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ANALYSIS OF AQUIFER DEPLETION CRITERIA WITH IMPLICATIONS FOR GROUNDWATER MANAGEMENT

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ABSTRACT—Groundwater is critical to many aspects of life on the Great Plains. Overdevelopment of this resource can have serious social, economic, and environmental consequences. Aquifer depletion criteria are used in many areas of the Great Plains to implement management responses and limit groundwater development. This study addresses groundwater-level triggers and depletion limits—criteria commonly used in Nebraska—within the context of interconnected ground- and surface-water systems. Generic models are used to calculate transient water budgets in three hypothetical systems given depletion limits of 5%, 10%, 15%, and 25%. In each simulation, the source of water to the wells changes from aquifer depletion to surface-water depletion, but at rates varying from 1 day to several hundred years. Separate simulations test the effectiveness of groundwater-level triggers at achieving a desired depletion limit. Results suggest that universal application of generic depletion criteria may lead to unintended consequences such as excessive surface-water depletion, excessive aquifer depletion, or conversely, unnecessary constraints on pumping. A holistic process framework for groundwater management is presented to promote the use of aquifer depletion criteria in conjunction with an adaptive management strategy. Such strategies can help ensure the future sustainability of water resources in Nebraska and elsewhere in the Great Plains.

Key Words: groundwater, water, pumping, sustainability, model, management

INTRODUCTION

Aquifer Depletion Criteria in Groundwater Management

Groundwater quantity management involves the planned development, use, and conservation of groundwater resources. A key goal is to control groundwater-level declines caused by pumping-induced depletion of water in an aquifer. Aquifer depletion can reduce well yields, increase pumping costs, be a source of litigation between users, reduce flows to wetlands and streams, cause land subsidence, and deteriorate water quality (Peralta et al. 1986; Galloway et al. 1999; Bouwer 2002; Sophocleous 2003). Such is the case for many areas in the Great Plains (Sophocleous 1998; Galloway et al. 1999).

Many states in the Great Plains have developed specific aquifer depletion criteria specifying maximum allowable pumping rates and/or limits on groundwater-level declines (McGuire et al. 2003). In parts of Oklahoma, Colorado, and Kansas, groundwater withdrawals are limited based on levels of “allowable depletion” over a specified timeframe, typically around 20-25 years (Ashley and Smith 1999). In South Dakota and some parts of Kansas, withdrawals and the issuance of well permits are limited based on comparison to the estimated aquifer recharge, an approach commonly known as “safe yield.” In Nebraska, aquifer depletion criteria are developed by Natural Resources Districts (NRDs), the local agencies responsible for groundwater management (Flowerday and Herrin 1993). Nebraska state statute requires NRDs to have groundwater management plans containing specific groundwater reservoir life goals and management objectives (Nebraska Revised Statute 46-709). Many NRDs have defined planning horizons during which aquifer depletion is limited to a certain level to protect the economic, social, and environmental interests that rely on the water. The challenge they face is defining limits that are relaxed enough to avoid unnecessary economic constraints yet restrictive enough to avoid overdevelopment.
The majority of groundwater withdrawals in Nebraska are for irrigation (94%), followed by municipal supplies (3%), livestock (1%), industrial/mining/power generation (1%), and domestic supplies (1%; Hutson et al. 2004). Controlling groundwater-level declines, therefore, requires a plan to control the volumes of water pumped for these purposes. Aquifer depletion criteria often contain triggering mechanisms that initiate management actions in response to an observed change. Triggers most commonly used in Nebraska are based on spring groundwater-level declines below a baseline level (e.g., UBBNRD 2004). The baseline groundwater-level may be the predevelopment level, the level for the year in which monitoring began, the level from some past period, or a long-term average. Other types of triggers are based on safe yield criteria or on specified densities of wells and irrigated acres (e.g., MRN RD 1986; MNNRD 1994; TPNRD 2004). The management responses attached to a trigger level might include incentives for reducing groundwater usage, restrictions on the installation of new wells, or allocations for existing users, among others.

The question of whether or not sustainable development of water supplies can be achieved using aquifer depletion criteria has been brought to light with recent water policy changes in Nebraska. Groundwater and surface water have historically been regulated separately in Nebraska, with surface water administered by the state under the appropriative rights rule, and groundwater under a modified correlative rights rule, but generally without a uniform administrative structure (Jess 2003; Ashley and Smith 1999). The NRDs have been the primary regulatory authority over groundwater since the mid-1970s. Only recently has the state begun to acknowledge ground- and surface-water connections in its law. In 2004 the Nebraska legislature passed a series of laws to address surface-water shortages that were recognized as being caused, at least in part, by the pumping of groundwater. These laws granted state authority to halt groundwater development and require integrated management plans in areas where both the surface-water supplies are insufficient to meet demands and the groundwater is hydrologically connected to surface water. Large areas of the Platte, Republican, and Niobrara river basins have been declared fully appropriated or overappropriated since the passage of these laws, and major portions of these basins have been defined as hydrologically connected by the state (NDNR 2009).

Many of the areas the state has declared fully appropriated or overappropriated were previously managed with the use of aquifer depletion criteria. Pumping restrictions were enforced in some of these areas due to groundwater-level declines, but in other areas the established triggers had not been tripped. The depletion criteria were not designed with surface-water connections in mind and were insufficient to prevent unacceptable depletion of surface-water flows. Nonetheless, aquifer depletion criteria remain in place in areas of Nebraska not fully appropriated or overappropriated. Uncertainties regarding the use of these criteria have caused some NRDs to place restrictions on the installation of new wells, halt expansion of irrigated acres, and initiate regional groundwater investigations to assess the degree of ground- and surface-water connections (e.g., Chen et al. 2008; Peterson et al. 2008; Divine et al. 2009). The need remains for studies focused specifically on the use of aquifer depletion criteria.

**Purpose of This Study**

The purpose of this study is to evaluate aquifer depletion criteria in terms of interconnected ground- and surface-water systems and to discuss their use in adaptive management. Generic groundwater models are used to analyze different aquifer depletion criteria commonly used in Nebraska in three different idealized stream-aquifer systems. This analysis, though highly simplified, demonstrates the use of long-term transient water budgets and illustrates important points regarding systemwide hydrologic response to aquifer depletion. Recognizing that stream-aquifer systems are complex and variable, and that social, economic, and environmental water needs vary in space and time, a process framework for adaptive groundwater management is presented. This framework, when coupled with site-specific monitoring, data analysis, and groundwater modeling, integrates aquifer depletion criteria with a dynamic, iterative approach to groundwater management that can be used by resource managers in the Great Plains and elsewhere.

**BACKGROUND**

**Safe Yield and Groundwater Mining**

“Safe yield” and “groundwater mining” are terms often used in water resources dialogue. Safe yield is the idea that groundwater development can be sustained as long as the amount of groundwater withdrawn by pumping does not exceed the amount recharged to the aquifer by precipitation. The natural recharge rate is an important factor in determining the amount of natural discharge of
a system and the relative amount of water available in the water budget, but the idea of safe yield can lead one to erroneously conclude that there is a specific pumping rate for which the impacts of development will be nondepleting. This idea is theoretically untenable (Theis 1940; Brown 1963; Bredehoeft et al. 1982; Sophocleous 1997; Bredehoeft 1997; Sophocleous 2000; Bredehoeft 2002; Alley and Leake 2004).

Aquifer depletion is sometimes referred to as groundwater mining or overdraft. Determining whether or not an aquifer is being mined depends on both the temporal and spatial scale of the problem. Balleau (1988) defines groundwater mining as the period when greater than 98% of the water to the wells comes from removal of groundwater in storage. In this sense, all groundwater developments initially mine water to some degree. In groundwater systems with excessive pumping or poor connection to surface water, mining will continue until it becomes impossible or uneconomical to pump the water. In many groundwater systems, if conditions remain more or less constant over a certain time period, groundwater mining will ultimately cease and give way to depletion of surface-water sources (Balleau 1988). The transition from groundwater mining to surface-water depletion happens regardless of whether the pumping rate is less than, equal to, or greater than the natural recharge rate. The amount of time required for this transition varies greatly depending upon the dynamic response of the aquifer. This response is governed by the aquifer characteristics, pumping rates, locations of wells, and boundary conditions such as rivers and groundwater divides. In some systems, the transition is rapid (days or weeks), whereas in other systems, the transition times may be longer than any reasonable planning period (hundreds or thousands of years).

**Hydrologic Mass Balance**

Hydrologic mass balance provides a rigorous basis for groundwater quantity management. Unlike safe yield or groundwater mining strategies, the concepts of mass balance allow resource managers to understand the projected planning horizon and pattern of development in terms of the transition from aquifer depletion to surface-water depletion (Balleau 1988; Sophocleous 2000). These concepts are explained briefly below.

Groundwater systems are part of the hydrologic cycle. Water is added to the system through recharge; it flows through the pores and cracks below ground and leaves the system as it is transpired by plants or discharged to surface water bodies. The mass of water entering, being stored in, and leaving the system must be conserved. A water budget is a simplified equation based on the laws of hydrologic mass balance (Alley et al. 1999):

\[
\text{Recharge (water entering)} - \text{Discharge (water leaving)} + \text{Change in Storage} = 0.
\]

If the recharge or discharge components become imbalanced, there must be a corresponding change in the volume of water in the aquifer (aquifer storage). If more water enters the system than leaves it, the storage change will be positive and groundwater levels will rise. If more water leaves the system than enters it, the storage change will be negative and groundwater levels will decline.

Groundwater-level fluctuations can be observed at many different temporal scales. Natural fluctuations may occur over short periods (minutes or hours) or long periods (many years). Nonetheless, the recharge-discharge regime of an aquifer system tends to adjust to prevailing conditions. For a predevelopment system, groundwater levels will fluctuate about some long-term average. The amount of water stored in the aquifer is essentially constant, in other words, recharge is equal to discharge:

\[
\text{Recharge (water entering)} = \text{Discharge (water leaving)}.
\]

This condition is known as dynamic equilibrium (Theis 1940). It does not preclude short-term changes in groundwater levels due to climatic variability.

Groundwater pumping upsets the dynamic equilibrium of a natural system. The water budget changes over time as the system responds to the stress (Fig. 1). Initially, all well water is derived from removal of aquifer storage. With time, the mining phase gives way to a transitional phase in which the effects of pumping spread throughout the hydrologic system. A modified water-budget equation reflects mass balance for such a system:

\[
Pumping = \text{Change in Recharge} + \text{Change in Storage} + \text{Change in Discharge}.
\]

The above water-budget equation does not describe the magnitudes and rates of these changes universally; they will vary from system to system. A state of dynamic equilibrium will return, however, if the pumping rate remains constant and does not exceed the maximum potential rate of flow from surface-water bodies into the aquifer (i.e., induced recharge). Assuming a new state of dynamic equilibrium, the change in storage will become...
zero, requiring an increase in recharge, a decrease in discharge, or some combination of the two:

\[
Pumping = \text{Change in Recharge} + \text{Change in Discharge}.
\]

Pumping of groundwater can have no direct effect on the rate of water recharged through precipitation. A fraction of the pumping may be returned to the aquifer if it seeps back into the soil and below the root zone, but this return flow will only partially offset the pumping. So the ultimate source of water to wells must be from depletion of surface-water flows, including capture of stream baseflow, induced recharge (flow from stream to aquifer), or capture of evapotranspiration (ET) from plants that tap the water table. The surface-water depletion phase begins when \( >98\% \) of the water to the wells comes from surface water (Fig. 1; Balleau 1988).

**MODEL DESIGNS AND METHODS**

**Generic Models of Hypothetical Systems**

The MODFLOW three-dimensional finite-difference groundwater flow model of McDonald and Harbaugh (1988) is used to analyze the hydrologic fluxes of three hypothetical stream-aquifer systems (Fig. 2). The systems are based broadly on those of Lohman (1972) and Balleau and Mayer (1988), modified to generally reflect physical conditions typically found in Nebraska (Flowerday et al. 1998). Each system is represented by a groundwater flow model described below.

**Alluvial Aquifer System.** The conceptual model, aquifer properties, and model parameters of the alluvial aquifer system are shown in Figure 2A. The aquifer is 8 km wide, 32 km long, and the water table is exposed to the atmosphere through openings in the overlying soil (i.e., it is an unconfined aquifer). The stream is 0.4 km wide and located in the center of the valley. The stream is in perfect hydrologic connection with the aquifer. Groundwater ET occurs over the entire domain. The water table slopes toward the stream prior to pumping and the initial average saturated thickness is 46.5 m. Well fields are located immediately adjacent to the stream on both sides. Groundwater does not flow across the outside boundaries of the model.

**Confined Aquifer System.** This system and its model parameters are shown in Figure 2B. The aquifer is 8 km wide and 60 m thick, and the groundwater is isolated from the atmosphere by an overlying impermeable layer (i.e., it is a confined aquifer). The stream is 50 m wide, 1 m deep, and oriented perpendicular to the long axis of the aquifer. The riverbed consists of silty clay, which impedes the vertical flow of water between the stream and aquifer. The surface of the valley is 1 m above the top of the aquifer, so phreatophyte roots are able to reach groundwater, causing
ET in the stream valley. The pre-pumping potentiometric surface slopes toward the stream and averages 68.3 m above the base of the aquifer (8.3 m above the base of the confining unit). A well field is located 15 km from the edge of the stream. Groundwater does not flow across the boundaries of the model, except along the stream in the uppermost layer.

**Regional Aquifer System.** This system and its model parameters are shown in Figure 2C. The aquifer is 100 km long on each side and is unconfined. Two streams bound the aquifer on either side. They are 0.25 km wide and 1 m deep and slope toward an area of ET located along the edge of the domain, perpendicular to the streams. The riverbed is silty, which moderately impedes flow to and from the aquifer. The pre-pumping water table slopes toward the streams and ET area, with an average saturated thickness of 112 m. A well field is located in the center of the model domain. Groundwater flows across the model boundaries only along the streams and ET area in layer 1.

**Generation of Pumping Schedules and Transition Curves**

Pumping rates were applied instantaneously and held constant until water levels stabilized at the desired depletion limit of 5%, 10%, 15%, or 25%. The transition curve and response times were not known prior to performing the model runs. Groundwater-level decline curves and transient water budgets were calculated from the MODFLOW output files.

A second series of model runs were performed to test the effect of lag times on the implementation of depletion criteria and to more realistically simulate aquifer...
development. A linearly increasing pumping rate sufficient to trip a 10% decline trigger after a period of 50 years was applied to each model, after which pumping was held constant for another 40 years.

RESULTS AND DISCUSSION

Groundwater-Level Decline Curves

A groundwater-level decline curve shows the response of an aquifer to development. This curve can be used to assess the degree of depletion at a given pumping rate and the amount of time necessary for stabilization (i.e., lag time). Figure 3 shows the groundwater-level decline curves for each model at each depletion limit. The shapes of the decline curves are similar for each depletion limit in the alluvial and regional aquifers. Stabilization times, however, are two orders of magnitude longer in the regional aquifer than in the alluvial aquifer. The groundwater-level decline curves for the confined aquifer system are somewhat more complex. The 5% and 10% decline curves show a single phase of decline followed by stabilization, whereas the other curves show two phases of decline. The first phase is followed by a short period of slower decline, and the second phase is followed by stabilization. The two-phase response is due to the aquifer’s transition from confined to unconfined. When the aquifer is confined, water is derived from the expansion of water and elastic compression of the aquifer matrix (Meinzer 1942). This pressure response is transmitted rapidly throughout the system. In the unconfined condition, water is derived from gravity drainage of water from pore spaces, a relatively slow process that is reflected as a delayed response in the decline curve (Neuman 1974).

An important point of discussion about the curves in Figure 3 involves the simple relationship between pumping and groundwater-level declines. Each aquifer depletion limit has a corresponding pumping rate, or aquifer yield. Furthermore, a specific curve shape is characteristic of any given well-field location and pumping rate. If groundwater levels are the only constraint on development, then managing the system to satisfy that constraint would require two key elements: (1) an aquifer depletion limit and (2) knowledge of its corresponding aquifer yield. For any given depletion limit, groundwater withdrawals would be allowed to increase until reaching the corresponding aquifer yield, then held constant thereafter. Groundwater withdrawal rates would need to be monitored closely and aquifer yield predictions would need to be checked against groundwater-level monitoring data.

Another point of discussion involves the time lag between the initiation of pumping and the stabilization of groundwater levels. If this time lag is shorter than the planning horizon, then the aquifer depletion limit would be based on a specific stabilization level. That specific level would have a corresponding aquifer yield. If, however, the time lag is longer than the planning horizon, the depletion limit would be based on a rate of decline. That rate would be defined such that groundwater levels do not exceed some specified limit over the length of the planning horizon. It too would have a corresponding

![Groundwater-level decline curves for each model with 5%, 10%, 15%, and 25% depletion limits. Corresponding aquifer yield is shown for each depletion limit.](image)
aquifer yield that could be used to define withdrawal rates.

These ideas assume that the system is undeveloped in terms of groundwater pumping prior to setting the depletion limit. In reality, most aquifers have undergone some level of development prior to the initiation of management plans. Figure 4 illustrates the use of groundwater-level triggers given a more realistic development scenario in which pumping rates steadily increase over a period of 50 years. A hypothetical trigger level of 10%, an aquifer depletion limit of 15%, and a planning horizon of 40 years were used. At year 50, the trigger is tripped, which initiates an immediate halt on new withdrawals (i.e., the pumping rate is held constant after that time). Groundwater levels are observed for the next 40 years.

In the alluvial and confined aquifer models, groundwater levels are still above the depletion limit at 90 years. The trigger is overly restrictive because withdrawals were halted prematurely. In the regional aquifer model, groundwater levels do not stabilize within the 40-year planning horizon and groundwater levels are 20% depleted at 90 years. Depletion has exceeded the limit by 5%, so the trigger is under-restrictive.

Figure 4 illustrates a simplified but inappropriate use of groundwater-level triggers. Generic aquifer depletion criteria are applied universally and without monitoring withdrawal rates. The immediate halt on new development is applied without knowledge of the specific relationship between aquifer yield and the targeted depletion limit. The result of this misapplication is excessive drawdown in the case of the regional aquifer, and conversely, unnecessary constraints on pumping in the alluvial and confined aquifers.

In actual stream-aquifer systems, there is some degree of uncertainty in aquifer yield predictions. Groundwater-level monitoring is necessary to check the accuracy of these predictions. Groundwater-level triggers should be used to identify problem areas or warn of conditions that might be different than predictions indicated. The triggers should initiate a management response that includes further study to develop a better understanding of the system and improve the reliability of the aquifer yield predictions.

**Transient Hydrologic Budgets**

Transient hydrologic budgets were calculated for each model at each depletion limit. The lengths of each of the three main phases of the transition curves are shown in Table 1. The alluvial aquifer displays a rapid transition for each depletion limit. The confined aquifer model, however, exhibits considerable variation in the length of the transitional phase. This variation is due to the aquifer changing from confined to unconfined during some simulations, as explained in the previous section. The regional aquifer model responds very slowly to development. It is
worth noting that in the 25% depletion scenario for the regional aquifer, the aquifer depletion after 100 years of development causes an 18% reduction in the overall aquifer yield.

As stated above, each aquifer depletion limit has a corresponding pumping rate, or aquifer yield. The principles of hydrologic mass balance require that surface water be depleted by an amount equal to the aquifer yield (minus any increased recharge) during the surface-water capture phase. The magnitude of this depletion in relation to the water demands will be important if it occurs within the planning horizon. If, however, the transition is incomplete at the end of the planning horizon, surface-water depletions will be some fraction of the aquifer yield. In such cases, it is necessary to examine the degree of depletion to each source at given times. Table 2 lists these depletions for the hypothetical systems based on available water for each source. The time interval of interest is selected from the left side of the table. The depletion limit of interest is selected from the top. The intersection of these two components gives the percent depletion of the aquifer (A), stream baseflow plus induced recharge (S), and evapotranspiration (ET). For example, the table could be used to compare predevelopment and postdevelopment water budgets for each system at 40 years under a 25% depletion scenario (Fig. 5).

To assess a more realistic development scenario in which pumping steadily increases over time, the example given in the previous section can be used. Figure 6 is based on the same example shown in Figure 4. It illustrates the effects of pumping on streamflow depletions (baseflow capture + induced recharge). In the alluvial aquifer, stream flow is depleted by 24% when the trigger is tripped and stays at that level until the end of the planning horizon. In the regional aquifer, the stream flow is depleted by 21% when the trigger is tripped, but it continues to increase throughout the planning horizon, reaching 49% at 90 years. In the confined aquifer, stream flow is depleted by 89% when the trigger is tripped and reaches 100% at around 75 years. If these depletions result in stream flows that are insufficient to meet demands, then it may be necessary to implement some management action to satisfy the criteria for the surface-water flows.

The use of aquifer depletion limits alone without knowledge of the aquifer yield and surface-water depletions (i.e., an aquifer mining strategy) would only be suitable for groundwater developments that do not proceed beyond the groundwater mining stage within the planning horizon. In the hypothetical systems in this study, the mining stage varies from 1 day to 7 years (Table 1). Planning horizons on the order of 20, 50, or even 100 years are not uncommon in groundwater quantity management, so a groundwater mining strategy based only on aquifer depletion limits would not be suitable in any of these hypothetical systems. Deeply buried aquifers in which pumping is located far away

<table>
<thead>
<tr>
<th>Model</th>
<th>Depletion limit (%)</th>
<th>Mining phase (years)</th>
<th>Transitional phase (years)</th>
<th>Beginning of surface-water depletion phase (years)</th>
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<td>0.002 (1 day)</td>
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<td>1.9</td>
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<td></td>
<td>10</td>
<td>0.002 (1 day)</td>
<td>2.2</td>
<td>2.2</td>
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<tr>
<td></td>
<td>15</td>
<td>0.002 (1 day)</td>
<td>2.4</td>
<td>2.4</td>
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<tr>
<td></td>
<td>25</td>
<td>0.002 (1 day)</td>
<td>3.1</td>
<td>3.1</td>
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<td>43</td>
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<td></td>
<td>10</td>
<td>0.5</td>
<td>42.5</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.5</td>
<td>439.5</td>
<td>440</td>
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<tr>
<td></td>
<td>25</td>
<td>0.5</td>
<td>799.5</td>
<td>800</td>
</tr>
<tr>
<td>Regional aquifer</td>
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<td>7</td>
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<td>25</td>
<td>7</td>
<td>263</td>
<td>270</td>
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</table>
### TABLE 2
WATER BUDGETS AT GIVEN TIMES SHOWING DEPLETION PERCENTAGE FOR EACH COMPONENT

#### A. Alluvial aquifer

<table>
<thead>
<tr>
<th>Component</th>
<th>5% Depletion limit</th>
<th>10% Depletion limit</th>
<th>15% Depletion limit</th>
<th>25% Depletion limit</th>
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<tr>
<td></td>
<td>A</td>
<td>S</td>
<td>ET</td>
<td>A</td>
</tr>
<tr>
<td>1 day</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1 week</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>1</td>
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<tr>
<td>1 month</td>
<td>1</td>
<td>6</td>
<td>15</td>
<td>2</td>
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<tr>
<td>6 months</td>
<td>3</td>
<td>10</td>
<td>49</td>
<td>6</td>
</tr>
<tr>
<td>1 year</td>
<td>4</td>
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<td>64</td>
<td>8</td>
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<td>2 years</td>
<td>5</td>
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<td>70</td>
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<td>75 years</td>
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<td>100 years</td>
<td>5</td>
<td>13</td>
<td>71</td>
<td>10</td>
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#### B. Confined aquifer

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<tr>
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<th>15% Depletion limit</th>
<th>25% Depletion limit</th>
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</thead>
<tbody>
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<td></td>
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<td>S</td>
<td>ET</td>
<td>A</td>
</tr>
<tr>
<td>1 day</td>
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<td>0</td>
<td>0</td>
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<td>1 month</td>
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<td>0</td>
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<tr>
<td>6 months</td>
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<td>17</td>
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<tr>
<td>1 year</td>
<td>6</td>
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<td>17</td>
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<td>75 years</td>
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<td>9</td>
<td>1</td>
</tr>
<tr>
<td>100 years</td>
<td>7</td>
<td>1</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

#### C. Regional aquifer

<table>
<thead>
<tr>
<th>Component</th>
<th>5% Depletion limit</th>
<th>10% Depletion limit</th>
<th>15% Depletion limit</th>
<th>25% Depletion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>S</td>
<td>ET</td>
<td>A</td>
</tr>
<tr>
<td>1 day</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1 week</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1 month</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>6 months</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>1 year</td>
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<td>0</td>
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<td>0</td>
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<td>2 years</td>
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<td>0</td>
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</tr>
<tr>
<td>5 years</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>10 years</td>
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<tr>
<td>100 years</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes: Percentages based on flows at given times compared to total available water during predevelopment. Numbers rounded to the nearest whole percentage. Available water values are as follows: Alluvial aquifer: A = aquifer saturated thickness (46.5 m), S = stream baseflow (0.07 × 10^6 m^3/day) + induced recharge (3.77 × 10^6 m^3/day maximum), ET = groundwater evapotranspiration (0.05 × 10^6 m^3/day). Confined aquifer: A = aquifer potential saturated thickness (68.3 m), S = stream baseflow (1,468 m^3/day) + induced recharge (2,447 m^3/day maximum), ET = groundwater evapotranspiration (2,936 m^3/day). Regional aquifer: A = aquifer saturated thickness (112 m), S = stream baseflow (0.02 × 10^6 m^3/day) + induced recharge (2.45 × 10^6 m^3/day maximum), ET = groundwater evapotranspiration (0.13 × 10^6 m^3/day).
from surface-water sources are more suitable candidates for an aquifer mining strategy (e.g., Lyford et al. 1980).

**PROCESS FRAMEWORK FOR GROUNDWATER QUANTITY MANAGEMENT**

Groundwater management should be part of a dynamic process, one in which aquifer depletion criteria are assessed in relation to the entire hydrologic system using site-specific monitoring, data analysis, and modeling of the specified stream-aquifer system being managed. This process should incorporate stakeholder involvement, scientific and engineering analysis, and a planned pathway for allowing multiple iterations and improvements. It requires knowledge of the social, environmental, and economic water requirements, as well as compromises between entities with competing needs.

Some degree of surface-water depletion is inevitable in most groundwater developments. Aquifer depletion criteria must therefore be viewed holistically, taking into consideration not only the magnitude and timing of aquifer storage depletion but also the degree of depletion to streams, springs, marshes, and lakes. Some groundwater management districts in Kansas, for example, have amended their safe yield policies to include consideration of baseflow to streams when evaluating well permit applications (Sophocleous 2000). In New Mexico and Colorado, new groundwater appropriators must purchase and retire surface-water appropriations or develop augmentation plans to offset stream depletion effects (Aiken 2003). These policies are also taking shape in Nebraska as the state works with NRDs in fully appropriated or overappropriated areas to develop integrated management plans (NDNR 2008).

Presented below is a generalized process framework for groundwater management in which the suitability of aquifer depletion criteria can be assessed for a groundwater system in relation to the various water demands and transient hydrologic effects of development. The process includes four basic steps: (1) define planning horizon and identify constraints on water supplies, (2) calculate predicted hydrologic fluxes for the given system, (3) evaluate effects of hydrologic fluxes on water supply constraints, and (4) prepare management strategy to satisfy constraints.

**Step 1: Define Planning Horizon and Identify Constraints**

This step identifies the physical, economic, social, and environmental needs for water. Stakeholder involvement is essential. Compromises will need to be made based on the tradeoffs between potential impacts to the water interests of the region (Maimone 2004). Specific questions need to be asked, such as: What is the first unacceptable effect that will occur upon a groundwater-level decline? Are there key locations that are particularly sensitive to water-level changes? What are the minimal water levels for the aquifer as a whole and the above-mentioned key locations? What are the physical and economic limits on

![Figure 5. Water budgets for each model at predevelopment and 40 years after development, with pumping rates for 25% depletion scenario (Fig. 3). Water budget calculations based on MODFLOW output files. Alluvial aquifer is in surface-water depletion phase, whereas the confined and regional aquifers are in the transitional phase. All units in 1,000 m$^3$/day.](image-url)
groundwater-level declines and induced recharge (Mandel and Shiftan 1981; Balleau 1988)? A pattern of development, including future projections of water use, will need to be compiled in order to understand the temporal aspect of these constraints. This process is likely to be complicated, and it may not be possible to reach complete agreement on answers to these questions. Nonetheless, it is important to identify specific constraints in this step so that the effects of development on these water needs and limits can be assessed during the next step.

**Step 2: Calculate Predicted Hydrologic Fluxes**

Information regarding hydrologic fluxes for an actual stream-aquifer system throughout the planning horizon, coupled with a projected pattern of drawdown, is a suitable hydrologic basis for groundwater planning policies (Balleau 1988). The generic models in this study demonstrate how numerical groundwater models are used to simulate stream-aquifer dynamics and calculate these fluxes. Development of a site-specific groundwater model during this step allows hydrogeologists to test various options for groundwater management for the system under consideration.

Developing transition curves for a particular stream-aquifer system requires detailed knowledge of the hydrogeologic framework, water budget, and projected future demands. Lack of this information may hamper efforts to develop groundwater models and implement new management schemes. It may therefore be preferable to find the least complex explanation that still results in a usable model of the system. Since this process is iterative, improvements and new information can be incorporated at any time.

**Step 3: Evaluate Effects of Fluxes in Relation to Constraints**

This step involves comparing the constraints identified in step 1 to the predicted hydrologic fluxes in step 2. Specific questions need to be asked, such as: Were minimal water levels maintained throughout the planning horizon? Were minimum stream flows maintained? Were there any specific areas in which groundwater-level declines or streamflow depletions were excessive? Are there any extra sources of water that can be used to offset the impacts? If certain areas are particularly sensitive, or if there is a large degree of uncertainty in the system, groundwater-level triggers can be used as one way to warn of system responses that might impact water users in a negative way. These triggers can only be used to initiate a proper management response if the system is understood correctly. Therefore, triggers used in this manner should initiate efforts to further understand the

![Figure 6. Streamflow depletion curves in relation to periods of increasing pumping rates and constant pumping rates using 10% groundwater-level trigger, 15% aquifer depletion limit, and 40-year planning horizon.](image)
system. This understanding can then be used to initiate a proper management response.

**Step 4: Prepare Management Strategy to Satisfy Constraints**

In this step, the limits identified in step 1 may need to be modified. This may require new compromises on the tradeoffs between different uses. For example, if the hydrologic fluxes are such that minimum groundwater levels are maintained within the limits, but stream flows are not, then one or both of the limits may need to be changed. It is necessary to identify the rates of pumping that will be required to satisfy the new constraints. Water conservation efforts or augmentation technologies may be employed to offset the impacts.

The process outlined here does not terminate with this step. Additional modeling of the system will likely be required regardless of the particular management strategy decided upon. The results of these analyses should be shared with stakeholders so that they can make further decisions to maximize the benefits, minimize negative impacts, and develop the water supplies within the identified constraints.

**CONCLUSIONS AND RECOMMENDATIONS**

Aquifer depletion criteria, commonly used in the Great Plains to manage groundwater resources, may not be suitable as stand-alone criteria for many stream-aquifer systems. Management actions should be based on knowledge of the effects of pumping at specific rates, locations, and durations. Withdrawal rates should be based on aquifer yield and groundwater-level drawdown predictions. Groundwater-level monitoring should be used to check these predictions. Groundwater-level triggers could be used to identify local problem areas, check aquifer yield predictions, and initiate further investigations aimed at identifying solutions or alternatives to the particular problem.

Management strategies should also be based upon knowledge of the transient hydrologic budget for a particular stream-aquifer system. A groundwater management policy based solely on aquifer depletion limits (groundwater mining strategy) is suitable for a system that does not proceed past the groundwater mining stage within the planning horizon. None of the hypothetical examples given here meet this criterion. An aquifer depletion limit should be considered as just one of many possible constraints on water usage. Identifying these constraints should be part of a dynamic and iterative management process.

The four-step process for groundwater quantity management is intended to promote the development of flexible strategies rather than rigid policies. This style of management, often termed adaptive management, is a collaborative and consensus-seeking approach that allows for improvements as new information or explanations come along (Sophocleous 2000; Maimone 2004). This framework can be used as a general guideline for assessing the suitability of aquifer depletion criteria and developing water resources management strategies that incorporate the hydrologic principles of mass balance.

**REFERENCES**


Nebraska Department of Natural Resources (NDNR). 2009. *Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. NDNR, Lincoln, NE.


