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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

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### Table 1
**Range of Aquifer Parameters**

| Parameter | Minimum | Maximum |
|---|---|---|
| Transmissivity (ft²/d) | 1000 | 100,000 |
| Storativity | $10^{-5}$ | 0.1 |
| Aquifer diffusivity (ft²/d) | $10^4$ | $10^{10}$ |

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 |

### 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 |

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 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.

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