ground water

Monitoring Regional Groundwater Extraction: The Problem

by J.D. Bredehoeft

Abstract

As hydraulic disturbances (signals) are propagated through a groundwater system two things happen: (1) the higher frequencies in the disturbance are filtered out by the physics of the system and (2) the disturbance takes time to propagate through the system. The filtering and time delays depend on the aquifer diffusivity. This means, for example, if one is observing a water table aquifer at some distance from where annual recharge is occurring, only the long-term average effect of the recharge will be transmitted to the observation point—the system filters out annual variations. These facts have profound impacts on what is feasible to monitor. For example, if one is concerned about the impact of pumping on a spring in a water table aquifer, where the pumping is more than 20 miles or so from the spring, there will be a long delay before the pumping impacts the spring and there will be an equally long delay before a long-term reduction in the pumping regime will restore the spring. The filtering by lower diffusivity groundwater systems makes it impossible to discriminate between the impacts of several major pumpers in the system and/or long-term climate changes.

Introduction

This article grew out of work associated with the Paleozoic Carbonate Aquifer in Nevada and California. Two projects involve the Carbonate Aquifer: the proposed Nuclear Repository at Yucca Mountain and the proposed groundwater development by the Southern Nevada Water Authority (SNWA) in east-central Nevada. Both proposed developments involve monitoring the groundwater system. In the case of SNWA, the idea is that if adverse impacts were to be observed the development would be modified so as to mitigate undesirable effects. On its face, this sounds like an eminently sensible proposal.

Although this study grew out of my Nevada experience, the principles illustrated in this discussion are widely applicable to large groundwater systems under development. Bredehoeft and Durbin (2008) discussed monitoring briefly, but the idea is sufficiently important that a fuller exploration is warranted. For this article, the proposed Carbonate Aquifer developments in Nevada are a prototype, but these ideas are much more universal.

As background, let me first provide a primer on groundwater in the Great Basin of eastern Nevada and western Utah. Geologically the area is broken into valleys by intervening mountain ranges. Most valleys contain alluvial sediments that are often very permeable aquifers. The aquifers are recharged by springtime runoff of snowmelt from the adjoining mountain ranges. Groundwater discharges usually as springs, some of which are large, and by riparian vegetation which has its roots in the water table—phreatophytes. Most valleys are relatively full of groundwater. Many valleys are self-contained groundwater systems with local recharge to the valley and local discharge from the valley. The valleys are large, roughly 100 miles or so in length and 25 miles wide—some smaller and some larger.

Underlying much of eastern Nevada and western Utah is a sequence of Paleozoic carbonate rocks. These carbonate rocks contain a permeable aquifer—the Paleozoic Carbonate Aquifer. This aquifer has the potential to integrate groundwater flow between valleys. This means, for example, recharge could occur in one valley, but

The Hydrodynamics Group, Sausalito, CA 94965; jdbrede@aol.com

Received September 2010, accepted December 2010.

doi: 10.1111/j.1745-6584.2011.00799.x

the discharge occurs in one or more downstream valleys. Thus, there are parts of the Great Basin where the groundwater flow systems are larger than the single valley. Seen in total, the groundwater system involved in the proposed SNWA development is enormous (Bredehoeft and Durbin 2008). The same is true for the Carbonate Aquifer groundwater system that underlies Yucca Mountain and discharges in the springs at Furnace Creek in Death Valley.

The most sensitive hydrologic features of the area are springs that create oases in the desert. Many of these springs date back to Pleistocene time and have been geographically isolated for many years. Unique species of life, especially unique fish, have evolved in the spring complexes. Some of these species are protected by Federal Law by endangered species designation. In addition, all the water from the springs is appropriated by someone.

SNWA has applied to the State of Nevada for permits to develop more than 150,000 ac-ft/year of groundwater from selected valleys in the Great Basin (Bredehoeft and Durbin 2008). Hearings were held before the Nevada State Engineer seeking permits to pump in a number of valleys. SNWA and the various U.S. Interior Department Agencies involved in administering federal land in the area (the Bureau of Land Management, the Fish and Wildlife Service, and the National Park Service) entered into monitoring agreements, of the kind, described earlier. As a result, the Interior Agencies did not oppose SNWA's development plans for applications associated with a number of valleys. It seemed eminently reasonable to monitor to identify deleterious impacts with the intent of modifying the development to ameliorate the impacts—at least, it did to the Feds.

Similarly should the proposed Nuclear Repository at Yucca Mountain be built, there will be monitoring of the associated groundwater system with the intent of discriminating unwanted effects with a cause.

The SNWA development saga has not played out. There is opposition to the development by the local people potentially impacted by the development and from the environmental community. Recently, the opponents have scored victories in the courts that have, at the very least, slowed the project. Similarly, the fate of the Yucca Mountain Nuclear Repository is still in limbo. The Democratic, Obama Administration would like to kill the project, but the federal courts point out that the United States has no other plans for a nuclear repository.

The question before us is can monitoring as proposed for such a large system as contemplated in Nevada be effective; will it even work?

First Principles

Let us first consider the age old question—where does water come from in the groundwater system when a well is pumped? Lohman (1972) speaking for the U.S. Geological Survey answered this question:

> Water withdrawn artificially from an aquifer is derived from a decrease in storage, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes (Theis 1940). The decrease in discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in groundwater discharge into streams, lakes, and the ocean, or decreases in that component of evapotranspiration derived from the saturated zone. After a new artificial withdrawal from the aquifer has begun, the head in the aquifer will continue to decline until the new withdrawal is balanced by capture.

This idea introduced by Theis (1940) contains the essence of quantitative groundwater hydrology and is elegant in its simplicity. It should be noted that capture is concerned with the changes in the recharge and/or the discharge created by the pumping—not the initial values of recharge and/or discharge.

When pumping occurs, the hydraulic head in the groundwater system declines. As the head declines, water is removed from storage in the aquifer. At some point, the hydraulic head declines in the vicinity of the discharge from the system and the discharge is reduced—in Lohman's words: "captured by the pumping." This means that in the vicinity of phreatophyte plants that draw water directly from the water table, the water table declines and the plants can no longer get water and they die. The head decline produced by the pumping lowers heads in the vicinity of springs and the spring flow declines. The head declines in the vicinity of streams that receive groundwater that creates baseflow and the streamflow declines.

The nature of groundwater systems is such that they have both hydraulic conductivity and hydraulic storativity and can be described mathematically by diffusion equations. Let us briefly look at the two aspects of the groundwater system that place a physical limitations on one's ability to monitor: (1) the filtering by the system of higher frequency signals and (2) the fact that it takes time for the effects of disturbances to propagate through the system.

Both these limitations are based on the diffusivity of the groundwater system which is defined as:

$$\kappa = T/S \quad (1)$$

where κ is the hydraulic diffusivity, T the aquifer transmissivity, and S the aquifer storativity.

We are interested in wells that will produce large quantities of water; we can think about the range of aquifer parameters given in Table 1.

Periodic Signal

Carslaw and Jaeger (1959) indicate that the practical limit of detection of a periodic wave in a diffusive medium is equal to the wave length of the disturbance:

$$\lambda = (8\pi^2\kappa/\omega)^{1/2} \quad (2)$$

where λ is the wavelength and ω the frequency of the disturbance (or signal).

Table 1
Range of Aquifer Parameters

Parameter	Minimum	Maximum
Transmissivity (ft^2/d)	1000	100,000
Storativity	10^{-5}	0.1
Aquifer diffusivity (ft^2/d)	10^4	10^{10}

Table 3
Time at Which a Well Pumping at 1 cfs Will Produce 0.1 Feet of Drawdown

T	*S*	d to 2 mi	d to 10 mi	d to 50 mi
1000	0.1	7700	19,000	
	0.001	77	190	4800
	0.00001	0.77	1.9	48
10,000	0.1	190	4800	
	0.001	1.9	48	1200
	0.00001	0.019	0.48	12
10,0000	0.1	30	750	
	0.001	0.30	7.5	190
	0.00001	0.003	0.075	1.9

A signal of interest is a cycle of recharge at a recharge boundary of an aquifer. We can evaluate the distance at which this signal might be detected in aquifer of varying diffusivities (Table 2).

We see that as the aquifer becomes more transmissive and more artesian, the diffusivity increases and the cyclical signals can be detected further and further into the aquifer. In the case of low diffusivity, usually indicative of a water table aquifer, the cyclical signals cannot be detected very far into the aquifer—the aquifer filters out the signal.

Pumping Disturbance

In a similar manner, we can evaluate the distance at which a pumping disturbance will arrive in an ideal aquifer. The drawdown produced by pumping is

$$S = Q/(4\pi T)W(u) \qquad (3)$$

where s is the drawdown, Q the pumping rate, and $W(u)$ the so-called well function (Lohman 1979).

To illustrate the point, one can evaluate when a well pumping at a rate of 1.0 cubic feet per second (cfs) will produce a 0.1 feet of drawdown at varying distances in aquifer of differing diffusivities (Table 3).

One sees that when aquifers have high storativity, representative of water table conditions, a pumping disturbance propagates slowly through the aquifer, even in aquifer with a high transmissivity. As the aquifer becomes better confined, with a lower storativity, disturbances propagate rapidly through the system.

These two examples are for idealized aquifer. For the cyclical signal analysis, a single aquifer extends to infinity away from the boundary where the periodic signal is applied. For the pumping well, the analysis is for a single aquifer that extends to infinity in all directions. These are idealized conditions shown only to illustrate basic principles. Real aquifers are much more complex, with boundaries, multilayers, and so on.

Table 2
Wavelength of Daily and Annual Cycle of Recharge in an Aquifer

Aquifer Diffusivity	Wavelength Daily Cyclical Signal (miles)	Wavelength Daily Cyclical Signal (miles)
10^4	0.17	3.2
10^6	1.7	32
10^8	17	320
10^{10}	170	3200

Groundwater models were invented in order to better approximate the complexities of real groundwater systems. They can handle complicated boundaries and the internal stratigraphy of multiple aquifers with distributed parameter, for example, an aquifer with widely changing transmissivity. The difficulty with the model analysis is that it becomes site-specific; therefore, it is hard to generalize from the results.

What to Monitor

Returning to our problem: the question is what to monitor? First and foremost we want to monitor the pumping—place and quantity. We can assume that the party doing the pumping will also monitor its pumping.

The pumping will produce drawdown in hydraulic head throughout the system. We want to monitor water levels both in the near and the far field.

As the drawdown propagates through the system, the discharge from the system will be impacted. We want to monitor the discharge: phreatophyte vegetation, spring flow, and streamflow.

As suggested earlier, the lower diffusivity groundwater systems will filter out high-frequency signals as they propagate through the system and the system will delay the impacts of pumping. The principal impact will be to lower the hydraulic head in the system. The lowering of head reduces the discharge from the system. Perhaps the most sensitive environments to be impacted are the springs. In the analysis to follow, I focus on monitoring the spring flow. In my illustration, the spring flow is linearly related to changes in head in the vicinity of the spring. What I say for the spring will be true for hydraulic head were that the focus of the analysis.

The Hypothetical Groundwater System

To illustrate the argument, I introduce a model of a hypothetical groundwater system. I am doing this with

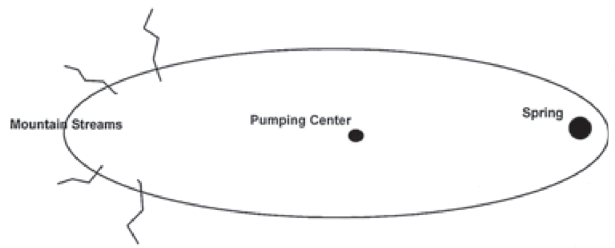

Figure 1. Schematic plan of the hypothetical valley. The pumping center is 50 miles from the spring.

the full awareness that the results are unique to the model. On the other hand, the model is quite simple and contains parameter values that are typical for many aquifers. I am going to generalize from the results of my model, knowing full well the limitations of my analysis and the limitations of generalizing from model results.

Figure 1 is a plan view of my hypothetical valley.

The valley aquifer has the hydrologic properties given in Table 4.

Flow in this aquifer was modeled using the numerical model JDB2D/3D (Bredehoeft 1991). The grid spacing is a uniform square grid, 2 × 2 miles. Recharge is simulated at a constant at 100 cfs where the springs recharge the valley aquifer in Figure 1. Initially, steady state is simulated with the spring, indicated on the right-hand side of Figure 1, the only discharge from the aquifer—initially discharging 100 cfs.

With this hypothetical aquifer, let us now look at how pumping at various locations in the system will impact the spring. We will examine pumping 100 cfs at three locations—4, 10, and 50 miles upstream from the spring. The hypothetical system, like the real system, is designed so that it can reach a new equilibrium state when the pumping fully captures the discharge, in this case the spring flow. Figure 2 is a plot of the spring flow, simulated for 1000 years, for the three pumping regimes.

The wells impact the spring starting at different times: at 4 miles the impacts start within a tenth of a year and at 50 miles there is practically no impact for 70 years. We also see that the system does not reach a new equilibrium, in which the pumping has captured the total spring flow in 1000 years. The system is slow to reach a new equilibrium because it is so large.

Let us assume that once the pumping causes the spring flow to decline by 10%, to 90 cfs, we stop pumping.

Table 4
Properties of the Hypothetical Aquifer (A Single Aquifer)

Valley aquifer dimensions	100 × 25 miles
Aquifer transmissivity	25,000 ft^2/d
Aquifer storativity	0.1
Recharge (mountain streams to west)	100 cfs
Spring discharge (initially)	100 cfs

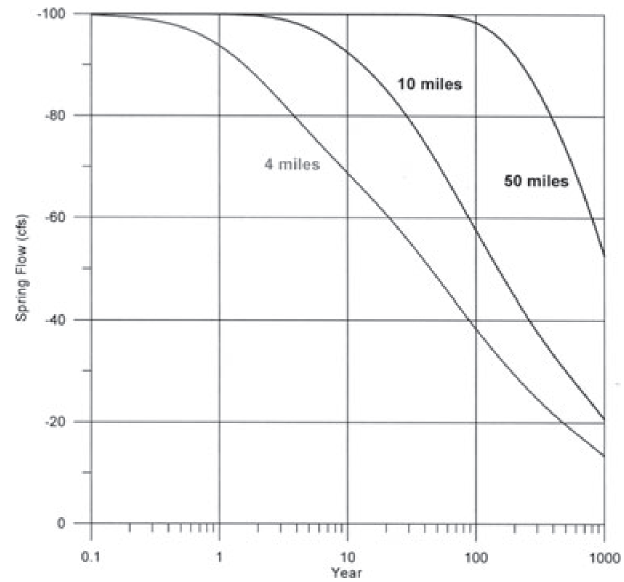

Figure 2. Simulated spring flow resulting from wells pumping 100 cfs in three different scenarios: pumping at 4, 10, and 50 miles from the spring.

Figure 3 shows what happens when we stop pumping when the spring flow reaches 90 cfs.

Let us now examine more carefully the spring flow for each pumping scenario.

Pumping at 4 Miles

With the pumping situated 4 miles from the spring, the spring discharge changes in response to the pumping much as we would expect. The spring flow decreases by 10% to 90 cfs in 1.6 years. Once pumping stops the springs recovers to 98 cfs in approximately 10 years.

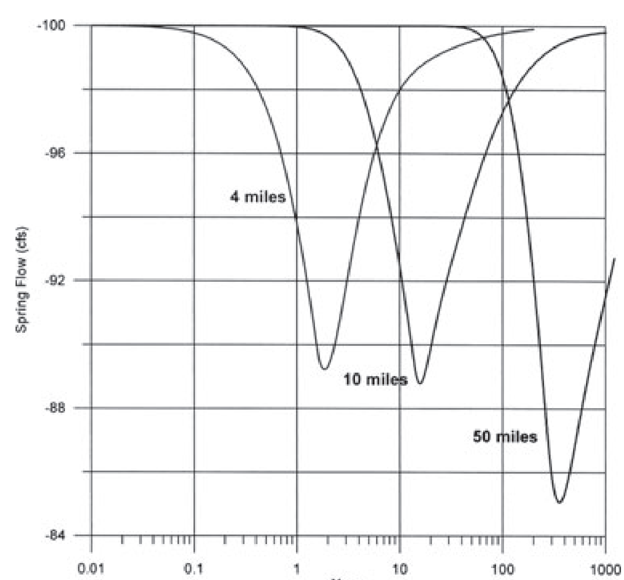

Figure 3. Three scenarios of pumping 100 cfs: at 4, 10, and 50 miles from the spring. Pumping ceased in each scenario when the spring flow declined by 10% to 90 cfs.

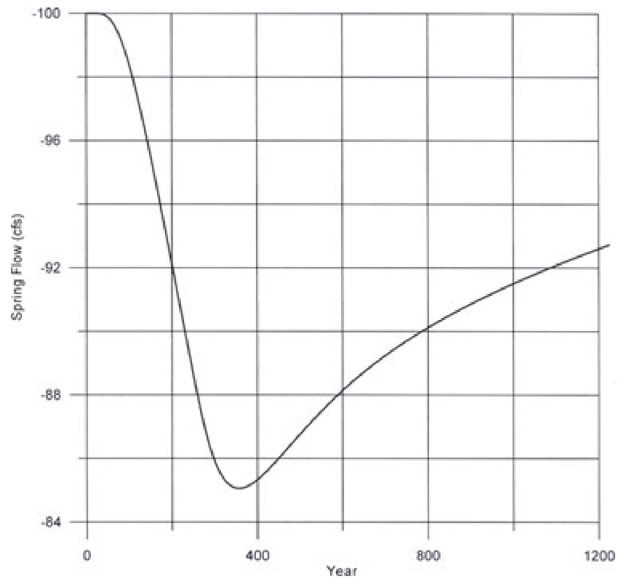

Figure 4. Plot of spring flow for pumping 100 cfs, 50 miles from the spring. Pumping was stopped after 230 years.

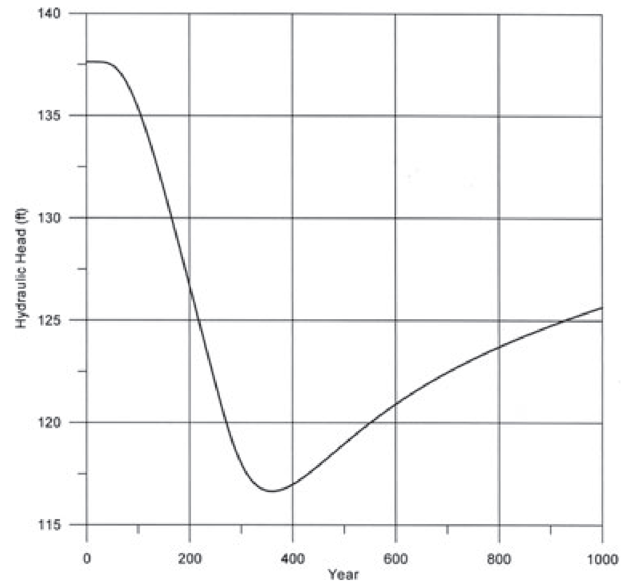

Figure 5. Plot of hydraulic head for the 50-mile pumping scenario; the observation well is 2 miles upstream, toward the pumping well from the spring. Pumping was stopped after 230 years.

Monitoring in this instance would have a high probability of detecting the impact of the pumping.

Pumping at 10 Miles

With the pumping 10 miles away, it is a year before the spring flow is impacted significantly by the pumping; it takes 13 years before the spring flow declines by 10%, to 90 cfs. Pumping is stopped after 13 years. After the pumping is stopped the spring flow continues to decline, at the same rate as that before stopping, for several more years. Detecting the impact of pumping becomes more problematic; an observer would be troubled by the continued decline even after pumping stopped.

Pumping at 50 Miles

Here we see the monitoring problem. There is no discernable impact on the spring flow for more than 70 years. Let us now look at the spring flow associated with the 50-mile pumping distance on a linear plot (Figure 4).

The spring flow declines by 10% to 90 cfs after 230 years, at which time the pumping is stopped. After stopping pumping the spring flow continues to decline, at approximately the same rate, for another 70 years. The spring flow starts to recover at about 350 years after pumping began; 120 years after the pumping was stopped.

The rate of spring decline is only 0.04 cfs/year for an extended period centered around 200 years. For an observer of spring flow, detecting the impact of pumping from these data is virtually impossible.

Figure 5 is a plot of hydraulic head 2 miles upstream, toward the pumping, from the spring.

In Figure 5, we see that the decline in hydraulic head plot resembles the plot of spring flow almost exactly, except that we are plotting head rather than flow.

From Figure 4 we see that the spring recovers to only barely above 92 cfs in the 770 years after the pumping ceased. It is instructive to plot the cumulative pumping and the change in storage for 50-mile pumping scenario (Figure 6).

A well pumping at 100 cfs pumps 72,000 ac-ft/year. After 230 years of pumping the well has pumped 16.6 million ac-ft of water. Figure 5 shows that most of this water came from storage in the groundwater system. Once pumping stops, the system puts water back into storage, but at a much lower rate than the pumping removed it. We can illustrate this in Table 5 by looking at the rates of water input and output from the system for

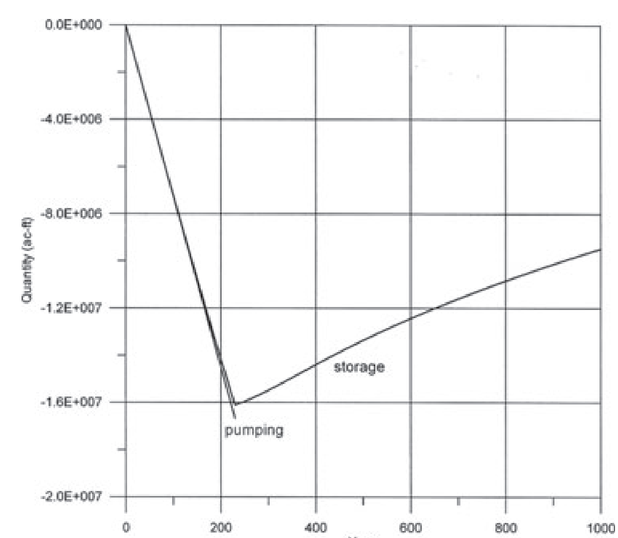

Figure 6. Plot of cumulative quantity of water pumped and cumulative change in storage for the scenario where the pumping is 50 miles from the spring.

Table 5
Rates of Water Input and Output from the Aquifer in Years 230 and 231

Rate of Flow (cfs)	Year 230	Year 231
Recharge	100	100
Pumping	−100	0
Spring flow	−90	−90
Change in storage	−90	10

the last year of pumping, Year 230, and the first year after pumping stopped.

We see that once pumping stopped, the system starts replacing storage at a rate of 10 cfs, one-ninth (11%) of the rate at which storage was depleted during the final stages of pumping. One can see why it takes such a long time for the spring flow to recover.

Discussion

One's first reaction is perhaps pumping at 50 miles away from a spring of concern is unrealistic. However, SNWA is proposing to pump from three valleys that adjoin north to south, Cave, Dry Lake, and Delamar Valleys. One of the principle discharge areas from these valleys is thought to be the Muddy River springs (Thomas and Mihevc 2007). The center of Dry Lake Valley, the middle of the three valleys, is approximately 100 miles north of the Muddy River springs.

Scenario 3, pumping at 50 miles, illustrated the regulator's dilemma. A responsible regulator attempts to preserve the spring flow for the current users and their water rights. Yet the model indicates that the spring is not significantly impacted for more than 70 years and the impact only reaches 10% in 230 years. These time frames are beyond most normal management planning horizons. The regulator's problem is what to do? (Always in such situations there are political considerations—lots of political pressure, on both sides.)

In ruling on SNWA's pumping applications for Cave, Dry Lake, Delamar valleys, the regulator, in this case the Nevada State Engineer stated:

> ...... The State Engineer finds the discussion of impacts that are not manifested until several hundred years after the initiation of pumping is far too uncertain to be the basis of reasonable and responsible decision making. 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.

In this instance, The Nevada State Engineer insisted on monitoring, but deferred the problem to future generations.

I cannot imagine an observer, with the best present monitoring techniques, discriminating the impact of the SNWA pumping from other pumping in the area or from other long-term impacts on the groundwater system such as changes in recharge associated with climate change.

Scenario 3 points out another important point. If the pumping were halted after 230 years, when the impact reached 10% of the spring flow there would have been a large quantity of water removed from storage in the system—almost all the water pumped. This storage, as indicated in the discussion, is only very gradually replaced. Another development strategy being suggested is (1) pump from some valley until an adverse impact is observed; (2) then stop pumping in this valley; (3) move the pumping to another valley; (4) let the original valley recover; and (5) return to pumping in the first valley when it has recovered sufficiently. The problem is it takes more than 10 times as long for a valley to recover as it did to be pumped down. Clearly pumping is a one-time operation.

This introduces another point. Suppose we pumped as suggested in Scenario 3, almost all the water pumped will come from storage (Figure 6). This means to me that this water is mined; the system will replace it, but only in several millennia. To any sensible person this represents water mining—a perspective I suggested before.

Aquifer Mechanics

Perhaps a heuristic explanation of what happens at a distant monitoring point as suggested by Scenario 3 with pumping 50 miles from the spring is worthwhile. In the theoretical approach to pumping test analysis, stopping pumping is analyzed by (1) continuing the pumping stress unabated and (2) superposing a recharge well of equal and opposite strength at the time the pumping is stopped. Let us assume for the sake of argument that our system will behave similarly. It took 70 years for the pumping to impact the spring once pumping started. It will take our mythical recharge well 70 years to impact the spring once pumping stops.

The groundwater system has other aspects that impact monitoring; with lower values of aquifer diffusivity, the system acts as a low-pass filter, filtering out higher frequency events. At a distance of 50 miles in many aquifers, one can observe only long-period phenomena; even seasonal impacts may be filtered out, and only long-term changes in recharge, long-term shifts in phreatophyte vegetation, and long-term changes in pumping can be observed. In many systems, this makes it virtually impossible to make seasonal or even annual changes in the pumping regime that can be detected 50 miles away—the system will not pass the signals.

Conclusions

At first glance, monitoring to detect the adverse impacts of pumping appears to be a meaningful strategy to protect public interests. However, when the pumping is positioned beyond 10 miles or so from the point of interest, discriminating the impact of pumping from other stresses or changes on the system becomes problematical. This is not to say one should not monitor. As a general rule in groundwater problems one lacks data. Certainly monitoring should accompany any development.

The model example in this article is a water table aquifer. As the discussion of theory indicates, the more the system tends toward water table behavior (lower diffusivity) the more problematic the monitoring problem becomes. In a complex situation like that in Nevada where much of the pumping will be from the alluvium in the valleys, but in many instances the alluvial aquifer overlies the Paleozoic Carbonate Aquifer (which where it is confined probably has high diffusivity), it will be difficult to predict how signals (and disturbances) will propagate through the system.

Others have suggested that large-scale monitoring of the hydraulic head within a groundwater system will allow one to discriminate major inputs and outputs from the system, including the impact of various pumpers. No monitoring system, by itself, will allow such discrimination.

Acknowledgments

I wish to thank all my reviewers, especially Keith Halford and David Rudolph, for their constructive remarks.

References

Bredehoeft, J.D. 1991. Microcomputer codes for simulating transient ground-water flow in two and three space dimensions (JDB2D/3D). International Ground Water Modeling Center—Ground-Water Modeling Software, Colorado School of Mines, Golden, CO, IGWMC-FOS 50, 110 p.

Bredehoeft, J.D., and T.J. Durbin. 2008. Ground water development—the time to full capture problem. *Ground Water* 47, no. 4: 506–514.

Carslaw, H.S., and J.C. Jaeger. 1959. *Heat Conduction in Solids*, 2nd ed., 510 p. Oxford: Oxford Press.

Lohman, S.W. 1972. Definitions of selected ground-water terms—revisions and conceptual refinements. U.S. Geological Survey Water Supply Paper 1988, 21 p.

Lohman, S.W. 1979. Ground-water hydraulics. U.S. Geological Survey Professional paper 708, 69 p.

Thomas, J.M., and T.M. Mihevc. 2007. Stable isotope evaluation of water budgets for the White River and Meadow Valley Wash regional groundwater flow systems in east-central and southeastern Nevada. Desert Research Institute Letter Report.

Theis, C.V. 1940. The source of water derived from wells. *Civil Engineer* 10: 277–280.