ground water

Issue Paper/

Ground Water Development—The Time to Full Capture Problem

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Abstract

Ground water systems can be categorized with respect to quantity into two groups: (1) those that will ultimately reach a new equilibrium state where pumping can be continued indefinitely and (2) those in which the stress is so large that a new equilibrium is impossible; hence, the system has a finite life. Large ground water systems, where a new equilibrium can be reached and in which the pumping is a long distance from boundaries where capture can occur, take long times to reach a new equilibrium. Some systems are so large that the new equilibrium will take a millennium or more to reach a new steady-state condition. These large systems pose a challenge to the water manager, especially when the water manager is committed to attempting to reach a new equilibrium state in which water levels will stabilize and the system can be maintained indefinitely.

Introduction

This article is an issue paper, a philosophical paper that expresses our viewpoint. A discussion of our perspective will provide a road map for readers. We are concerned with the management of ground water development; we restrict ourselves to water quantity—water quality is always an issue, but it is not our concern here.

Undeveloped ground water systems are commonly found in a state of equilibrium, where, on average, equal amounts of water are recharged and discharged. Ground water systems tend to filter out higher frequency fluctuations in weather; the larger the system, the more filtering it tends to provide. The base flow of streams reflects the effects of the ground water system as a filter. In other words, the larger the ground water system, the more the equilibrium between inflow and outflow reflects long-term averaging of fluctuations in weather. Our analyses generally assume that climate is stationary; if the climate is changing, as recent evidence suggests, then the assumption of equilibrium should be questioned.

Ground water development perturbs the natural equilibrium. We are assuming that a principal objective in managing ground water development is to extend the life of the development as long as is feasible. It is possible for some ground water developments to reach a new equilibrium that includes pumping—we assume that this is desirable from a management perspective. In the new equilibrium state, pumping can be continued indefinitely. In reaching the new equilibrium, the natural state will be perturbed—there will be inevitable impacts on the natural system. Society may decide that the impacts imposed in reaching the new equilibrium are too detrimental, and they may in some way constrain the development. Our focus in this paper is the length of time that some ground water systems take to transition to a new equilibrium state that includes pumping.

Hydrogeologists predict the response time of ground water systems using models. Models provide good predictions in the near field at early times. For example, pumping test analyses give good predictions on how to size the infrastructure, well dimensions, pump size, and so forth. As predictions extend in both time and space, they become more uncertain. Much has been written about this uncertainty. We use model predictions from field situations to illustrate some of our ideas; we are aware of the many pitfalls in modeling and the resulting uncertainty associated

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with predictions (Konikow and Bredehoeft 1992; Bredehoeft 2003, 2005). Nowhere in these discussions of uncertainty did the authors argue that the predictions are not useful. Quite the contrary, we argued that predictions were worthwhile but should be used with a full awareness of the difficulties and resulting uncertainties.

We use Nevada as a prototype for our discussion. Nevada ground water law codifies some of the basic principles of ground water hydrology; for this reason, it is a nice example. Hence, we illustrate our ideas with two examples from Nevada. The most recent example is the proposal by the Southern Nevada Water Authority (SNWA) to develop a large ground water supply in eastern Nevada. The proposed SNWA development is ongoing and in the news. We present model predictions of the proposed SNWA development as an illustration of the major point of our paper. We also discuss how the water manager, in this instance the Nevada State Engineer, dealt with the model prediction that a long time would be required to reach a new equilibrium that includes the proposed pumping.

Nevada, with a few exceptions, treats each individual valley as a legally distinct ground water system. Some of the valleys are hydrologically self-contained; others are integrated by the underlying Carbonate Aquifer that underlies the region. SNWA is seeking water rights in a number of valleys. Each of these valleys requires a separate hearing and ruling by the State Engineer—granting or denying applications to pump ground water. So far there have been two hearings and ruling by the State Engineer who provided SNWA with rights to pump in Spring Valley and more recently in Cave, Dry Lake, and Delamar valleys.

The Water Budget

Meinzer (1931) elaborated on the idea of the water budget to estimate the “safe yield” of aquifers. Meinzer was not the first to express these ideas; he refers back to the earlier work of C.H. Lee from 1908 to 1911 in Owens Valley, California. According to Meinzer (1931), “Before any large ground-water developments are made, the average rate of discharge for any long period is obviously equal to the average rate of recharge.” This was obvious to Meinzer and presumably his colleagues in the ground water community of the day—we have yet to find who first stated this idea. The principle establishes the reciprocal relationship between recharge and discharge in the undeveloped state and allows us to measure one as a surrogate of the other. Meinzer went on to urge the periodic inventory of the system in order to establish the elements of the budget through time.

A budget is a static accounting of the state of the system at a given time, often before the system is developed. Meinzer’s idea was that the amount that could be developed depended upon the quantity of discharge from that system that could be salvaged. Nevada water law codified this idea in their definition of perennial yield:

> *Perennial yield* of a ground-water reservoir may be defined as the maximum amount of ground water that can be salvaged each year over the long term without depleting the ground water reservoir. Perennial yield is ultimately limited to the maximum amount of the natural discharge that can be salvaged for beneficial use . . . .

It follows that:

$$R_0 = D_0 \tag{1}$$

where R_0 is the undeveloped recharge and D_0 is the undeveloped discharge. We can introduce pumping into this expression:

$$R_0 - (D_0 - \Delta D_0) - P = \mathrm{d}V/\mathrm{d}t \tag{2}$$

where ΔD_0 is the change in the discharge created by the pumping (the salvage or capture), P is the rate of pumping, and $\mathrm{d}V/\mathrm{d}t$ is the rate of change of ground water in storage in the system.

Meinzer and others recognized that water must be removed from storage before a new equilibrium state could be reached. Again, Nevada water law codified this storage:

> *Transitional storage reserve* is the quantity of water in storage in a particular ground water reservoir that is extracted during the transition period between natural equilibrium and new equilibrium conditions under the perennial yield concept of ground water development. . . . the transitional storage reserve of such a reservoir means the amount of stored water which is available for withdrawal by pumping during the non-equilibrium period of development (i.e., the period of lowering of water levels).

At the new equilibrium state, the water budget is as follows:

$$\mathrm{d}V/\mathrm{d}t = 0 \quad \text{(by definition)} \tag{3}$$

$$P = \Delta D_0, \quad \text{where } \Delta D_0 \leq D_0 \tag{4}$$

and we constrain the pumping to be less than or equal to the discharge in order to allow a new equilibrium. If we allow for pumping to induce recharge, then at the new equilibrium:

$$P = \Delta R_0 + \Delta D_0 \tag{5}$$

where ΔR_0 is the change in undeveloped recharge produced by the pumping, ΔD_0 is the change in recharge produced by the pumping, and $\Delta R_0 + \Delta D_0$ is defined as the *capture*.

Capture

Theis (1940) introduced the principle of capture. Later, the USGS in Lohman (1972) published the following definition of capture:

> Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture.

Capture is an all-important concept in managing ground water; a ground water system can only be maintained indefinitely if the pumping is equaled by the capture—a combined *decrease* in the undeveloped discharge and *increase* in undeveloped recharge. If pumping continually exceeds capture, then water levels in the system can never stabilize, and the system will continue to be depleted. In other words, if pumping exceeds the potential capture in the system, a new equilibrium state that includes the pumping can never be reached. Again, let us remind the reader that our focus in this discussion is ground water systems that, when developed, can be maintained indefinitely.

The water budget applies to the system at a given time—a snapshot in time. The usual practice is to calculate a budget for the undeveloped state and then for the final state when the system reaches the new equilibrium. In discussing the budget, or inventory idea, Meinzer (1931) drew the analogy to a surface water reservoir. One can pump anywhere from a surface water body and have a similar impact; however, where one pumps in a ground water system becomes important, as we show subsequently. While the water budget describes the state of the system at a given time, it does not inform us about the time path the system will take to reach the new equilibrium state; the time path depends upon aquifer dynamics. It should be remembered that in 1931, when Meinzer wrote his paper, Theis' (1935) seminal paper that presented a general transient ground water flow equation had not yet been published.

In 1931, hydrogeologists did not have the ability to predict the time to reach a new equilibrium state. However, we argue that the expectation of Meinzer's work, and the work of others, was that once pumping was introduced, a new equilibrium would be reached in a reasonable period of time. However, it takes some ground water systems an inordinately long period to reach a new equilibrium. The time may be so long that the fact that a new equilibrium eventually is reached becomes meaningless. It is this problem we address subsequently.

Aquifer Dynamics

Theis (1935) introduced time into ground water theory. This allowed hydrogeologists to make temporal predictions. Historically, the profession went through several phases of prediction. In the 1940s, well hydraulics blossomed. Led by Theis and Jacob, ground water hydrologists solved the boundary value problem associated with various conceptual models of the aquifer and the associated confining layers. The predictive capability associated with the solutions allowed hydrogeologists to estimate relevant parameters of the ground water system—transmissivity, storage coefficient, leakance of a confining layer, and so forth. Armed with a theoretical conceptual model, one could predict response to pumping, which in turn allowed for well design, the sizing of pumps, and well spacing, among other facets of development.

Hydrologists of the day also sought to investigate ground water systems; however, they recognized the limitations imposed by the theoretical approach. Bob Bennett and Herb Skibitski, working at the USGS in the 1950s, developed the resistor/capacitor network, analog model of ground water systems. This allowed the creation of analog models of field systems in which realistic boundary conditions and internally variable parameter distributions could be simulated. The USGS created an analog model laboratory in Phoenix in approximately 1960, where models were constructed and predictions made for several tens of ground water systems. Walton and Prickett (1963) created a similar laboratory at the Illinois State Water Survey where they built analog models of Illinois ground water systems.

By the late 1960s, digital computers had advanced to the point that realistic ground water models could be constructed and analyzed using digital methods (Pinder and Bredehoeft 1968). The technology for solving the resulting massive matrix inversion problems had been pioneered by petroleum reservoir engineers and applied mathematicians working for petroleum companies. Reservoir engineers are involved with solving the same basic flow equation that we use for ground water, and the techniques were readily adapted to ground water problems. Digital computers have become increasingly more powerful; as the computer advanced, so did the ground water modeling technology. One can now create very realistic ground water models on a PC. Techniques are available to optimize the parameter distributions within the models (Hill and Tiedeman 2007). Advances in technology now make it feasible to make predictions of the behavior of complex ground water systems. Predictions, even in the best-calibrated model, have an associated uncertainty. Our predictive capability has grown steadily since Theis (1935) used the analogy between the flow of ground water and the flow of heat and Jacob (1940), starting from first principles, showed that the analogy was correct. Hydrogeologists now routinely predict ground water system behavior.

The Time to Reach a New Equilibrium

Given our ability to predict, it is of interest how long it takes for a ground water system to reach a new equilibrium, assuming that a new equilibrium state is possible. One can envision ground water systems in which the pumping greatly exceeds any potential capture. In such an instance, the system can never reach a new equilibrium, and water levels within the system will continue to decline until the system is depleted. We are concerned here with systems in which a new equilibrium state is feasible—that is, pumping can ultimately be balanced by capture.

Hypothetical Basin- and Range-Valley-Fill Aquifer

We first examine a hypothetical system that resembles some of the valleys in the Basin and Range (Figure 1). The two streams entering the basin on the left provide on

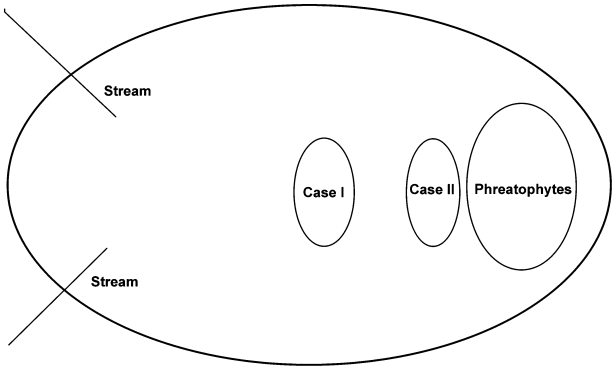

Figure 1. Plan view of a hypothetical valley-fill aquifer in the Basin and Range.

average 100 cubic feet per second (cfs) of recharge to the aquifer. The area of phreatophytes, to the right, discharges on average 100 cfs of ground water through evapotranspiration (ET) before ground water development. We consider two scenarios of ground water development located in the areas labeled case I and case II, respectively; each development pumps at a rate equal to the recharge—100 cfs.

We assume two-dimensional horizontal flow and the properties listed in Table 1. In our hypothetical system, we assume that ground water consumption by phreatophytes is diminished as pumping lowers the water table in the area containing phreatophytes. We deliberately created a ground water system in which capture of water that would otherwise be lost by ET can occur. As the water table drops between 1 and 5 feet, the consumption of ground water by ET is linearly reduced. The phreatophyte reduction function is applied to each cell in the model.

In order for this system to reach a new state of sustained yield, the phreatophyte consumption must be eliminated entirely. Using the model, we can examine the phreatophyte use as a function of time. Figure 2 is a plot of the phreatophyte use in our system vs. time since pumping was initiated. The location of the pumping makes a significant difference in the dynamic response of the system. In case II, where the pumping is close to the phreatophytes, the ET is reduced to 65 cfs in 10 years. In contrast, in case I, the ET is reduced to approximately 5 cfs in 10 years. Case I takes a long time to fully eliminate the ET; it is approximately 1000 years before the ET is totally eliminated. Even seasoned hydrologists are surprised at how long it can take an unconfined system to reach a new equilibrium state in which no more water is removed from storage.

Table 1
Aquifer Properties for Hypothetical Basin Shown in Figure 1

Basin size	50 × 25 miles
Model cell dimensions	1 × 1 mile
Hydraulic conductivity	0.00025 ft/s
Saturated thickness	2000 feet
Transmissivity	0.5 ft^2/s (~43,000 ft^2/d)
Storage coefficient	0.1%–10%
Phreatophyte consumption	100 cfs
Wellfield pumping	100 cfs
Recharge	100 cfs

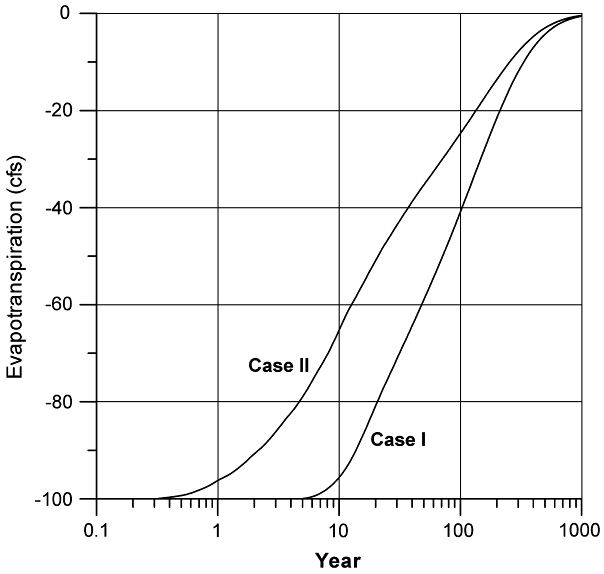

Figure 2. ET vs. time in our hypothetical valley-fill aquifer.

We can also investigate the total amount of water removed from storage in our hypothetical valley-fill aquifer (Figure 3). It is important to notice that even though the two developments (case I and case II) are equal in size, the aquifer responds differently depending upon where the developments are sited. In case II, where the pumping is close to the phreatophytes, the amount of water removed from storage is approximately 50% less than that in case I. In case I, a large cone of depression must be created in order to impact the phreatophyte ET.

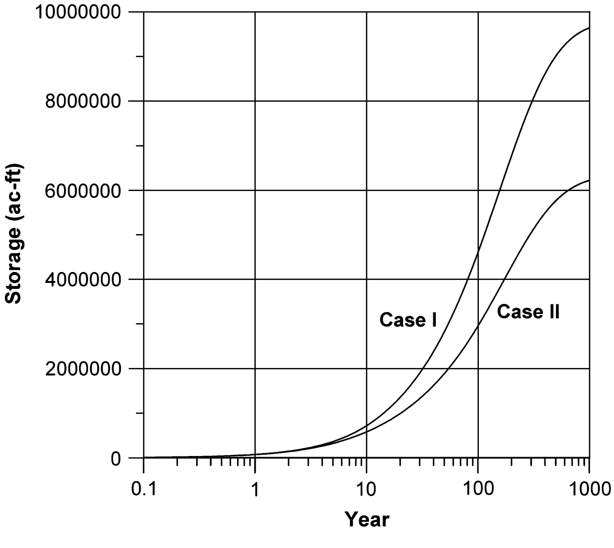

Figure 3. The volume of water removed from storage as a function of time in our hypothetical valley-fill aquifer with two developments—case I and case II (Figure 1).

This example of our rather simple Basin- and Range-valley-fill aquifer illustrates the importance of understanding the dynamics of aquifer systems. While this is a simple example, the principles illustrated apply to aquifers everywhere. In this case, it is the rate at which the phreatophyte consumption can be captured that determines how this system reaches sustainability; this is a dynamic process. Capture always involves the dynamics of the aquifer system. It makes a big difference in the response of the system where the wells are located. Thomas et al. (1989) describe the ground water hydrology of Smith Creek Valley, Nevada, where the USGS did a Regional Aquifer Systems Analysis (RASA) investigation; our simple example has many of the elements of Smith Creek Valley.

Paradise Valley

Alley and Leake (2003) explored the concept of "sustainability"; they used as their example a development in Paradise Valley in northern Nevada. The Humboldt River flows across the southern end of the valley. They used a model of ground water pumping near the southern end of the valley, not too far to the north of the Humboldt River, to examine the source of the ground water pumped vs. time (Figure 4). There are four sources of water that support the pumping: (1) water from storage; (2) capture of ET; (3) capture of surface water leaving the valley; and (4) induced recharge from the Humboldt River. Each of these sources varies with time.

The principal source of ground water in Paradise Valley during the early period is depletion of storage in the system. The storage declines to only 4% of the supply in year 300. The capture of water from ET grows from 20% in year 1 to approximately 75% of the total in year 300. The induced recharge from the Humboldt River grows from 0% in the early years to approximately 20% of the total in year 300. The capture of outflow from the valley grows to 3% in 300 years. The ground water system in Paradise Valley will take more than 300 years to reach a new equilibrium state. The time is about one-third as long as in case I in our hypothetical valley-fill aquifer explored earlier. Even after 300 years, 4% of the water pumped is still coming from storage.

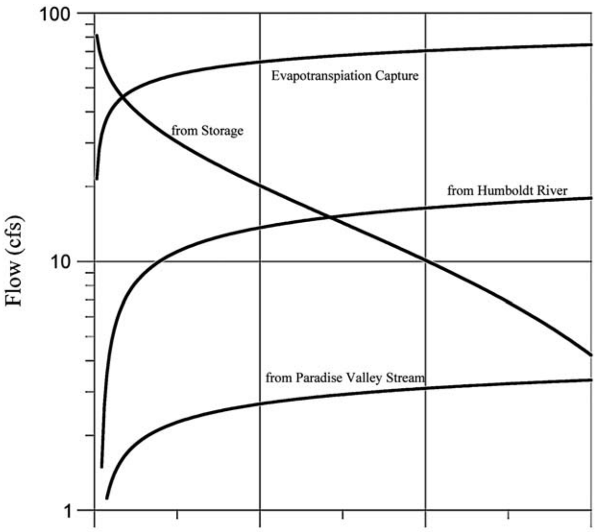

Figure 4. Computed sources of ground water to supply the pumping in Paradise Valley, Nevada (data from Alley and Leake 2003).

Both the induced recharge from the Humboldt River and the reduced outflow from the valley decrease the streamflow of the Humboldt River. This poses a potential future problem since the surface water in the Humboldt River, like most streams in the West, is overappropriated. Downstream surface water users will be hurt as this ground water development goes forward. An investigation of the undeveloped water budget for Paradise Valley would not have indicated induced recharge from the Humboldt River to be a significant source of water to the wells.

SNWA Development

The SNWA is proposing to pump 170,000 acre-feet/year of ground water just to the south of Ely, Nevada—approximately 200 miles north of Las Vegas. The water will be conveyed, via a pipeline, to Las Vegas. This will increase the water supply for Las Vegas by perhaps 40%; the fraction depends upon how much water is available in the future for Las Vegas from the Colorado River. The cost of the pipeline is currently estimated to be more than $3.5 billion.

The area under consideration for development is within the Carbonate Rock Province as defined by the USGS RASA investigation (Prudic et al. 1995), where there is a thick sequence of Paleozoic carbonate rocks. This sequence of rocks usually contains a Carbonate Aquifer that has the potential to integrate ground water flow between the valleys in the area (Eakin 1966). Analyzing ground water flow in this system entails investigating a much larger set of valleys than simply those that contain the pumping. The proposed SNWA pumping is situated mostly within the White River Regional Flow System (Figure 5).

There are several estimates of the recharge and/or discharge for portions of the ground water system pictured in Figure 5 (Eakin 1966; Las Vegas Valley Water District 2001; Welch and Bright 2007). A USGS RASA study of the system indicated that the pumping would reach a new steady state (Schaefer and Harrill 1995). The RASA, while calculating the impacts of a new equilibrium that included the pumping, did not estimate the time to reach the new state, other than to indicate that it was more than 200 years.

We realize that uncertainties associated with models and model predictions place confidence bounds around predicted values. However, we present single-valued graphs of predicted results to illustrate our points; we recognize that this oversimplifies the results. Figure 6 is a model prediction of the expected drawdown of the water table at the new equilibrium state that includes the

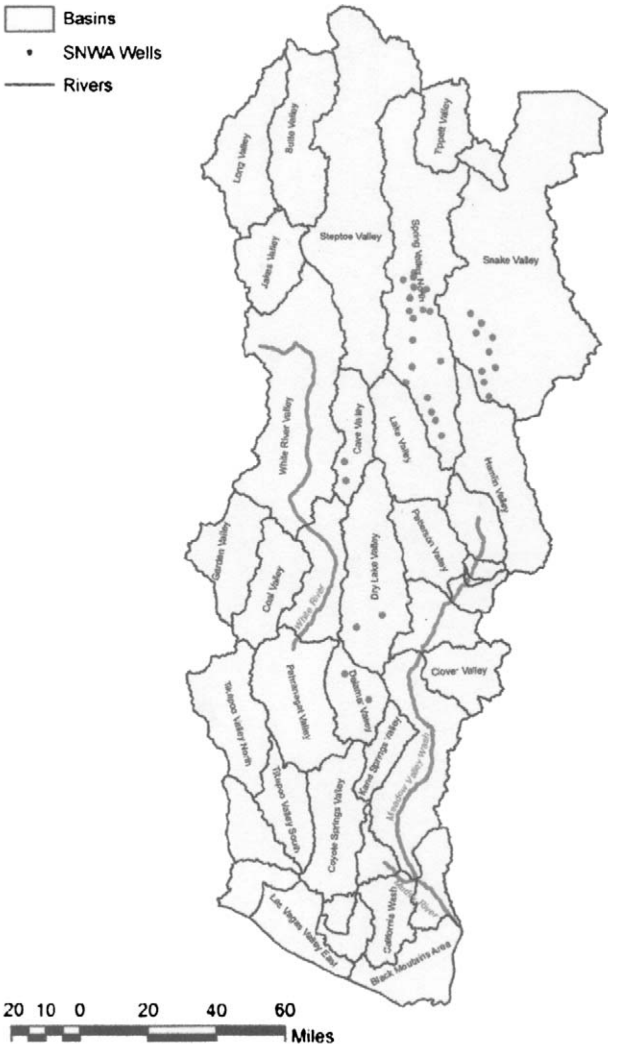

Figure 5. Map of the valleys in Nevada impacted by the proposed SNWA development. The proposed pumping wells are indicated.

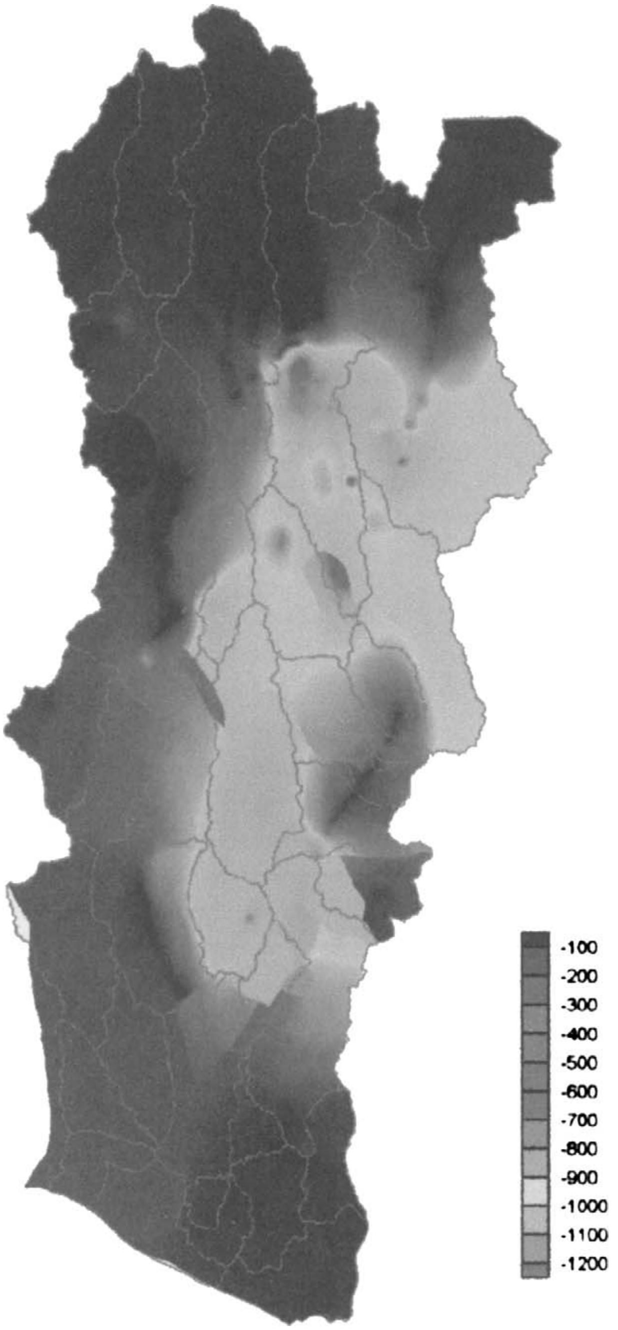

Figure 6. Computed expected drawdown in the water table at the new equilibrium state that includes the proposed SNWA pumping—predicted steady-state model.

proposed SNWA pumping. There is a very large area where the drawdown exceeds 700 feet. The deeper Carbonate Aquifer has similar drawdowns. Of particular interest is how long this system takes to reach the new equilibrium. Figure 7 is a plot of the change in storage in the system vs. time.

This figure is especially telling. The storage should level out and reach a stable level as the system reaches a new equilibrium (as in Figure 3), but this system is not close to reaching a new equilibrium state after 2000 years of projected pumping. A plot of the predicted ET vs. time (Figure 8) shows that the system has not reached a new equilibrium in 2000 years.

Combining Figures 7 and 8, we see that at 500 years, approximately 32% of the water pumped is coming from the depletion of storage and 65% from capture of ET. At 1000 years, 23% is coming from storage and 74% from capture of ET. At 2000 years, 14% is still coming from storage, while 82% is from capture of ET.

Nevada water law has only an implied reference to time; it only requires that the system reaches a new equilibrium state at some undetermined future time. The law was written before the tools were available to predict the future dynamics of ground water developments. The fact that the model predicts times more than 2000 years to reach a new equilibrium should change one's perspective on ground water management of this system.

Monitoring to Control Impacts

A strategy known as adaptive management relies on preventing impacts by monitoring the ground water

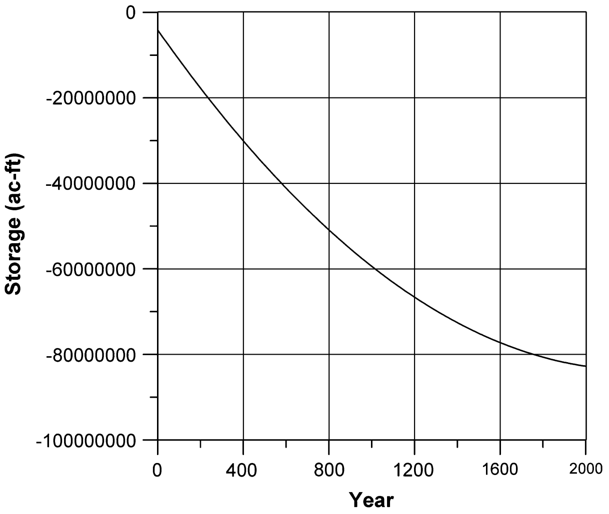

Figure 7. Predicted change in storage with proposed SNWA pumping.

system and changing the pumping stress when an undesirable impact is observed. The federal government entered into such agreements with SNWA before withdrawing their objections to the project. However, long-term monitoring also suffers from a prediction problem associated with the response time of the ground water system. We illustrate the monitoring problem with our hypothetical aquifer (Figure 1). We will examine a situation where we are attempting to maintain a spring at the lower end of our valley. Let us imagine that rather than having an area of phreatophytes discharging ground water, we have a single spring that discharges at 100 cfs before development. Our objective is to maintain the spring flow. We now start the case I ground water development that also pumps at 100 cfs.

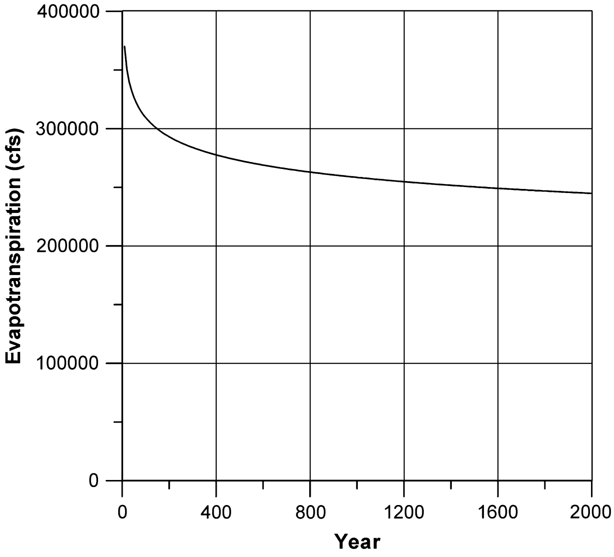

Figure 8. Computed plot of ET vs. time.

Let us further suppose we impose a monitoring and control strategy on the system. We monitor the spring with the intent that once the spring flow drops below 90 cfs (a 10% decline in flow), we will stop pumping ground water; in other words, our intent (as stated earlier) is to preserve the spring flow. We will use a 10% drop in flow as an observable signal that indicates that pumping is impacting the spring; smaller drops in flow could be ambiguous. (We are not arguing that this is a rational policy; rather we are illustrating a point.) Figure 9 shows the discharge of our spring vs. time; pumping stopped in area 1 in approximately 50 years when the spring discharge dropped to 90 cfs. The minimum spring flow occurs at approximately 75 years, 25 years after we stopped pumping. The reduction in flow is 13 cfs—larger than what it was when we stopped pumping. The maximum drawdown at the spring, created by the pumping, takes 25 years after pumping stops to work its way through the system.

We also see that the system does not recover readily to its predevelopment state even though the spring discharge equaled the recharge and was 100 cfs. Perhaps this is best understood if we look at the water removed from storage by the pumping and the rate at which it is replenished. During the period of pumping, the spring flow drops more or less linearly from 100 to 90 cfs. The amount of water removed from storage during this period averages approximately 95 cfs. The reduction in spring discharge averaged 5 cfs over the 50-year period—the capture of spring discharge averaged 5 cfs over the period. In other words, 95% of the ground water pumped during the 50 years of pumping came from storage. During the remaining 250 years since pumping stopped, the spring discharge averaged approximately 90 cfs. During that period, we are putting back in storage, on average, 10 cfs. This means that during the 250 years since the pumping ceased, we have restored just more than 50% of the water that was removed from the storage during the pumping period. You can easily see that this simple system will take approximately 500 years to return to its original state.

This hypothetical model illustrates the monitoring problem. If the monitoring point is some distance removed from the pumping, there will be (1) a time lag between the maximum impact and the stopping of pumping and (2) the maximum impact will be greater than what is observed when pumping is stopped (unless one has reached a new equilibrium state during the pumping period). The time for full recovery of the system will be long, even in the case where one has not reached the new equilibrium.

The real world is more complex. Those that advocate monitoring seldom envision totally stopping the pumping; rather, they imagine changes in the development that minimize damages. Stopping the pumping is a management action of last resort and we showed that it has problems. Less stringent management actions have a correspondingly lesser beneficial impact and even more problems.

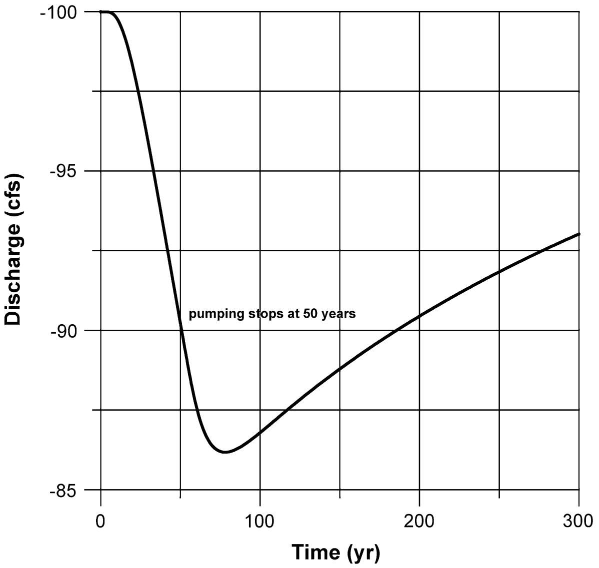

Figure 9. Predicted spring flow from a hypothetical aquifer (Figure 1 with phreatophytes in area 1 replaced by a spring). Pumping ceases after 50 years when the spring flow drops to 90 cfs.

Discussion

We do not think that the SNWA development in Nevada is all that unique nor do we think that this is typically only a western problem. Large aquifer systems exist throughout the country and the world. The response time problem is typical of large systems; there are other developments where the hydrologic boundaries where capture can take place are far from the pumping. Long times will be involved before the system can reach a new equilibrium—assuming that a new equilibrium is feasible. When the time to reach, or even approach, a new equilibrium exceeds a millennium or more, one has to ask—"Is the fact that the system will ultimately reach a new equilibrium meaningful?" It may be too distant in the future to have much meaning—too much can happen, civilizations change, the climate itself may change, and so forth. The bottom line is—it is important to predict the time trajectory of ground water systems, especially if one hopes to manage the system. Hydrogeologists have the tools to make these predictions.

The more vexing problem faces the water managers. For example, the SNWA development in Nevada can, given thousands of years, reach a new equilibrium. The question for the water manger, in this case the State Engineer, is how to deal with a system that takes so long to reach the new state—clearly, the law did not anticipate such long times.

Monitoring for control also has fundamental problems. The maximum impacts are larger than those observed at the time pumping stops, and they occur some time after the pumping stops. This is especially true if the monitoring is some distance away from the pumping. In addition, ground water systems will be very slow to recover to their predevelopment state once pumping is stopped.

In the case of SNWA's recent applications to pump in Cave, Dry Lake, and Delamar valleys, the Nevada State Engineer (2008) dealt with the problem as follows:

> The State Engineer finds that there is no dispute that the basins of the White River Flow System are hydrologically connected, but that does not mean that isolated ground-water resources should never be developed. The State Engineer finds he has considered the hydrologic connection and is fully aware that there will eventually be some impact to down-gradient springs where water discharges from the carbonate-rock aquifer system, but the time frame for significant effects to occur is in the hundreds of years.
>
> The State Engineer finds that a monitoring-well network and surface-water flow measurements will be part of a comprehensive monitoring and mitigation plan that will be required as a condition of approval and will provide an early warning for potential impacts to existing rights within the subject basins and the down-gradient basins of White River Flow System. The State Engineer finds that if unreasonable impacts to existing rights occur, curtailment in pumping will be ordered unless impacts can be reasonably and timely mitigated.

Conclusions

Some ground water systems in which a new equilibrium state that includes pumping can be achieved may take a long time to reach the new equilibrium. This is especially true where the discharge from the system that can potentially be captured by the pumping is a long distance away from the pumping center. Such a system may take more than a millennium, some more than two millennia, to reach the new equilibrium state.

This can pose a problem for the water manager, especially if the manager seeks to achieve a new equilibrium that will allow the pumping to persist for a prolonged period—essentially indefinitely.

One strategy, adopted by the State Engineer in Nevada, is to allow a large amount of pumping, more that can be sustained by a new equilibrium, while monitoring the system for adverse impacts. This strategy poses two problems: (1) a large ground water system creates a delayed response between the observation of an impact and its maximum effect and (2) there is a long time lag between changing the stress and observing an impact at a distant boundary.

If a water manager allows more pumping than the pumping can capture, then sooner or later the pumping must be curtailed or a new equilibrium can never be reached and the system will be depleted.

Acknowledgments

The authors wish to thank the editor and reviewers for their helpful suggestions.

Disclaimer

In fairness to the reader, we need to state that both authors of this paper acted as consultants on issues related to proposed ground water development in eastern Nevada. We consulted on opposing sides—Durbin for SNWA and Bredehoeft for the environmental coalition that opposes the development. Durbin's model of the proposed development for SNWA was documented, including its calibration, in a public document presented to the Nevada State Engineer at a hearing on SNWA's application for permits to pump ground water in Spring Valley, Nevada. Both authors presented the results of Durbin's model analysis in a public statement to the Nevada State Engineer at a hearing on SNWA's application to pump ground water in Cave, Dry Lake, and Delamar valleys, Nevada. The results are presented here as an example of model predictions; the predictions reflect all the caveats stated earlier.

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