Limits to Groundwater Development—

Toward a Better Understanding

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How much groundwater do we have left? Are we running out? How sustainable is our use of groundwater, and how responsive is groundwater to different management strategies? These basic and seemingly simple questions are being asked throughout the Southwest and even in more humid parts of the country.

The answers depend, in part, on assumptions about future population growth, agricultural and industrial water demands, water transfers, and technological innovations—each of which can have large uncertainties. For example, what are the future technological contributions from desalination, water reuse, cloud seeding, and so forth? Likewise, changing circumstances (such as climate change) and a growing knowledge base imply the need for periodically updated resource estimates.

Assessments of change induced by groundwater withdrawals commonly have focused on water-level and storage declines. However, depletion of a small part of the total volume of water in storage (sometimes only a small percentage) may have large effects on surface water, water quality, and land subsidence, which become the limiting factors to development of the resource. For example, areas with well-known and significant concerns about the effects of pumping on surface-water resources, yet where depletion of total groundwater storage is limited, include the Edwards aquifer in Texas, the Upper San Pedro Basin in Arizona, and the Upper Republican River Basin in Colorado, Kansas, and Nebraska (Alley, 2007). Likewise, the Central Valley of California and the greater Houston area of Texas have vast groundwater resources, but land subsidence from pumping has forced expensive conversions to a partial reliance on surface water.

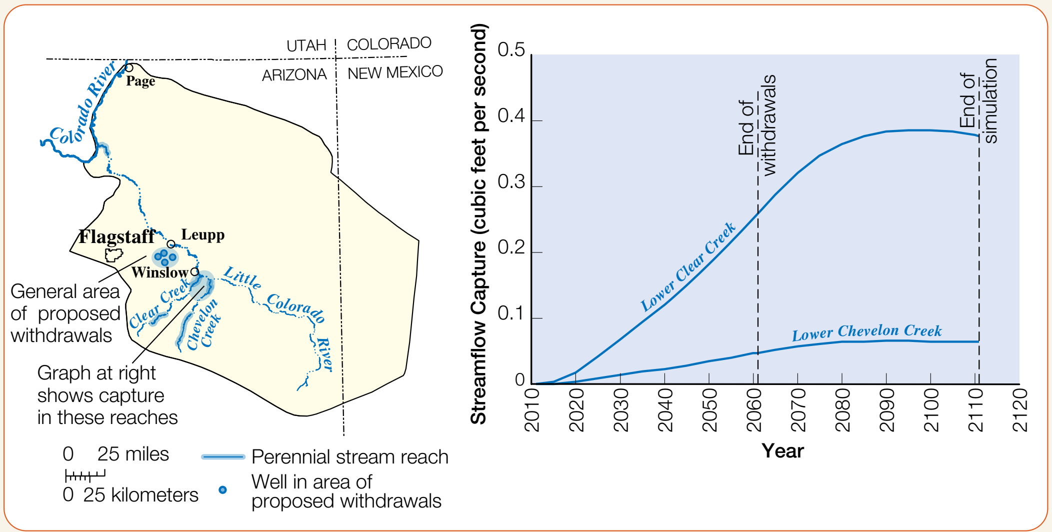
Understanding the limits to groundwater development is thus an evolving and value-laden process. Defining an acceptable level of groundwater use commonly is framed in terms of sustainability, a concept that is not purely scientific, but rather depends on society's willingness to accept the long-term consequences of different levels of groundwater development (Alley and Leake, 2004). Because many of the changes manifest themselves slowly, modeling is an essential tool for addressing these issues. Water-level data alone will not indicate how future streamflow depletion will evolve from pumping that has already occurred. With these considerations in mind, we highlight three technical areas where improved applications of models can contribute to a better understanding of the limits to groundwater development.

The Dynamics of Streamflow Capture

"Capture" is the total withdrawal-induced change in the rate of groundwater flow to or from surface-water features. The areal distribution and timing of capture is central to many debates about the limits of groundwater development. As an example of the types of questions now being asked, Leake and others (2005) looked at possible capture from proposed groundwater withdrawals from the C aquifer around Leupp, Arizona (see figures below). Of concern was capture of streamflow in lower Clear and Chevelon creeks, about 20-25 miles southeast of the withdrawal site. A relatively simple (superposition) groundwater model was constructed to represent most of the aquifer and the hydraulically connected stream reaches of interest. One scenario that was tested involved withdrawals of about 6,500 acre-feet per year (9 ft^3/sec) from 2010 to 2060, with no withdrawals occurring thereafter. A number of insights can be gained from the resulting graph of capture (below left). First, the rate of capture is greatest (but not exclusively) from Clear Creek, which is closer to the withdrawal location. Second, with the distances and aquifer properties involved, the process of capture is slow, occurring gradually over decades. Third, the maximum capture in each stream is much smaller than the withdrawal rate and occurs several decades after pumping ceases. These and other insights from capture analyses can be used in the larger decision-making process regarding whether or not a specific proposed withdrawal scenario exceeds an acceptable limit to groundwater development.

Use of Simulation-Optimization Modeling

Groundwater simulation models have been linked with optimization techniques to determine optimal water-management



Simulated streamflow capture from a scenario of proposed groundwater withdrawals from the C aquifer near Leupp, Arizona. Source: Leake and others, 2005.

strategies. This same approach can be used to evaluate the limits of sustainable groundwater development under specified objectives and constraints (Barlow, 2005). Although the optimal distribution of pumping may not be implemented, insights into system limits and the tradeoffs between those limits and specified constraints can benefit future management.

Consider the Mississippi River Valley alluvial aquifer in southeastern Arkansas (shown at right). A groundwater model indicated that a continuation of 1997 withdrawal rates would violate requirements to maintain saturated thickness at greater than 50 percent of predevelopment levels, and even indicated dry areas within the aquifer. Simulation-optimization modeling was used to estimate maximum possible withdrawals from the aquifer such that the saturated-thickness constraints were satisfied and streamflow in hydraulically connected streams remained above minimum specified rates to maintain water quality, navigation, and species habitat. The modeling indicated that the desired results could be achieved with a 4-percent reduction in groundwater pumping, with the difference made up by surface-water withdrawals. Simulated hydraulic heads under the two scenarios are shown on page 21.

Integrated Monitoring and Modeling

Monitoring and modeling are complementary activities, but too often are treated separately, ignoring important linkages and feedbacks. In a more integrated approach (see chart below), monitoring data serve as primary information for calibration of computer models. But the process of model calibration and use also provides important insights into the adequacy of and gaps in monitoring data. Unfortunately, evaluation of monitoring networks at the conclusion of a modeling study rarely occurs. Likewise, periodic model updates are needed to incorporate new data and understanding about aquifer systems. For example, estimates from environmental tracers of the age of groundwater (time since recharge) compared to ages inferred from modeling may lead to updated conceptual models of how the groundwater system works. Overall, an iterative process is needed to periodically update conceptual and simulation models, which in turn provide feedback to long-term monitoring strategies and scientific studies. This is a simple concept rarely achieved in practice.

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Going Forward

Defining limits to groundwater development is complex because of the dynamics of groundwater systems, climate, population, and technology. The significant uncertainties associated with the spatial and temporal effects of pumping on surface-water resources present particular challenges. Simulation-optimization modeling tools can help provide bounds on possible sustainable groundwater use under different management objectives and constraints. Using an integrated approach to monitoring and modeling, the status of the groundwater system can be tracked and a better factual foundation obtained to determine the limits to groundwater development.

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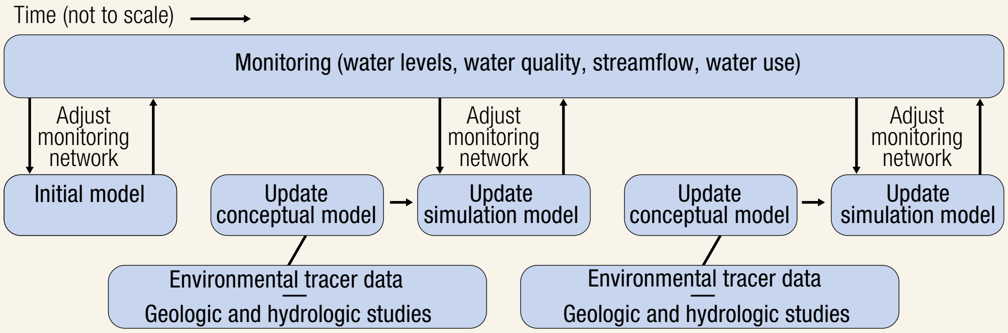
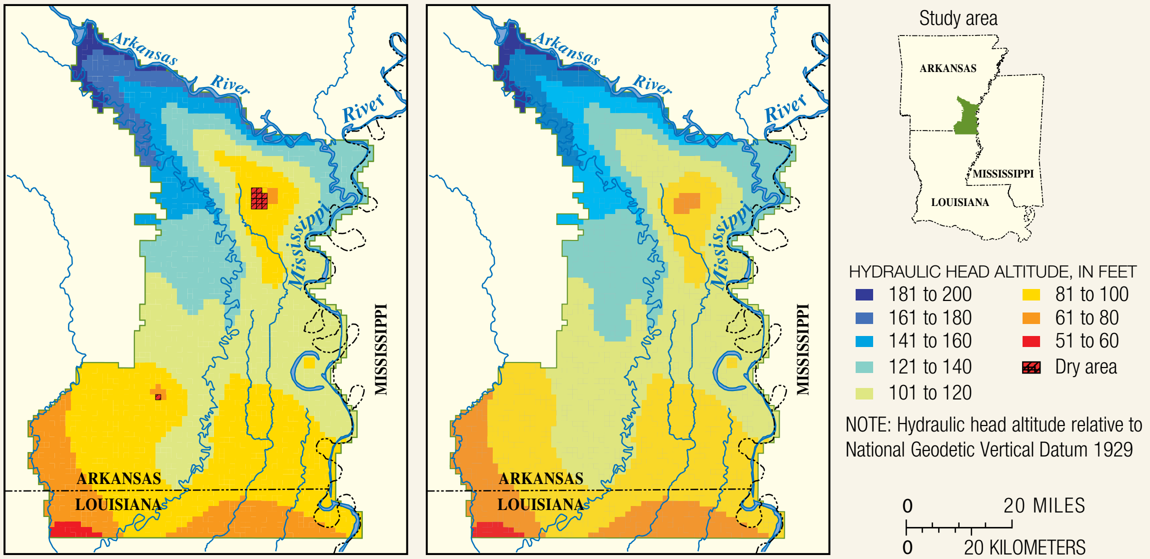


Integrated approach to monitoring and modeling. Source: Alley, 2006.



Simulated steady-state water levels in the Mississippi River Valley alluvial aquifer using (left) 1997 withdrawal rates, and (right) withdrawal rates calculated with an optimization model that maintained saturated thickness at greater than 50 percent of predevelopment levels. Source: Czarnecki and others, 2003.

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