ground water

Issue Paper/

The Journey from Safe Yield to Sustainability

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Abstract

Safe-yield concepts historically focused attention on the economic and legal aspects of ground water development. Sustainability concerns have brought environmental aspects more to the forefront and have resulted in a more integrated outlook. Water resources sustainability is not a purely scientific concept, but rather a perspective that can frame scientific analysis. The evolving concept of sustainability presents a challenge to hydrologists to translate complex, and sometimes vague, socioeconomic and political questions into technical questions that can be quantified systematically. Hydrologists can contribute to sustainable water resources management by presenting the longer-term implications of ground water development as an integral part of their analyses.

Introduction

With increased worldwide attention to the theme of sustainable development and its extension to the sustainability of ground water resources, one might ask how this new concept of sustainability relates to safe yield, and to what extent do the controversies surrounding safe yield carry over to sustainability. Has the term safe yield simply been reinvented as sustainability? To examine these questions, we begin with a brief review of how the two concepts evolved.

The Concept of Safe Yield

The safe-yield concept derives from water supply engineering studies. Originally, the concept focused on the relation between the size (capacity) of a surface water reservoir and its safe yield, defined as the maximum quantity of water that could be supplied from the reservoir during a critical period. With respect to ground water resources, Lee (1915) first defined safe yield as the quantity of water that can be pumped "regularly and permanently without dangerous depletion of the storage reserve." Meinzer (1923) later defined safe yield as "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." It is noteworthy that Meinzer's definition used economic factors as a key determinant and, like Lee, focused on depletion of ground water resources. Over time, the concept expanded to include degradation of water quality (Conkling 1946), the contravention of existing water rights (Banks 1953), and other factors. Todd (1959) succinctly and broadly defined the safe yield of a ground water basin as "the amount of water which can be withdrawn from it annually without producing an undesired result."

Various authors have recommended abandoning the term safe yield (Thomas 1951; Kazmann 1956) because of its vagueness, its misinterpretation by laypersons as implying a fixed underground water supply, and its dependence on the particular locations of wells, among other reasons. Nonetheless, the term is still used, and is even found in some state codes. The fundamental idea behind safe yield—quantifying the desirable development of a ground water basin—remains relevant today.

Many suggestions for improving the safe-yield concept have focused on considering the yield concept in a socioeconomic sense within the overall framework of optimization theory. The optimum yield is determined by selecting the optimal management scheme from a set of possible alternative schemes. Of course, within such a framework, consideration of present and future costs and benefits may lead to optimal yields that involve mining ground water, perhaps to exhaustion.

A common misperception has been that the development of a ground water system is "safe" if the average annual rate of ground water withdrawal does not exceed the average annual rate of natural recharge. Bredehoeft et al.

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(1982) and Bredehoeft (2002) give examples of how safe development depends instead on how much of the pumpage can be captured from increased recharge and decreased discharge. Sophocleous (1997) and Bredehoeft (1997) have further discussed this in editorials.

The Concept of Sustainability

The concept of sustainable development, which emerged in the early 1980s, centered on the idea of limiting resource use to levels that could be sustained over the long term. 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 report was followed by the United Nations Conference on Environment and Development (Earth Summit) held in Rio de Janeiro, Brazil, in 1992. Several agreements were signed at the conference, the centerpiece of which was a 40-chapter report—*Agenda 21*, an action plan for sustainable development that integrates environmental and developmental concerns. The recent World Summit on Sustainable Development held in Johannesburg, South Africa, highlighted the challenges of achieving the ideals that have been attached to the concept of sustainable development. Water resources sustainability also continues to move into the international spotlight amidst warnings that more than a third of the world's population will not have access to sufficient freshwater by 2025 (Gleick 2001).

Similar to safe yield, ground water sustainability commonly is defined in a broad context, and somewhat ambiguously, as the development and use of ground water resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. Application of the concept of sustainability to water resources requires that the effects of many different human activities on water resources, and on the overall environment, be understood and quantified to the extent possible (Sophocleous 1998; Alley et al. 1999; Sophocleous 2000). In this respect, the importance of managing water at the basin scale, or watershed approach, has emerged along similar lines to the concepts of sustainable development.

Sustainability, like safe yield, is a value-laden concept and one that in many respects is in the eye of the beholder. Defining and measuring sustainability is a major challenge (UNESCO 1999; Loucks 2000). The term sustainability embodies conceptual ambiguities that can be difficult to resolve because they rest on philosophical disagreements (Norton and Toman 1995). For example, ecologists might consider sustainability as use of resources that allows perpetual survival of existing ecosystems, while economists view it more as an allocation of resources that leaves future generations no worse off than present generations. Economists further tend to think about a continuum of sustainability ranging from weak to strong sustainability, with variations in between (Stewart 2003). Weak sustainability requires one generation to hand over to the next a nondeclining total capital stock, which assumes that perfect substitution exists between different types of capital, e.g., new technologies for water treatment or improved water use efficiencies might be developed that somehow substitute for the reduced capital stock of aquifer water. Strong sustainability, on the other hand, assumes that some kinds of natural capital have no substitutes.

In addition to this complexity of values at a given point in time, values relating to the sustainability of ground water resources change with time. For example, in the first comprehensive paper on the effects of withdrawals on aquifer flow components, Theis (1940) indicated no economic loss would be suffered in the capture of ground water that was previously being discharged by nonbeneficial vegetation. In the mid–20th century, native vegetation that consumed ground water was considered, particularly in the American West, to be nonbeneficial. Today, economists recognize a nonmarket value of features such as native vegetation (Brookshire et al. 1986). As values have evolved in the past decades, they are likely to evolve further in the coming decades. These evolutions will continue in various ways in different countries at different stages of development.

Some have argued that humans have advanced at times by a series of unsustainable developments. For example, use of ground water from the Chalk Aquifer of the London Basin in Great Britain during the 19th and early 20th centuries was not sustainable over the long run, but enabled London to develop as a major center of population and manufacturing (Downing 1993). Likewise, Los Angeles, California, relied on ground water in storage even though the supply was being depleted because of the expectation that imported water eventually would take the place of water used from storage. Thus, when talking about sustainability, it may be necessary to stipulate the period over which the use is planned and any assumptions about future sources of water supply (Hiscock et al. 2002).

From Safe Yield to Sustainability

It should be clear the concept of sustainability in relation to ground water resources is far from new and is closely aligned with that of safe yield. The differences represent more of a transition, or to paraphrase a National Research Council (1999) report on sustainability, a journey, in our understanding of the dynamic nature of ground water and its linkages across the biosphere and to human activities (Alley et al. 2002).

Safe yield is almost always defined in terms of an annual water withdrawal, whereas the temporal patterns of withdrawal are more open-ended in definitions of sustainability. Indeed, in many situations, a long-term approach to water resources sustainability may involve withdrawals from ground water storage during dry periods that are balanced by replenishment during intervening wet periods.

The definition of safe yield was developed initially based on a very simple view of how a ground water basin might be developed to maximize the quantity of water withdrawn. The concept expanded with time to include economic, legal, and water quality considerations. Sustainability, on the other hand, emerged around the complex interdependence of society and the environment, and the view that no single environmental issue can be addressed in isolation. Presumably, sustainable development encourages integrated water management approaches such as artificial recharge, conjunctive use of surface water and ground water, and use of recycled or reclaimed water, all of which can profoundly affect the magnitude of development that can be sustained.

Although not originally developed with surface water effects in mind, definitions of safe yield in the United States gradually came to consider the effects of pumping on surface water resources, primarily with respect to water rights in streams. Thus, it became accepted that a yield that is safe with respect to ground water storage might not be so safe with respect to natural discharge areas of aquifers. More recently, concerns about the long-term effects of ground water development have been extended to lakes, wetlands, springs, and estuaries, but these issues seem to have been less tied to determinations of safe yield and more generally related to concepts of sustainability. Today, it is widely recognized that pumping can affect not only surface water supply for human consumption, but also the maintenance of streamflow requirements for fish and other aquatic species, the health of riparian and wetland areas, and other environmental needs. The tradeoff between the water used for consumption and the effects of withdrawals on the environment are increasingly the driving force in determining the sustainability of many ground water systems (Alley et al. 1999). Kendy (2003) emphasizes the importance of distinguishing between water consumption and pumping when assessing sustainability.

Water resources cannot be developed without altering the natural environment; thus, one should not define basin yields, either as safe or sustainable, without carefully explaining the assumptions that have been made about the acceptable effects of ground water development on the environment. Even with assumptions about acceptable changes, the concept of a static safe, or sustainable, yield may not be realistic in light of potential changes in hydrology from land-use activities and climate change. For example, urbanization and agricultural development in a basin affect infiltration, runoff, evapotranspiration, and recharge, effectively changing the hydrologic cycle through time.

The Role of Hydrologists

An important attribute of the concept of water resources sustainability is that it fosters a long-term view toward management of water resources. The response characteristics of ground water systems and their boundaries often lend themselves to such a long-term view. For example, pumping decisions made today may ultimately affect surface water resources (riverflows, lake levels, discharges to wetlands and springs, etc.), but these effects may not be fully realized for many years. Equilibrium to pumping is reached only when withdrawal is balanced by capture and, in many circumstances, long periods are necessary before even an approximate equilibrium condition can be reached. Some ground water systems do not have boundaries with sufficient potential for capture to match existing or proposed levels of ground water withdrawals, and, thus, new equilibrium is not possible.

Water resources sustainability is not a purely scientific concept, but rather should be viewed as a perspective that can frame scientific analysis. Key to this idea is that the sustainability goal is very much at the heart of current concerns about the long-term effects of ground water development. We briefly illustrate how ground water hydrologists can contribute constructively to sustainability issues, using Paradise Valley in north-central Nevada as an example.

Case Study: Paradise Valley, Nevada

Natural drainage through the basin-fill aquifer within Paradise Valley runs southward toward the Humboldt River (Figure 1). According to a calibrated predevelopment steady-state model, natural inflow to, and outflow from, the Paradise Valley ground water system was 91 hm^3/year (Prudic and Herman 1996). Approximately 88% of the inflow (recharge) occurred through leakage from perennial and ephemeral streams, and the rest occurred through leakage along mountain fronts and ground water inflow across the eastern part of the southern boundary from the adjacent Humboldt River Valley. About 96% of the discharge occurred through evapotranspiration; the rest occurred through outflow across the western part of the southern boundary to the Humboldt River Valley and as seepage to streams.

Analyses of the flow system in Paradise Valley (Figure 1) were carried out using a three-layer numerical ground water flow model (Prudic and Herman 1996). The model was calibrated for a period of historical pumping, and additional simulations were carried out to study possible effects of long-term pumping and recovery. One of the analyses was the simulation of 300 years of pumping using the magnitude and distribution of pumping in 1982, followed by 300 years with no pumping. The pumping rate was 44 hm^3/year, which is almost half the natural inflow to Paradise Valley.

Results of the analysis (Figure 2) show the long-term consequences of ground water withdrawals. Withdrawals of ground water in Paradise Valley have little potential to increase the total rate of surface inflow to the ground water system because almost all of the surface water that flows into the valley already seeps into the ground water system. Pumping, however, can change ground water underflow to and from the adjacent Humboldt River Valley. The source of water withdrawn by wells initially is a decrease of water in storage in the aquifer. With time, storage changes diminish and the sources of water result in a decrease in evapotranspiration in Paradise Valley and an increase in inflow from, and decrease in outflow to, the Humboldt River Valley. After 300 years, the system is approaching a new steady-state condition, with only 4% of the pumped water coming from storage. At that time, 72% of the pumped water is derived from a reduction in evapotranspiration and 21% is derived from an increase in inflow from the Humboldt River Valley.

This analysis of the effects of long-term withdrawals in Paradise Valley illustrates the role that hydrologists can play in providing information related to sustainability (or nonsustainability) of a particular ground water development. Key information in this case includes measures of water level (head) decline, which can help assess consequences of removal of water from storage; information on

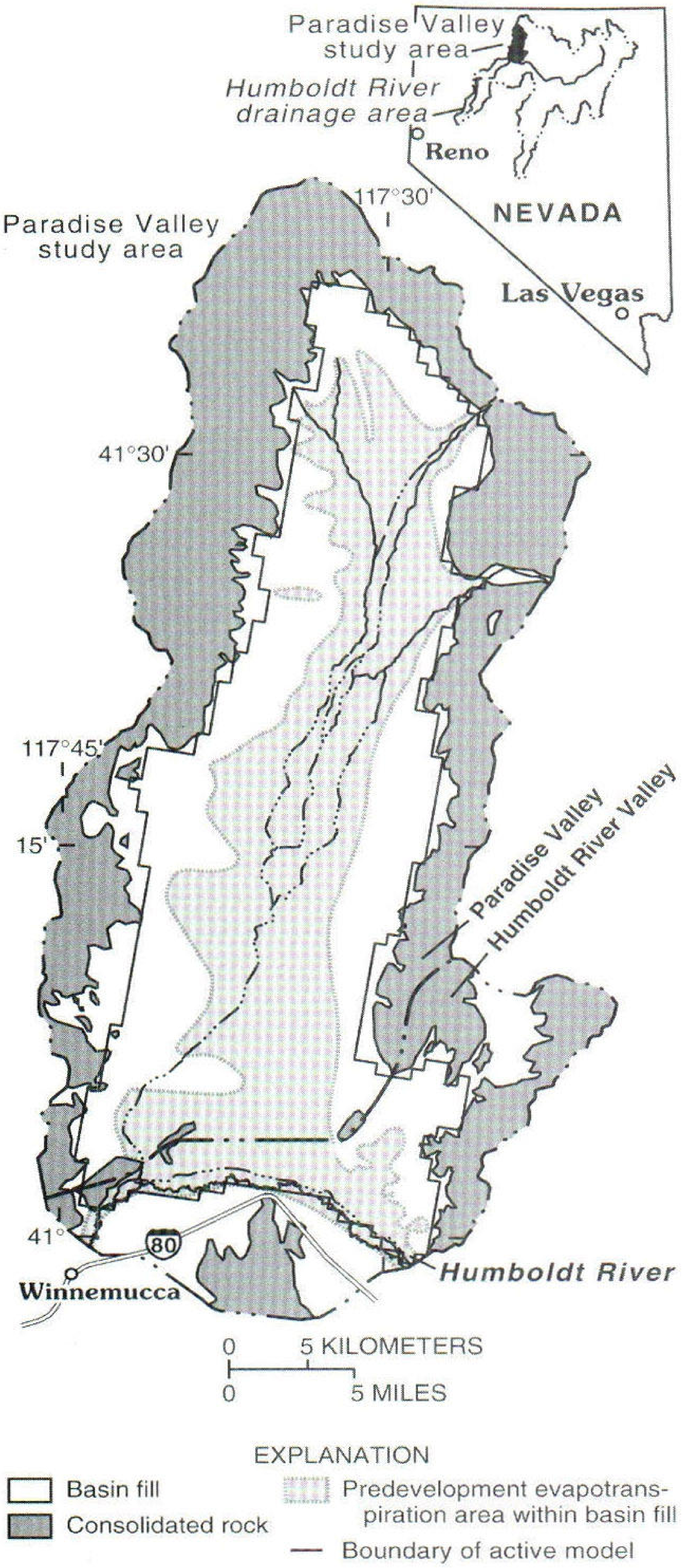

Figure 1. Location of Paradise Valley, Nevada, study area, and select hydrologic and model features. (Modified from Prudic and Herman [1996]).

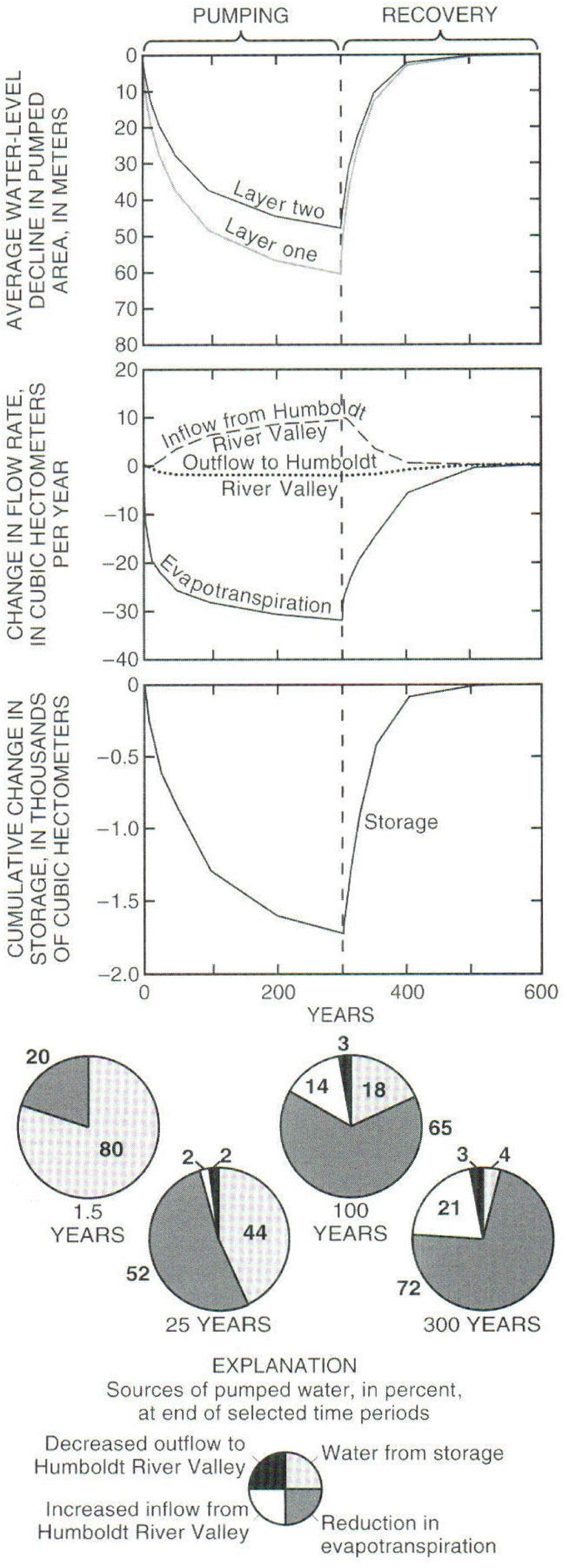

Figure 2. Select results of simulation of ground water withdrawal and recovery for Paradise Valley, Nevada. (Modified from Prudic and Herman [1996]).

likely reduction in availability of water for evapotranspiration; and the long-term effects of withdrawals in one area (Paradise Valley) on the flow system in an adjacent area (Humboldt River Valley), which might be managed separately (Figure 2). The possible progression of these changes because of pumping, as well as the dynamics of system recovery if pumping is reduced or ceased, provides a deeper understanding of the consequences of ground water development. A series of such analyses can portray long-term effects caused by alternative scenarios in which the amounts and locations of ground water withdrawals are varied. With this information, society can make better-informed decisions about how to manage their ground water resources in a long-term context. Such analyses also ideally lead to the design and implementation of long-term hydrologic networks to monitor projected outcomes of the ground water development and to improve the ability to predict future system responses. A key challenge is to extend the types of long-term forecasts of changing water budgets presented here to forecasts of other associated potential impacts, such as riparian vegetation decreases.

Summary Remarks

Although many people have expressed concerns about the ambiguity of the term sustainability, the fact remains that prudent development of a ground water basin in today's world is a complicated undertaking. A key challenge for sustained use of ground water resources is to frame the hydrologic implications of various alternative development strategies in such a way that their long-term implications can be properly evaluated. Each hydrologic system and development situation is unique and requires an analysis adjusted to the nature of the water issues faced, including the social, economic, and legal constraints that must be taken into account. The role of hydrologists in addressing issues of sustainability is evolving as technologies, understanding of the long-term effects of ground water consumption, and societal priorities evolve. For example, meeting the challenges of water resources sustainability increasingly involves understanding and predicting long-term ecological and water quality impacts and applying innovative approaches to conjunctive use of ground water and surface water, artificial recharge, and water reuse. Scientists and engineers should continue to play a key role in shaping this transition.

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