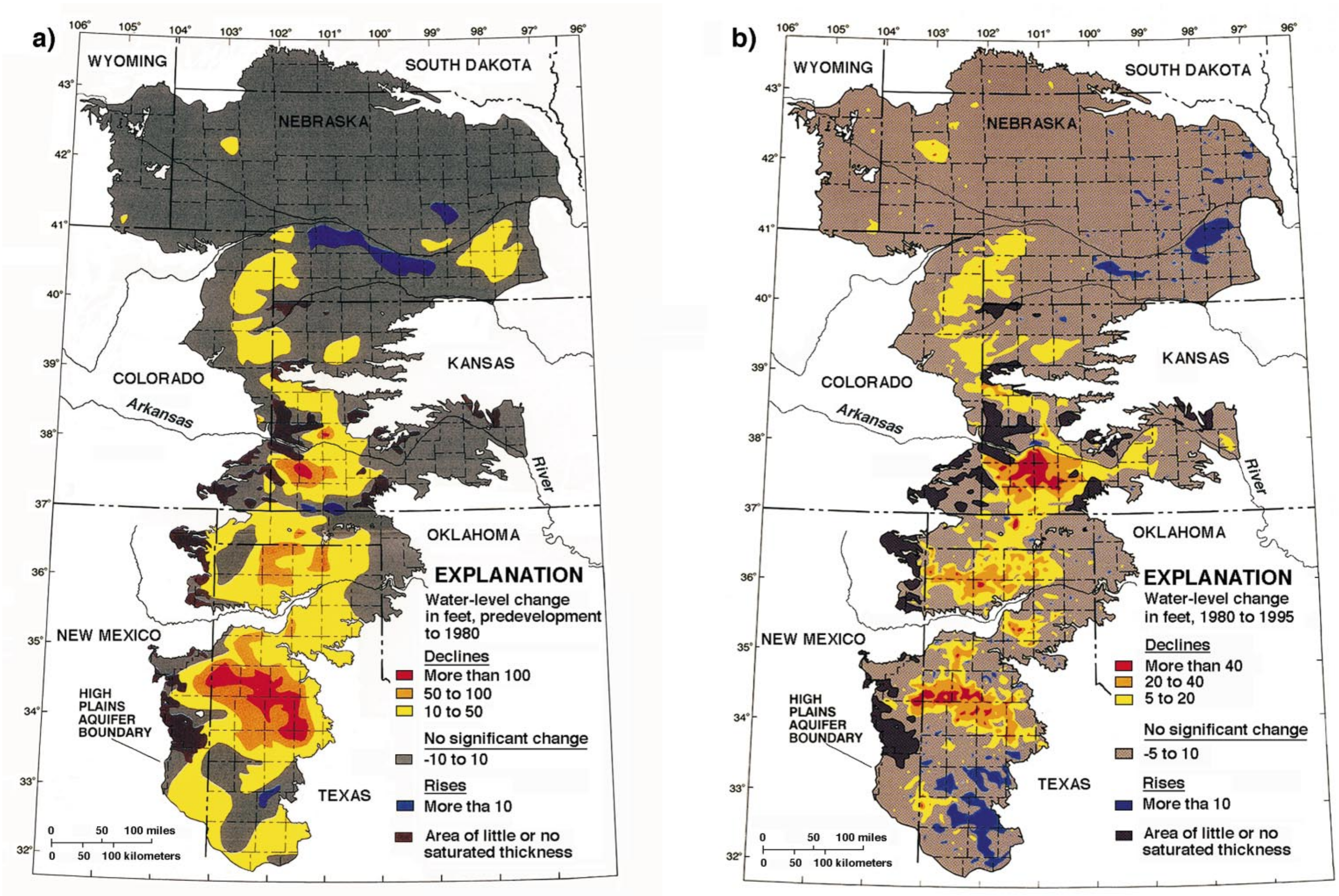


Fig. 1. Water-level changes (in ft) in the High Plans aquifer (A) predevelopment to 1980; (B) 1980–1995. To convert to meters multiply by 0.3048. Adapted from US Geological Survey (http://www-ne.cr.usgs.gov/highplains/hpactivities.html).

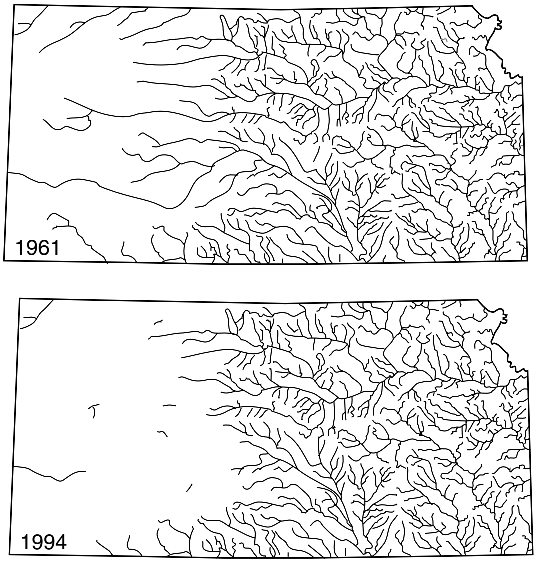


Fig. 2. Major perennial streams in Kansas, 1961 versus 1994 (adapted from Angelo, 1994).

supplies. The great challenge facing the world today is how to cope with the impact of economic growth on the environment. Sustainable development emerged during the late 1980s as a unifying approach to concerns about the environment, economic development, and quality of life. The World Commission on Environment and Development (1987), better known as the Brundtland Commission, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This intergenerational perspective implies that we must use the water resources in ways that are compatible with maintaining them for future generations, thus constraining *our* management of water.

Although progress has been made in defining the goals of sustainable development, the mechanisms to bring about these changes are still a matter of debate. The challenge is to turn the principles of sustainable development into achievable policies. The move from principle to practice is far from easy. Like other abstract concepts, sustainable development is a powerful and dynamic concept that will continue to be refined.

Science can explore the implications of different interpretations of sustainability, but it can not choose the "correct" interpretation for society. Nonetheless, if sustainable development of water resources is to have any meaning, it must be based on sound hydrologic analyses and appropriate technologies.

The objectives of this overview presentation are: (1) to explore the hydrologic underpinnings and shortcomings of the sustainability concept of safe yield as a basis for developing ground-water planning policy; (2) to provide a brief examination of our evolving broader environmental sustainability concepts; and (3) to highlight the path Kansas has taken towards achieving water sustainability, as a case example. This paper represents a critical synthesis of water sustainability issues from the hydrologic perspective. The focus on Kansas is intended to emphasize selected applications of the concepts presented.

2. Safe yield and underlying hydrologic fundamentals of the concept

2.1. Hydrologic principles

Safe yield is commonly defined as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge (Sophocleous, 1997; Sophocleous and Sawin, 1997). Therefore, safe yield allows water users to pump no more ground water than is replenished naturally through precipitation and surface-water seepage, generally known as natural recharge. But safe yield ignores the fact that over the long term under natural or equilibrium conditions, natural recharge is balanced by discharge from the aquifer by evapotranspiration or into streams, springs, or seeps. Consequently, if pumping equals recharge, eventually streams, marshes, and springs may dry up. Continued pumping in excess of recharge also may eventually deplete the aquifer. This has happened in several locations across the Great Plains (Sophocleous, 1998c). Probably the best-known example is the Ogallala or High Plains aquifer, where declines of more than 30 m over a 30-yr period were common in parts of Texas, New Mexico and Kansas (Fig. 1). Maps comparing the perennial streams in Kansas in the 1960 to those of the 1990 (Fig. 2) show a marked decrease in kilometers of streamflow in the western third of the state.

To understand this depletion, a thorough knowledge of the hydrologic principles (concisely stated by Theis, 1940) is required. Under natural conditions, prior to development by wells, aquifers approach a state of dynamic equilibrium: over hundreds of years, wet years in which recharge exceeds discharge offset dry years when discharge exceeds recharge. Discharge from wells upsets this equilibrium by producing a loss from aquifer storage; a new state of dynamic equilibrium is approached when there is no further loss or minimal loss from storage. This is accomplished either by an increase in recharge, a decrease in natural discharge, or a combination of the two.

Consider a stream-aquifer system such as an alluvial aquifer discharging into a stream. (Please note that I use the term "stream" in the broadest sense of the word; the issues, approach, and results also apply to rivers, lakes, ponds, and wetlands). A new well drilled at some distance from the stream and pumping the alluvial aquifer forms a cone of depression. The cone grows as water is taken from storage in the aquifer. Eventually, however, the periphery of the cone arrives at the stream. At this point, water will either start to flow from the stream into the aquifer, or discharge from the aquifer to the stream will appreciably diminish or cease. The cone will continue to expand with continued pumping of the well until a new equilibrium is reached in which induced recharge from the stream balances the pumping.

The length of time, t, before an equilibrium is reached depends upon (1) the aquifer diffusivity (expressed as the ratio of aquifer transmissivity to storativity, T/S), which is a measure of how fast a transient change in head will be transmitted throughout the aquifer system; and (2) upon the distance from the well to the stream, x. For radial flow of ground water, a tenfold increase in distance from the surface-water body causes a hundredfold delay in the response time, whereas a change in diffusivity is linearly proportional to the response time (Balleau, 1988). Generally, if the wells are distant from the stream, it takes tens or hundreds of years before their influence on streamflow is felt.

Once the well's cone has reached an equilibrium size and shape, all of the pumping is balanced by flow diverted from the stream. In that case, there is no difference between a water right to withdraw ground water from the well, as described, and a water right to divert from the stream at the same rate. A crucial point, however, is that before equilibrium is reached (that is, before all water is coming directly from the stream), the two rights are not the same (DuMars et al., 1986). Until the perimeter of the cone reaches the stream, the volume of the cone represents a volume of water that has been taken from storage in the aquifer, over and above the subsequent diversions from the stream. It is this volume that may be called *ground-water depletion*. Thus, ground-water sources include ground-water (or aquifer) storage and induced recharge of surface water.

2.2. Limitations of safe yield

The concept of safe yield is often associated with the annual exploitation of a single product—the number of trees cut, the number of fish caught, the volume of water pumped from the ground or river—without destroying the resource base (Sophocleous, 1997). However, other resources inevitably depend on, interact with, or flow from the exploited product. We can maximize our so-called safe yield of water by drying up our streams, but when we do, we find that the streams were much more than just containers of usable water. This is what happened with a number of streams in Kansas, such as the Arkansas River from western Kansas up to the city of Great Bend in south-central Kansas (the author visited the dry streambed of that river at multiple locations during the summer of 1985, and at other times), the Pawnee River, and other streams in west-central Kansas.

The conventional safe-yield approach is limited and restrictive. It fails to address the beneficial impacts of natural ground-water discharge on related ground-water-dependent ecosystems, and on the surface-water system in general. To many people, safe yield is equated with an annual yield on which a water user can rely. It is easily confused with a water right (i.e. a right under which a person may lawfully divert and use water). However, any change in conditions, such as changes in vegetation, land use, urbanization, location of pumping wells, incorporation of new water supplies, or climate change would require calculation of a new yield.

For example, closely spaced wells will cause much more rapid decline of local water levels than the same number of wells more widely dispersed. In some

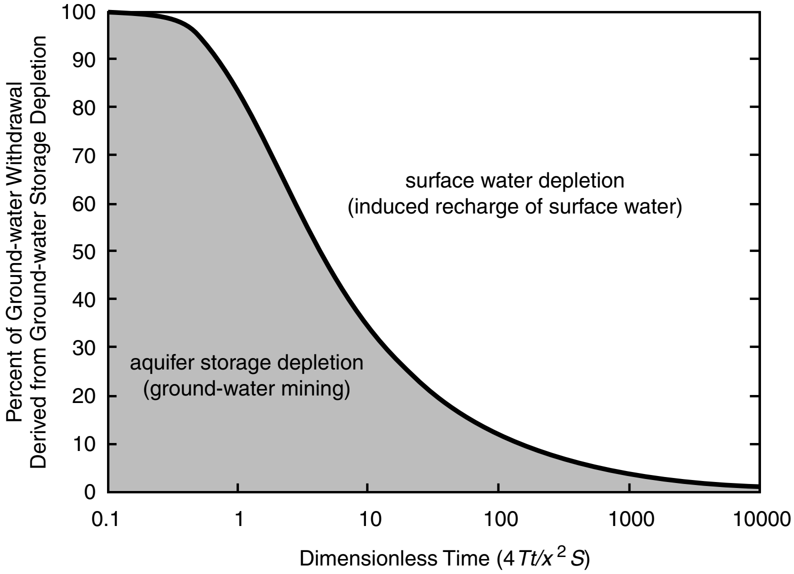


Fig. 3. Transition from reliance upon ground-water storage to induced recharge of surface water. *T* is transmissivity, *S* is storage, *x* is the distance from pumping well to stream, and *t* is time (adapted from Balleau, 1988).

basins the quantity of water in the aquifer governs the safe yield; in others, water quality is the limiting factor; in yet others, especially in confined aquifers with areas of recharge far away from pumping centers, the rate of flow towards the wells is the limiting factor. Changes in vegetation may affect surface infiltration and subsequent percolation to the water table. Clearly, no unique and constant value can be attached to safe yield.

The safe yield of an aquifer, in some instances, can be substantially augmented by engineering controls (ASCE, 1987). For example, more water can be made available through artificial recharge by spreading or injection wells, or by lowering ground-water levels to reduce evapotranspiration, to capture rejected recharge, or to capture surface water from streams. The amount of water production represented by "safe yield" is fixed at any point in time only in the sense that no more money may be available for engineering construction, or that other conditions (discussed above) remain unchanged, or that no more water may be legally obtained from any source (ASCE, 1987). Should these constraints be changed-for example, by the importation of water or the utilization of underground storage—safe yield could be increased.

The failures and unintended consequences of conventional and safe-yield approaches to water management provide some of the strongest incentives for retiring the concept. As the following examples show, such failures can have both local and regional consequences (Sophocleous et al., 1998).

- Ground-water pumping has dried up or threatened numerous reaches of baseflow-dependent streams, wetlands, and subirrigated land—with many examples found in Kansas along the fringes of the High Plains aquifer (some shown earlier), and in other states.
- Irrigation has contaminated the land in many areas. Increases in consumptive water use leave behind the salts dissolved in the water. The example of irrigation drainage water contaminating the ponds at Kesterson National Wildlife Refuge in California with toxic levels of selenium (NRC, 1989) is well known. Saline water from irrigation return flow into the Upper Arkansas River basin now threatens the ground-water resources of the alluvial and Ogallala aquifers in Kansas. The Kansas Geological Survey (Whittemore et al., 1999) is now embarked on a multi-year study to analyze the impact of Arkansas River salinity on the underlying alluvial and Ogallala aquifers in western

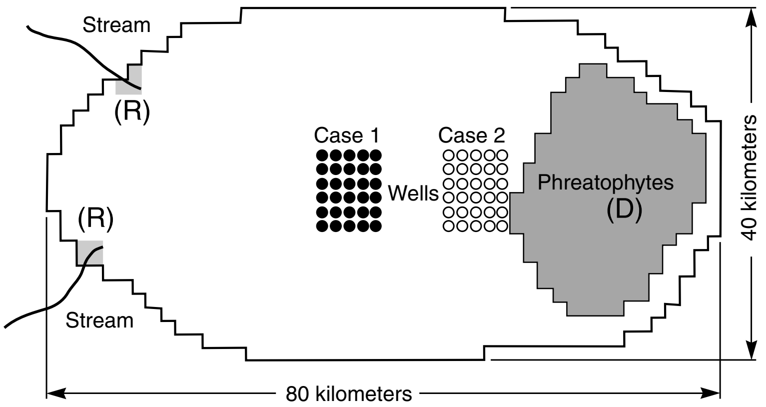


Fig. 4. Schematic map of an intermontane basin showing areas of recharge (R), Discharge (D), and two hypothetical water-development schemes, Case 1 and Case 2 (adapted from Bredehoeft, et al., 1982).

Kansas resulting from irrigation return flow in Colorado.

- Whole regional ecosystems change and disappear with large-scale water development—the Gulf of California has changed from an estuary to a marine lagoon as the Colorado River has been dried up. Nutrient runoff from the central US, including Kansas, has changed the ecology of the area surrounding the mouth of the Mississippi and led to the hypoxia problem in the Gulf of Mexico we witness today (Rabalais et al., 1991).

3. Developing a sound ground-water planning policy: some examples

As discussed previously in Section 2.1 on hydrologic principles, ground-water sources include aquifer storage and induced recharge of surface water. The timing of the change from storage depletion (or mining) to induced recharge from surface-water bodies is key to developing water-use policy (Balleau, 1988).

The shape of the transition or growth curve for an idealized, two-dimensional, homogeneous and isotropic system is shown in Fig. 3 in nondimensional form, based on Glover's (1974; Chapter 9) analytical solution and tabulation. In Fig. 3, the percent of ground-water withdrawal derived from ground-water storage is plotted on the *Y*-axis against dimensionless time (or normalized time, $t^* = \{4(T/S)/x^2\}t)$ on the *X*-axis. The general shape of the transition curve is retained in systems with apparently different boundaries and parametric values (Balleau, 1988). The rate at which dependence on ground-water storage (as shown at the left portion of the graph) converts to dependence on surface-water depletions (as shown on the right portion of the graph) is highly variable and is particular to each case. For example, if aquifer storage is 85% of the source of water after 1 month (or 1 year) of pumping, it will end up being only 5% of the water pumped coming from aquifer storage after 1000 months (or 1000 years) of pumping (Fig. 3).

The initial and final phases of the transition curve (Fig. 3), representing mining on the left and induced recharge on the right, are separated in time by a factor of nearly 10 000. As the example above showed, full reliance on indirect recharge takes an extremely long time. The distinct category of ground-water mining depends entirely upon the time frame. Initially, all ground-water developments mine water but ultimately they do not (Balleau, 1988). The eventual reduction in surface-water supply as a result of ground-water development, and the distinction between natural recharge and induced recharge complicates the administration of water rights.

Aquifer drawdown and surface-water depletion are two results of ground-water development that affect policy. Both are fundamentally related to pumping rate, aquifer diffusivity, location, and time of pumpage. The natural recharge rate is unrelated to

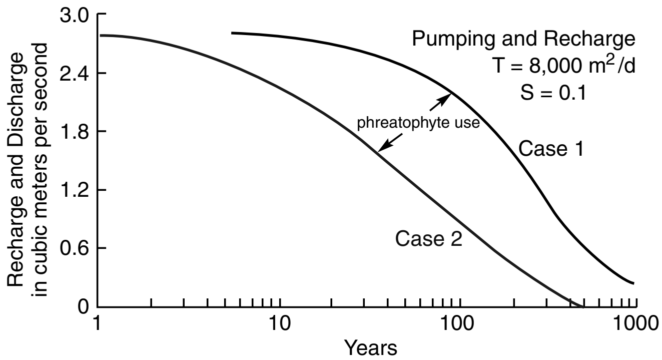


Fig. 5. Plot of the rate of recharge, pumping, and phreatophyte use versus time (adapted from Bredehoeft et al., 1982).

any of these parameters. Nonetheless, natural recharge is often used by policy makers to balance ground-water use, based ostensibly on a steady state (Balleau, 1988). As Balleau (1988) pointed out, public purposes are not served by adopting the attractive fallacy that the natural recharge rate represents a safe rate of yield.

To illustrate the influence of the dynamics of a ground-water system in response to development, Bredehoeft et al. (1982) chose a simple, yet realistic, system for analysis—a closed intermontane basin of the sort common in the western United States (Fig. 4). Under predevelopment conditions, the system is in equilibrium: phreatophyte evapotranspiration in the lower part of the basin (the natural discharge from the system) is equal to recharge from the two streams at the upper end. Pumping in the basin is assumed to equal the recharge. This system was simulated by a finite-difference approximation to the equations of ground-water flow (Bredehoeft et al., 1982) for one-thousand years. Stream recharge, phreatophyte-water use, pumping rate, and change in storage for the entire basin were graphed as functions of time. Two development schemes were examined: case 1, in which the pumping was more or less centered within the valley, and case 2, in which the pumping was adjacent to the phreatophyte area (Fig. 4).

The system does not reach a new equilibrium until the phreatophyte-water use (i.e. the natural discharge) is entirely salvaged or captured by pumping (Fig. 5). In other words, phreatophyte water use eventually approaches zero as the water table drops and plants die. In case 1, phreatophyte-water use is still approximately 10% of its initial value at year 1000 (Fig. 5). In case 2, it takes ~500 years for the phreatophyte-water use to be completely captured.

This example illustrates three important points (Bredehoeft et al., 1982). First, the rate at which the hydrologic system can be brought into equilibrium depends on the rate at which the discharge can be captured. Second, the placement of pumping wells changes the dynamic response and the rate at which natural discharge can be captured, and third, some ground water must be mined before the system can approach a new equilibrium. Steady state is reached only when pumping is balanced by capturing discharge and, in some cases, by a resulting increase in recharge. In many circumstances, the dynamics of the ground-water system are such that long periods of time are necessary before any kind of an equilibrium condition can develop. In some circumstances the system response is so slow that mining will continue well beyond any reasonable planning period.

A suitable hydrologic basis for a ground-water planning policy aimed at determining the magnitude of possible development would be a curve similar to the transition curve we saw earlier, coupled with a projected pattern of drawdown for the system under consideration. Since the 1980s, three-dimensional numerical models of the complete stream-aquifer hydrogeologic system have been used for water-rights purposes (Balleau, 1988). These models provide a predictive tool explaining the connection between well-field withdrawal and surface-water depletion at particular sites. Ground-water models are capable of generating the transition curve for any case by simulating the management or policy alternatives in terms of the sources of water from ground-water storage and

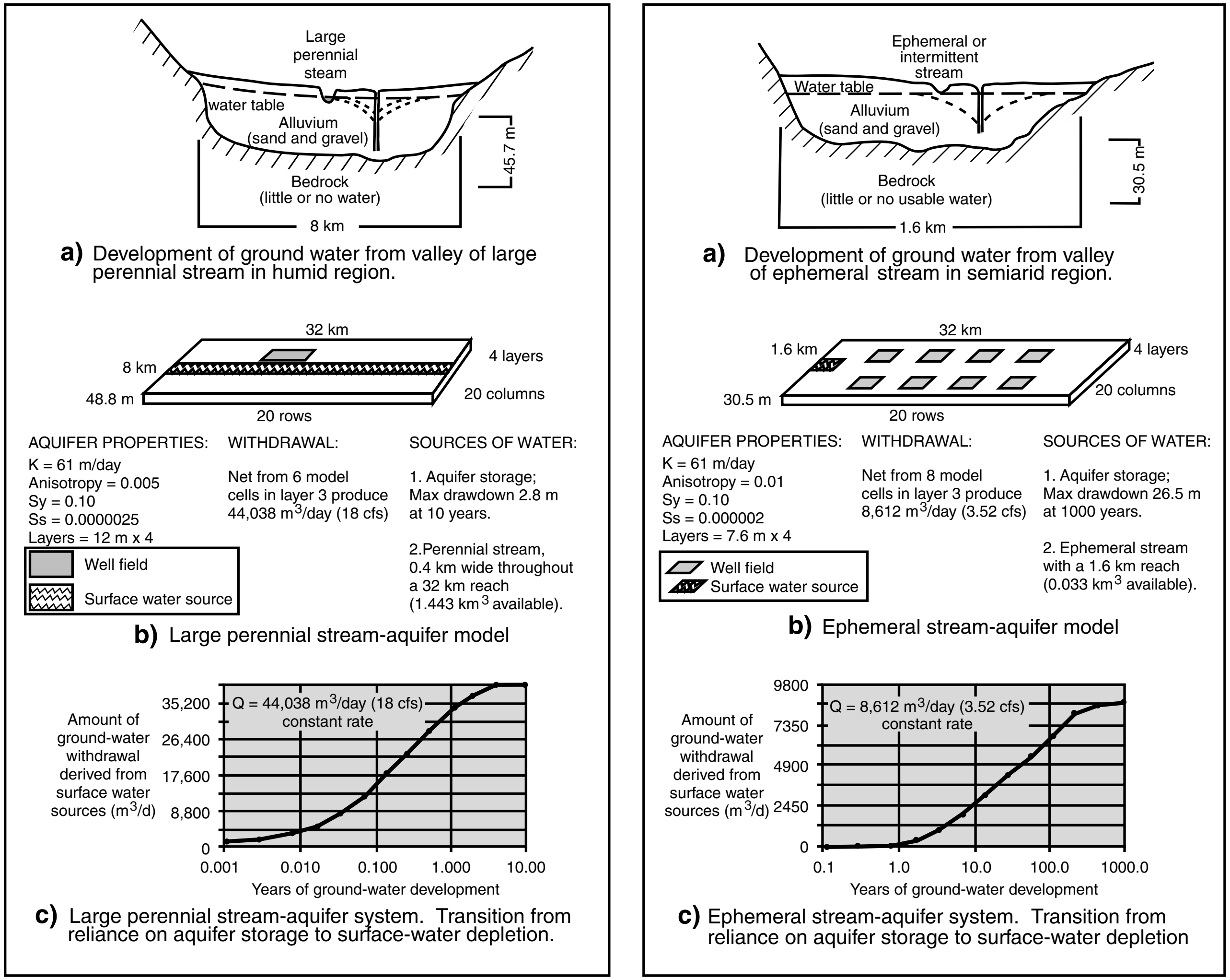


Fig. 6. Two example aquifer systems showing (a) their geometry, (b) the employed model input and (c) the resulting transition curves (adapted from Balleau and Mayer, 1988, and Lohman, 1972).

from surface-water depletion throughout the area of response. Specified withdrawal rates, well distribution, and drawdown of water levels to an economic or physical limit are used in the model for such projections (Balleau, 1988). However, a planning horizon must be defined to assess which phase of the transition curve will apply during the period of the management plan.

Lohman (1972) discussed safe yield and the sources of water derived from well fields using a series of five example aquifer types. His conceptual model was extended by Balleau and Mayer (1988) to illustrate quantitatively the rate of change of water sources in the types of systems that Lohman discussed. The three-dimensional aquifer model program MODFLOW of McDonald and Harbaugh (1988) was used to calculate the drawdown and depletion rates for the five example flow systems following Lohman's description. Two aquifer types are discussed briefly below: (1) a valley of large perennial stream in humid regions; and (2) a valley of an ephemeral stream in a semi-arid region. See Fig. 6a for illustration of the geometry of each aquifer system (Lohman, 1972). Additional input required for the three-dimensional simulations, particularly withdrawal rates and hydrogeologic properties, are illustrated in Fig. 6b (Balleau and Mayer, 1988). In each case, a well field was specified to produce at practical rates from each system. Withdrawal was simulated at a constant rate. Generally, the surface sources were simulated as an amount available to be captured from perennial streams, springs, or from reduction of evapotranspiration.

Calculated curves display the transition from full reliance on aquifer storage to full reliance on induced recharge of surface waters (Fig. 6c). These show the importance of selecting a suitable planning horizon when evaluating the effect of a ground-water withdrawal. The phase during which more than 98% of the withdrawals are derived from induced recharge ranges from 4 to 375 years in these two examples. The results suggest that a ground-water policy based either on equilibrium conditions or on a mining strategy should be thoroughly examined for its physical and economic effects through the years. Both arid and humid regions may require this type of information before the effects of a water plan are fully understood (Balleau and Mayer, 1988).

4. Expanding sustainability concepts: the broader view

Over the past several decades, the philosophy underlying management of water resources gradually has shifted from a deterministic world view based on the balance of nature to a recognition that nature is characterized by chance and randomness, and that natural systems are inherently variable, patchy, and often require disturbance to persist (Meyer, 1993). Stream ecosystems in particular depend on natural disturbances such as flooding. This new recognition means that we must manage for change and for complexity. Not only must we manage in the context of the ecosystem (rather than managing parts as though they were in isolation), but we must also use an adaptive management scheme that is responsive to changing environmental conditions (Meyer, 1993).

Managing in an ecosystem context (NRC, 1991) means that we have to think about the sustainability of the system—not just the fish, but the aquatic food chain; not just the trees, but the whole forest; not just the ground water, but the running streams, wetlands, and all of the plants and animals that depend on them (Sophocleous, 1997; Sophocleous et al., 1998). Such an approach is fraught with difficulty. We cannot use a natural system without altering it, and the more intensive the use, the greater the alteration. How much is too much? What are the central characteristics that must be preserved or sustained? And is there any way to answer these questions before it is too late? This is the crux of the sustainability problem-even if we care about the next generation, do we permit things that cannot be proven dangerous or forbid what cannot be proven safe? Science can never know all there is to know because science is a process and not an end point. Rather than allowing the unknown or uncertain to paralyze us, we must apply the best of what we know today, while providing sufficient management flexibility to allow for change and for what we don't yet know.

In outlining the current challenges for ecology, Meyer (1993) made the following perceptive comments, directly relevant to the water sustainability debate:

> "An additional component of management for change is managing in a probabilistic and

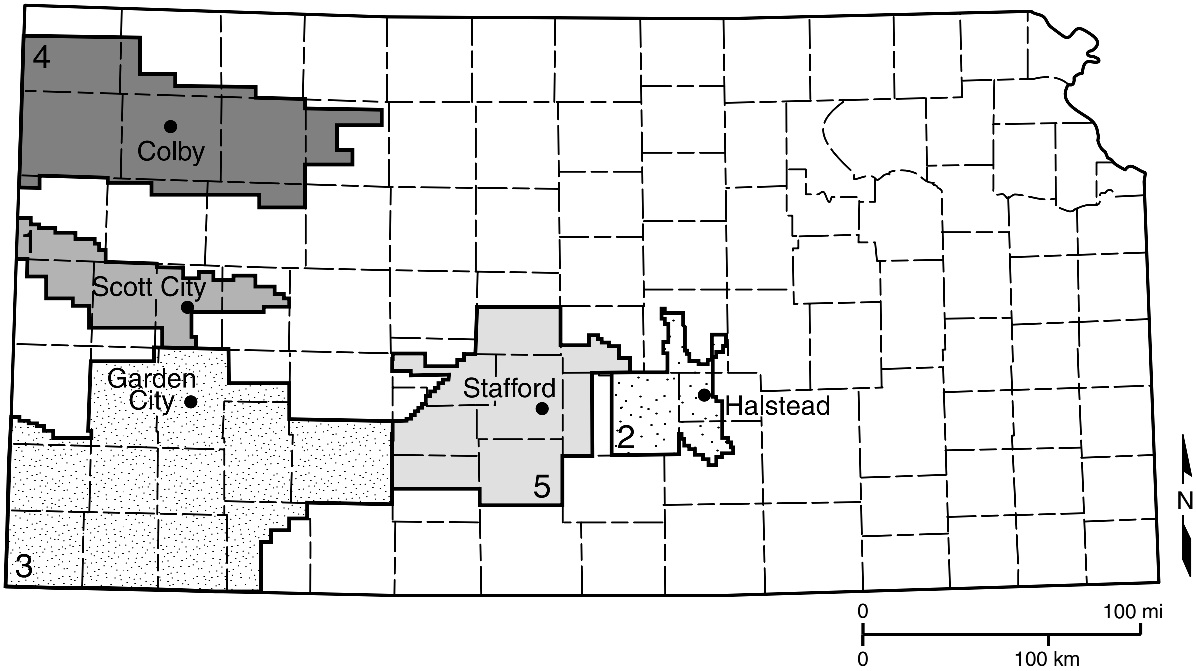


Fig. 7. Ground-water Management Districts (GMDs) in Kansas.

risk-assessment framework in which one recognizes the inherent unpredictability of nature… Rather than determining a fixed sustainable yield, the manager recognizes that yield should vary over time as environmental conditions vary. In the long term this produces a more sustainable yield. This type of management requires greater input of scientific understanding and continued monitoring than is currently practiced…[The evidence shows that] we have altered the hydrologic cycle as well as cycles of most elements; human activities seem to be affecting climate; biodiversity is declining rapidly. Events such as these require scientists and managers alike to think on a global scale…As human assaults on natural systems have accelerated over the past decade, so has the need for a more holistic concept of system management that has the goal of maintaining and restoring the ecological integrity of the resource rather than simply preserving water quantity or quality."

The need to manage ground-water resources as an integral part of overall available water resources and in recognition of their place in the equilibrium of the natural environment is better understood today by scientific experts and water-resource managers. *Integrated resource planning* has recently emerged as a tool for total water management, "assuring that water resources are managed for the greatest good of people and the environment and that all segments of society have a voice in the process" (AWWA, 1994). This concept of enlightened management, which in the past has eluded those directly or indirectly involved in the day-to-day management operations of ground water, is now taking hold in Kansas (Warren et al., 1995) and other states.

5. Kansas water-resources-management experience

In response to persistent ground-water-level declines, especially in western Kansas, the Kansas Legislature in 1972 passed the Kansas Ground Water Act authorizing the formation of local ground-water management districts (GMDs) to help

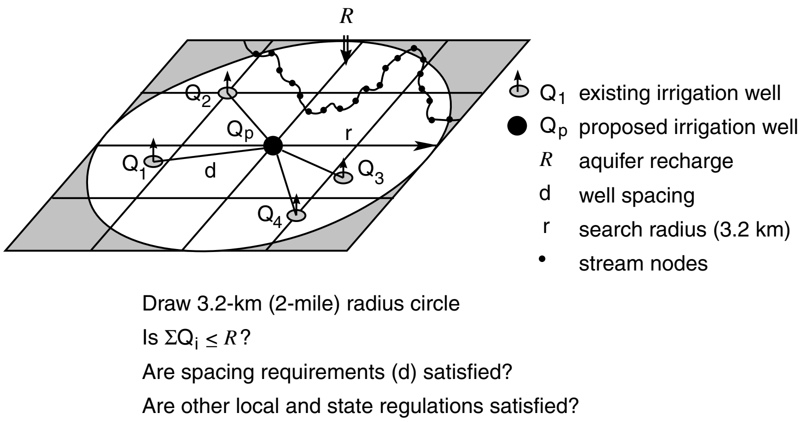


Fig. 8. Kansas "safe-yield" management policy.

control and direct the development and use of ground-water resources (Fig. 7). Since passage of the enabling act, five districts have been formed, of which the three western districts (1, 3, and 4; Fig. 7) overlie all or parts of the Ogallala aquifer. {The term High Plains aquifer is a more encompassing term, incorporating not only the Ogallala aquifer proper, covered by GMDs 3, 1, and 4, but also its eastern extensions in the Great Bend Prairie and Equus Beds regions, covered by GMDs 5 and 2, respectively (Fig. 7; Sophocleous, 1998b)}. The three western districts have the greatest number of large-capacity wells and the highest rate of water-level declines, in addition to having the least precipitation (ranging from west to east from less than 400 to 550 mm/year on average) and least ground-water recharge (generally less than 13 mm/year, Hansen, 1991). Because recharge rates are so low in western Kansas, so-called "safe-yield" policies, in which ground-water withdrawals are restricted to average recharge rates, have not been adopted as being too harmful to the region's economy. Thus, each of these districts has employed a plan that allows a part of the aquifer to be depleted (no more than 40%) over a period of 20–25 years (this is the so-called "planned-depletion" policy). This implies that the Ogallala is not a renewable resource, at least within a human generation. The rationale for the 20–25 year time span and for the 40% allowable depletion is as follows (Sophocleous, 2000). Given that loans were being made on approximately a 20–25 year term for irrigation system installations, a 20–25 year period was considered a reasonable planning period after which it was assumed the irrigation supply would be somewhat physically limited or perhaps legally restricted. Also, given that the aquifer had a relatively large amount of water in storage but a small amount of natural recharge, it was felt that 40% of the saturated thickness was a reasonable amount of depletion over the 20–25 year investment amortization period, and would essentially represent the economic life of the aquifer.

However, these western Kansas districts recognized that their long-term goal was to reduce the rate of water use in order to prolong the life of the aquifer and to assure future economic stability in the region. Towards this end, the Northwest Kansas GMD 4 implemented a so-called "zero depletion" policy in 1991 for new wells. This "zero depletion" policy limits the pumping of water from the aquifer for new wells so as not to exceed the estimated average amount of natural recharge. As a result, very few water rights are approved under this regulation. In fact, because of past over-appropriation, the western Kansas GMDs are mostly closed to further new appropriations. For a new appropriation to be approved, it has to satisfy the following two requirements (in addition to satisfying the above-mentioned "planned depletion" policy, as well as certain well-spacing requirements): (1) that the saturated thickness of the area of the new appropriation has been depleted by less than 15% since 1950; and (2) that such thickness is more than 12 m. The GMDs also took additional measures aimed at reducing water use as will be briefly outlined further below.

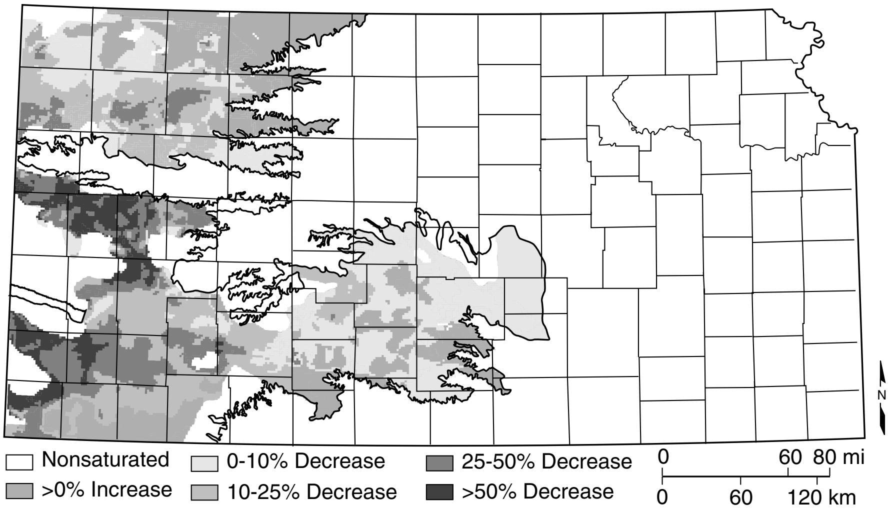
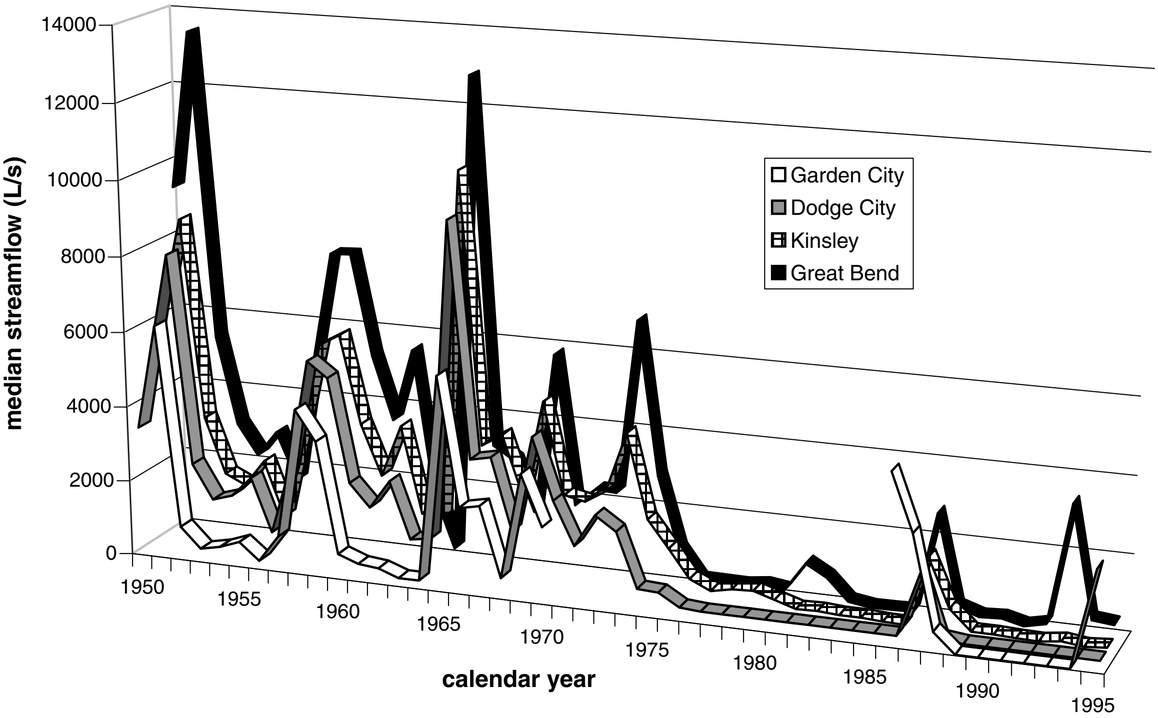


Fig. 9. Percent change in saturation thickness in the High Plains aquifer in Kansas (predevelopment to 1996).

The districts to the east (GMDs 2 and 5; Fig. 7), which have more precipitation (ranging from west to east from 580 to 810 mm/year on average) and thus more ground-water recharge, initially adopted a so-called "safe-yield" management policy to balance ground-water pumping with the average annual recharge. Under this policy, total appropriations in a 3.2-km-radius circle around the proposed diversion (such as an irrigation well) were limited to the long-term average annual recharge calculated for the circle (Fig. 8). Drawdown analysis for typical well and aquifer parameters in the High Plains aquifer in Kansas indicated that drawdown was limited beyond a radius of 3.2 km from a pumping well (Sophocleous, 2000). Thus, the quantity already appropriated within that 3.2-km circle plus the quantity proposed under the new application must not exceed the long-term average annual recharge (implying a renewable ground-water resource). (For a history and rationalization of these policies in Kansas, the reader is referred to Sophocleous, 2000).

This safe-yield policy has slowed the rate of ground-water decline, but it has not stopped ground-water declines. Both GMDs 2 and 5 experienced ground-water-level declines of more than 6 m in parts of their districts since establishment of the "safe-yield" policy in the mid-1970s. Ground-water pumping between predevelopment (circa 1940) and 1990 depleted significant portions of the High Plains aquifer and caused water-level declines of as much as 60 m at places in southwestern Kansas. Fig. 9 shows the declines in saturated thickness since predevelopment across western and central Kansas, where the darkest color indicates more than 50% decrease in saturated thickness. As a result of these declines, the Division of Water Resources (DWR; the water rights regulatory agency) of the Kansas Department of Agriculture has officially closed many areas of western and central Kansas to new ground-water development.

In addition, as a result of these ground-water-level declines, streamflows of western and central Kansas streams have been decreasing, especially since the mid-1970s. As a consequence, riparian vegetation has been progressively degrading in western and central Kansas (Spray, 1986), with numerous dead cottonwood and poplar trees visible across the countryside. This demonstrates that persistent ground-water declines affect sustainability of the resource long before the resource base is threatened with physical exhaustion, and that additional attributes of the resource, such as depth to water table, have a profound impact on the environment. In response to these streamflow declines, the Kansas Legislature passed the minimum instream flow law in 1984, which requires that minimum desirable streamflows (MDS) be maintained in different streams in Kansas. Although the establishment of MDS is a major step toward conservation of riverine habitat within the



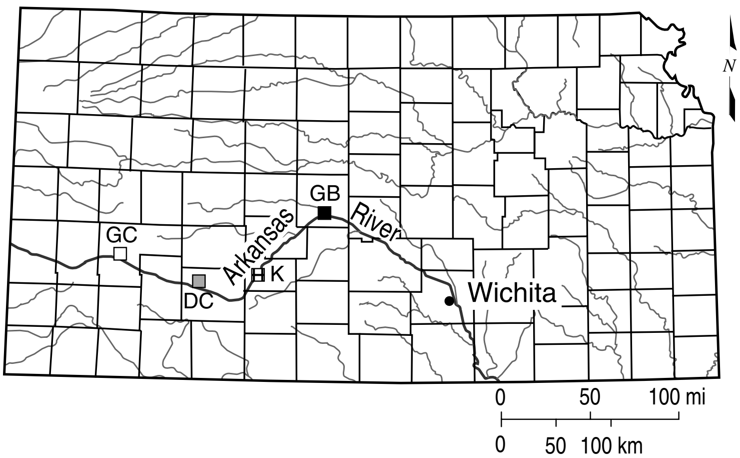


Fig. 10. Median annual discharge of the Arkansas River based on daily streamflow records from 1950 to 1995 at Garden City (GC), Dodge City (DC), Kinsley (K), and Great Bend (GB) stream gaging stations, and location map. (The Garden City station daily record from 1971 to 1985 is non-existent).

state, the trend in reduction of discharge since the mid-seventies, although reduced, appears to be continuing. Fig. 10 is a graph of median annual discharge in the Arkansas River, based on daily streamflow records for Garden City, Dodge City, Kinsley, and Great Bend for the period of 1950–1995. The pattern in reduction of surface discharge since the mid-1970 is clearly visible. As we showed earlier, maps comparing the perennial streams in Kansas in the 1960s to those of the 1990s show a marked decrease in kilometers of streamflow in the western third of the state.

The GMDs realized that the problem of controlling ground-water depletion is complex, involving not only hydrogeologic but also socioeconomic and legal considerations. The DWR and GMDs adopted a suite of management programs involving controls on new development, regulation of existing development, well-spacing requirements, annual water use reporting, water metering on all new non-domestic wells and on all wells in specially-designated areas, water-supply augmentation programs [including water conservation measures, water-use efficiency schemes, artificial recharge structures, participation of the western districts in an active weather modification program (Eklund et al., 1999), participation in recently proposed water banking schemes, and other programs], as well as public education and involvement programs. [For additional information on these programs the reader is referred to the GMD 4 web page (http://colby.ixks.com/~wbossert/); also for an overview of ground-water problems and management approaches to these problems in Kansas and other High Plains states, the reader is referred to Kromm and White (1992).]

As a result of continuing declines in ground-water levels and streamflow under their safe-yield management program, GMDs 2 and 5 recognized that some water provisions needed to be made in order to maintain some minimum desirable flow in the streams and satisfy wetland water requirements. Thus, in the early 1990s, these districts moved toward conjunctive stream-aquifer management by amending their safe-yield regulations to include baseflow (that is, the natural ground-water discharge to a stream) as ground-water withdrawals along with regular water-permit appropriations when evaluating a ground-water permit application. [Baseflow is estimated as the streamflow that is exceeded 90% of the time on a monthly basis, as a measure of dry-weather flow. (For a more detailed explanation and evaluation of these policies, the reader is referred to Sophocleous, 2000).]

The concept, shown in Fig. 8, is to prorate the baseflow to a series of phantom wells, known as “baseflow or stream nodes,” which are shown as dark dots in the figure. These nodes are located on the stream centerline at 0.4-km intervals (the GMDs’ well-spacing requirement), each having an annual quantity of water assigned to it equal to its prorata share of the estimated baseflow, which is considered its appropriation for “3.2-km circle” computations (Sophocleous, 2000). If there are such nodes in a 3.2-km circle, they are each treated as water rights for purposes of determining whether or not a new application should be approved. It is hoped that this new measure, together with the establishment of minimum desirable streamflow-standards, and the newly established total maximum daily load (TMDL) limits to achieve water quality standards on selected streams (http://www.kdhe.state.ks.us/tmdl/), will provide additional needed protection to the riverine-riparian ecosystem.

DWR and the Kansas Water Office (the state’s water planning agency) have initiated a comprehensive basinwide-management program in areas of Kansas with significant water problems. A holistic and proactive approach, as well as close consultation and cooperation with the local districts, irrigators, and other interested parties are integral parts of this program. The Kansas Geological Survey assisted in the program’s development by developing and applying integrated watershed and ground-water models (Perkins and Sophocleous, 1999; Sophocleous et al., 1999; Ramireddygari et al., 2000). [For a general overview of the approach and results of this methodology, the reader is referred to Sophocleous and Perkins (2000)]. The approach taken by DWR and the basin-working group was that of incentive-based alternatives to affect change in target, problem areas within the basin.

The City of Wichita has also developed an innovative Integrated Resource Planning program (Warren et al., 1995), which includes both conventional and non-conventional local water supplies to meet projected demands, such as capturing excess-flow river water and river bank storage water from the Little Arkansas River on an as-available basis. This water is being recharged and stored in the Equus Beds aquifer, just north of Wichita, Kansas to be recovered in times of drought. The plan established a priority of water use, whereby water that would normally flow through the area would be used first, saving slowly replenished water resources for times when the first-priority water is not available (Stous et al., 1999). [For additional information on this project, the reader is referred to the project web page, maintained by the US Geological Survey (http://www-ks.cr.usgs.gov/Kansas/equus/).]

The progressive evolution of Kansas water management, which incorporates local GMDs and their water-management programs, minimum-streamflow standards, the water use reporting and water metering programs, the use of modified safe-yield policies in some districts, the integrated resource planning by the City of Wichita, and the DWR subbasin water-resources-management program, as well as other programs, are all appropriate steps toward the attainment of sustainable development. Additional information on Kansas water management, policies, and agencies is provided in Sophocleous (1998a).

6. Concluding comments and outlook

In the past, the volume of recharge to an aquifer was accepted as the quantity of water that could be removed from an aquifer on a sustainable basis, the so-called safe yield. We now understand that the sustainable yield of an aquifer must be considerably less than recharge, if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and ground-water-dependent ecosystems. Sustainable resource management is managing ground-water for both present and future generations, and providing adequate quantities of water for the environment. Quantifying what these environmental provisions are is presently an urgent research need. Ground-water management responses in areas of over-extraction must include bringing use back to sustainable or at least community-acceptable levels while exploring more sustainable options. In other areas, ground-water management needs to adapt to working within the finite limits set by the goal of sustainability. Wise management of water resources needs to be approached not only from the viewpoint of focussing on the volume of water available for sustainable use, but also from the impact of ground-water exploitation on the natural environment.

It is now recognized that a comprehensive and integrated approach to the management of ground-water resources is required if their quality and supply are to be sustained in the longer term, and other ecosystems dependent on ground water are to be protected. However, because of their interdependence, ground water cannot be managed separately from surface waters. To ensure sustainability of aquifers, it is imperative that water limits be established based on hydrologic principles of mass balance. Because of uncertainties and spatio-temporal variabilities of key controlling variables (such as recharge and other hydrologic-budget components), sustainability assessment should be understood as a dynamic and iterative process, requiring continued monitoring, analysis, prioritization, and revision. The progressive evolution of water management policies in the Kansas GMDs (Sophocleous, 2000) and the state in general, offer a real-world example of community-acceptable measures in the ongoing pursuit of the goal of water sustainability.

Management of natural resources has developed significantly during the past few decades. In particular, numerical modeling became an indispensable decision tool in ground-water management. Such models can generate the transition curve from storage depletion to induced recharge from surface-water bodies for the system under consideration, so that management plans and planning horizons can be thoroughly assessed. However, the reliability of such models suffers from the uncertainty of their input parameters. Because of the strong spatial and temporal variability of important primary variables in such models, the estimation of key parameters such as recharge will be a predominantly statistical undertaking. Therefore, quantification of risk and uncertainty will increasingly be of major importance to ground-water management. Present trends in the use of models for water-resource management purposes include greater use of more sophisticated models that increasingly integrate land, vegetation, climate, and water interactions. Such models also capitalize on recent technological improvements with the development of graphical user interfaces and decision-support systems, taking advantage of the continuing development of Geographic Information Systems (GIS) and visualization technologies. The design and implementation of such models has already been initiated in Kansas (Perkins and Sophocleous, 1999; Sophocleous et al., 1999; Ramireddygari et al., 2000; Sophocleous and Perkins, 2000) and elsewhere.

Local decision-making is considered the preferred route to water management as is indicated by the establishment of local GMDs in Kansas and elsewhere. Because local conditions vary significantly within the High Plains region, environmental differences affect water availability and use. Detailed water-management plans will necessarily be sub-regional to adequately adjust to local conditions. As Zwingle (1993) aptly stated, communities want to solve their problems, but not using rules that apply to somebody else.

The solution of regional and local water problems requires education, technical assistance, and supporting research. It is imperative that the community at large participates in policy formulations and in judgments of what is to be sustained. Strong public education and outreach programs are needed to improve understanding of the nature, complexity, and diversity of ground-water resources, and to emphasize how this understanding must form the basis for operating conditions and constraints. This is the only way to positively influence, for the long term, the attitudes of the various stakeholders involved. Pressure from the community for better management of our natural resources will be the main driving force for most changes.

As we confront the water problems of the present, armed with greater scientific and technological power than before, and with the benefit of hindsight, we have a better sense of the complexities inherent in our choices. This allows us to manage in a more strategic and integrated way, no longer committed to simplistic solutions but able to take a wise and balanced view of water resources as we strive to achieve sustainability in the management of our water resources.

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References

ASCE (American Society of Civil Engineers), 1987. Ground Water Management, ASCE Manuals and Reports on Engineering Practice No. 40. 3rd ed., ASCE, New York, NY (263pp).

AWWA (American Water Works Association), 1994. Integrated Resource Planning in the Water Industry. Mainstream, June 1994 issue, 4pp.

Angelo, R.T., 1994. Impacts of declining streamflow on surface water quality. 11th Annual Water and the Future of Kansas Conference Proceedings, Manhattan, KS, pp. 1–2.

Balleau, W.P., 1988. Water approximation and transfer in a general hydrogeologic system. Natural Resources Journal 29 (2), 269–291.

Balleau, W.P., Mayer, A.B., 1988. The transition from groundwater mining to induced recharge in generalized hydrogeologic systems. Proceedings of FOCUS conference on Southwestern Ground Water Issues, National Water Well Association, Dublin, Ohio, pp. 81–103.

Bredehoeft, J.D., Papadopulos, S.S., Cooper, H.H., Jr., 1982. Groundwater: The Water Budget Myth. In: Scientific Basis of Water Resource Management, National Academy Press, Studies in Geophysics, pp. 51–57.

DuMars, C.T., Brown, F.L., Cummings, R.G., Lansford, R., Rodgers, A.B., Utton, A.E., 1986. State appropriation of unappropriated ground water: A strategy for insuring New Mexico a water future. New Mexico Water Resources Research Institute and Univ. of New Mexico Law School, WRRI Report no. 200, 297pp.

Eklund, D.L., Jawa, D.S., Rajala, T.K., 1999. Evaluation of the western Kansas weather modification program. Journal of Weather Modification 31, 91–101.

Glover, R.E., 1974. Transient Ground Water Hydraulics. Department of Civil Engineering, Colorado State Univ., Fort Collins, CO, 413pp. Reprinted in 1985 by Water Resources Publications, Highlands Ranch, CO.

Hansen, C.V., 1991. Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas. US Geological Survey Water-Resources Investigations Report, 87-4230, 100pp.

Hufschmidt, M.M., 1993. Water policies for sustainable development. In: Biswas, A.K., Jellali, M., Stout, G.E. (Eds.). Water for Sustainable Development in the Twenty-first Century, Oxford University Press, Delhi, India, pp. 60–69.

Kromm, D.E., White, S.E. (Eds.), 1992. Groundwater Exploitation in the High Plains. University Press of Kansas, Lawrence, KS (240pp).

Lohman, S.W., 1972. Ground-water Hydraulics. US Geological Survey, Professional Paper 708, 70pp.

McDonald, M.G., Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. US

Geological Survey, Technical of Water Resources Investigations Book 6, Chap. A1, 586pp.
Meyer, J.L., 1993. Changing concepts of system management. In: Sustaining our Water Resources, Proceedings National Academy Press, Washington, DC (pp. 78–91).
NRC (National Research Council), 1991. Toward Sustainability. Soil and Water Research Priorities for Developing Countries, National Academy Press, Washington, DC (63pp).
NRC (National Research Council), 1989. Irrigation-Induced Water Quality Problems. What can be learned from the San Joaquin Valley experience, National Academy Press, Washington, DC (150pp).
Perkins, S.P., Sophocleous, M.A., 1999. Development of a comprehensive watershed model applied to study stream yield under drought conditions. Ground Water 37 (3), 418–426.
Rabalais, N.N., Turner, R.E., Wiseman Jr., W.J., Boesch, D.F., 1991. A brief summary of hypoxia on the northern Gulf of Mexico continental shelf: 1985–1988. In: Tyson, R.V., Pearson, T.H. (Eds.). Modern and Ancient Continental Shelf Anoxia, Geological Society Special Publication No. 58Geological Society, London, pp. 35–47.
Ramireddygari, S.R., Sophocleous, M.A., Koelliker, J.K., Perkins, S.P., Govindaraju, R.S., 2000. Development and application of a comprehensive simulation model to evaluate impacts of watershed structures and irrigation water use on streamflow and ground water: The case of Wet Walnut Creek watershed, Kansas. Journal of Hydrology, in press.
Sophocleous, M.A., 1997. Managing water resources systems: Why safe yield is not sustainable. Ground water 35 (4), 561.
Sophocleous, M.A. (Ed.), 1998a. Perspectives on Sustainable Development of Water Resources in Kansas. Kansas Geological Survey, Bulletin 239, Lawrence, KS, 239pp.
Sophocleous, M.A., 1998b. Water Resources of Kansas: A Comprehensive Outline. In: Sophocleous, M.A. (Ed.), Perspectives on Sustainable Development of Water Resources in Kansas. Kansas Geological Survey, Bulletin, 239, pp. 1–59.
Sophocleous, M.A., 1998c. On the elusive concept of safe yield and the response of interconnected stream-aquifer systems to development. In: Sophocleous, M.A. (Ed.), Perspectives on Sustainable Development of Water Resources in Kansas. Kansas Geological Survey, Bulletin, 239, pp. 6–85.
Sophocleous, M.A., 2000. The origin and evolution of safe yield policies in the Kansas Groundwater Management Districts. Natural Resources Research 9 (2) (in press).
Sophocleous, M.A., Sawin, R.S., 1997. Safe yield and sustainable development of water resources in Kansas. Kansas Geological Survey, Public Information Circular, 9, 6p. Also available at http://www.kgs.ukans.edu/Publications/pic 9/pic 9_1.html/.
Sophocleous, M.A., Perkins, 2000. Methodology and application of combined watershed and ground-water models in Kansas: Journal of Hydrology, in press.
Sophocleous, M.A., Buddemeier, R.W., Buchanan, R.C., 1998. Evolving sustainability concepts: Modern developments and the Kansas Experience. In: Sophocleous, M.A. (Ed.), Perspectives on Sustainable Development of Water Resources in Kansas. Kansas Geological Survey, Bulletin 239, pp. 86–95.
Sophocleous, M.A., Koelliker, J.K., Govindaraju, R.S., Birdie, T., Ramireddygari, S.R., Perkins, S.P., 1999. Integrated Numerical Modeling for Basin-wide Water Management: The Case of the Rattlesnake Creek Basin in South-central Kansas. Journal of Hydrology 214 (1–4), 179–196.
Spray, K.L., 1986. Impact of surface-water and ground-water withdrawal on discharge and channel morphology along the Arkansas River, Lakin to Dodge City, Kansas. MSc thesis, Dept. of Geology, The Univ. of Kansas, Lawrence, KS, 102pp.
Stous, D.H., Aucott, W.R., Blain, G.T., Dealy, M.T., 1999. Wichita recharge project: Sustaining and preserving the Equus Beds aquifer. Abstracts with Programs, 1999 Annual Meeting and Exposition, Geological Society of America, October 25–28, 1999, Denver, CO, 31(7): A-493.
Theis, C.V., 1940. The source of water derived from wells: essential factors controlling the response of an aquifer to development. Civil Engineering 10 (5), 277–280.
Warren, D.R., Blain, G.T., Shorney, F.L., Klein, L.J., 1995. IRP (Integrated Resource Planning): A case study from Kansas. American Water Works Association Journal 87 (6), 57–71.
Whittemore, D.O., Tsou, M.-S., Young, D.P., Healy, J.M., 1999. The Upper Arkansas River Corridor Study: An Update. Hydrogram. The Quarterly Journal of the Kansas Water Office, Spring, 17–20.
World Commission on Environment and Development (WCED), 1987. Our Common Future, Oxford University Press, New York, NY (383pp).
Zwingle, E., 1993. Ogallala aquifer: Wellspring of the High Plains. National Geographic 183 (3), 80–109.