DEATH VALLEY LOWER CARBONATE AQUIFER MONITORING PROGRAM WELLS DOWN GRADIENT OF THE PROPOSED YUCCA MOUNTIAN NUCLEAR WASTE REPOSITORY

U.S. DEPARTMENT OF ENERGY GRANT DE-RW0000233 2010 PROJECT REPORT

PREPARED BY THE HYDRODYNAMICS GROUP, LLC FOR INYO COUNTY YUCCA MOUNTAIN REPOSITORY ASSESSMENT OFFICE

Inyo County completed the first year of U.S. Department of Energy Grant Agreement No. DE-RW0000233. This report presents the results of research conducted within this grant agreement in the context of Inyo County's Yucca Mountain oversight program goals and objectives. The Hydrodynamics Group, LLC prepared this report for Inyo County Yucca Mountain Repository Assessment Office. The overall goal of Inyo County's Yucca Mountain research program is the evaluation of far-field issues related to potential transport, by ground water, of radionuclide into Inyo County, including Death Valley, and the evaluation of a connection between the Lower Carbonate Aquifer (LCA) and the biosphere. Data collected within the Grant is included in interpretive illustrations and discussions of the results of our analysis. The central elements of this Grant program was the drilling of exploratory wells, geophysical surveys, geological mapping of the Southern Funeral Mountain Range. The culmination of this research was 1) a numerical ground water model of the Southern Funeral Mountain Range demonstrating the potential of a hydraulic connection between the LCA and the major springs in the Furnace Creek area of Death Valley, and 2) a numerical ground water model of the Amargosa Valley to evaluate the potential for radionuclide transport from Yucca Mountain to Inyo County, California.

This report provides a description of research and activities performed by The Hydrodynamics Group, LLC on behalf of Inyo County, and copies of key work products in attachments to this report.

DOE Grant Work Activities

Inyo County with the support of Hydrodynamics drilled the Nevares exploratory monitoring well in Death Valley National Park. A summary of work activities is provided below.

The Nevares Spring represents an important water resource to the Death Valley National Park Cow Creek residential and park management and maintenance facilities. The spring is located on the west flank of the Funeral Mountain Range within the Furnace Creek fault complex at the headwaters of Cow Creek. The areal extent of the Nevares Spring mount is shown on Figure 1. The Nevares Spring is located at approximately 36˚ 30' 44" N, 116˚ 49' 16.83" W (Figure 1). The spring was developed as a water supply well with the construction of a water collection box over the spring orifice. Discharge into the spring box is into a water supply pipeline that extends down Cow Creek to water treatment facilities. Excess discharge from the spring is evident in some standing water around the spring box area and the vegetation around the spring box (Figure 1).

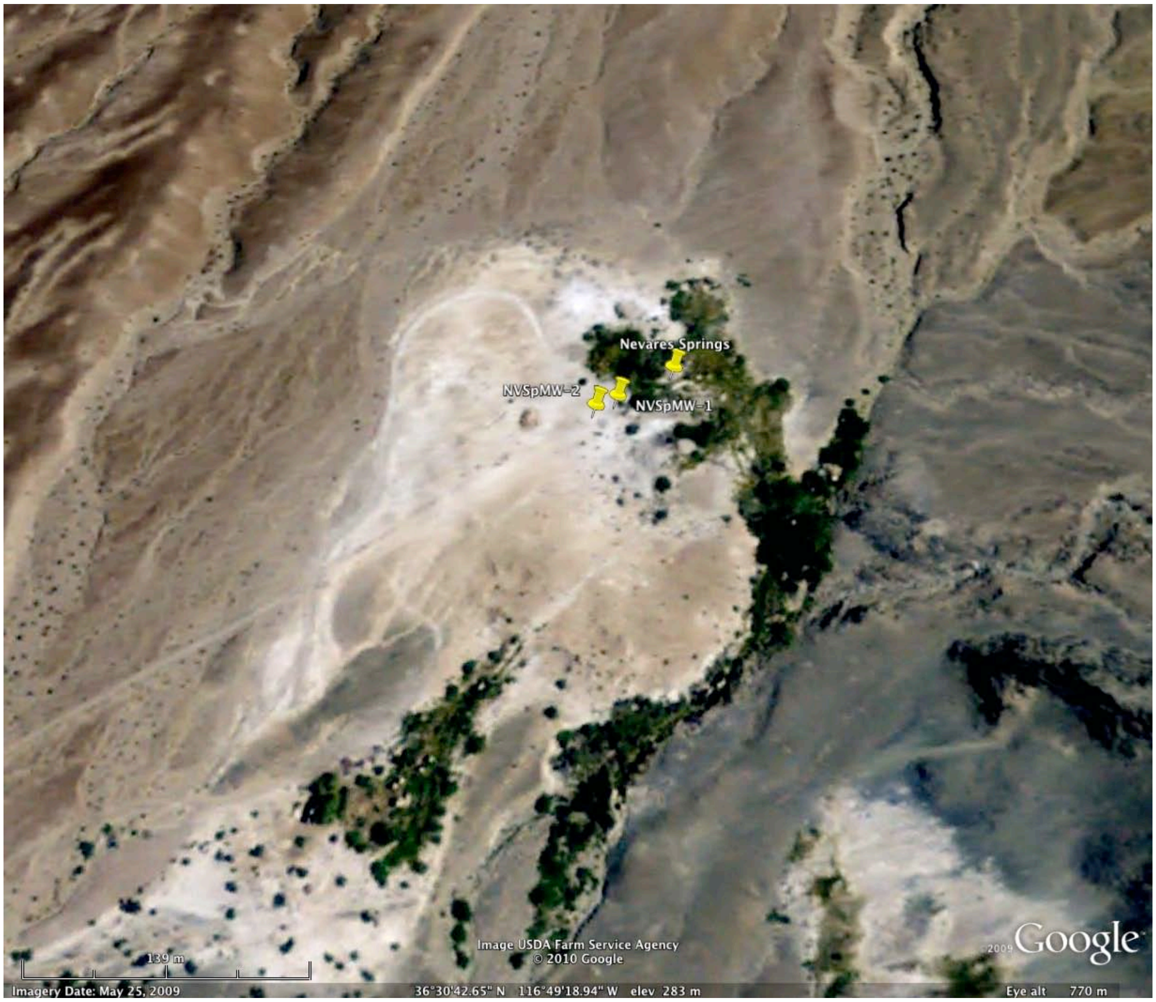

Figure 1. Air Photo Image of Nevares Spring Mount.
(Spring Mount is the whitish brown area in the center of the image)

Hydrodynamics investigated the hydrogeology of the Nevares Spring for Inyo County and the National Park Service starting in 2004. Initially, Time Domain and Resistivity geophysical surveys were performed across the spring mount to characterize the subsurface geological materials, the geological structure associated with the spring mound, and attempt to identify the source of the groundwater to the spring. The identification and characterization of the LCA was a key aspect of these surveys. The results of the survey are presented in Figure 2. The results of the surveys indicate that 1) the Furnace Creek Fault extends below the spring mount, 2) the LCA is present between 300 and 500 feet below the spring mount, and 3) the Nevares Spring is the result of a possible conduit/fracture originating in the LCA.

Two exploratory monitoring wells were drilled and constructed adjacent to the Nevares Spring box based on the results of our geophysical surveys (Figure 1). The purpose of these monitoring wells was to determine the subsurface geology through the spring mount, and to construct a LCA monitoring well to 1) determine the source of groundwater to the Nevares Spring, and 2) evaluate the hydraulic connection of the LCA in Death Valley with the LCA present below the Amargosa Valley area. The NVSpMW-1 monitoring well is located approximately 151 feet west of the Nevares Spring box, and the NVSpMW-2 is an additional 31 feet west of the NVSpMW-1 (Figure 1). A brief description of the study results from the NVSpMW-1 and -2 wells are provided below.

Nevares Well: NVSpMW-1 (Nevares 1)

The Nevares Springs Monitoring Well (NVSpMW-1) was drilled and constructed by Layne Christensen Company in January 2008 (well at 36˚ 30' 44.3" N, 116˚ 49' 18.1" W). The borehole was advanced into the Cambrian-age Bonanza King dolomite aquifer using the mud rotary drilling methodology. The geophysical/geological log for NVSpMW-1 is provided in Figure 3. Construction of the well consists of 2-inch inside diameter (ID) schedule 40 PVC, with a 20-foot screen placed between 178 and 198 feet below ground surface. Following construction of the well, it was hydraulically developed via airlifting.

To facilitate collection of hydraulic and additional chemical data from the dolomite aquifer an approximate 13-hour pump test was completed at Nevares Springs Monitoring Well NVSpMW-1 on June 17, 2009. The main objectiveof the testing was to allow for the collection of a suite of ground water samples to provide additional information on the chemistry of the dolomite aquifer. An estimated T value for the dolomite aquifer was calculated using the residual drawdown measured in the well following shutting off the pump. Analysis of the residual drawdown data yields an estimate of the aquifer T that is not affected by well construction or well efficiency. The estimated T derived from the residual drawdown data is 31 gpd/ft. The theoretical T was also calculated using the Jacob modified non-equilibrium equation. The T derived from the calculated specific capacity at NVSpMW-1 prior to shutting off the pump was estimated at 80 gpd/ft.

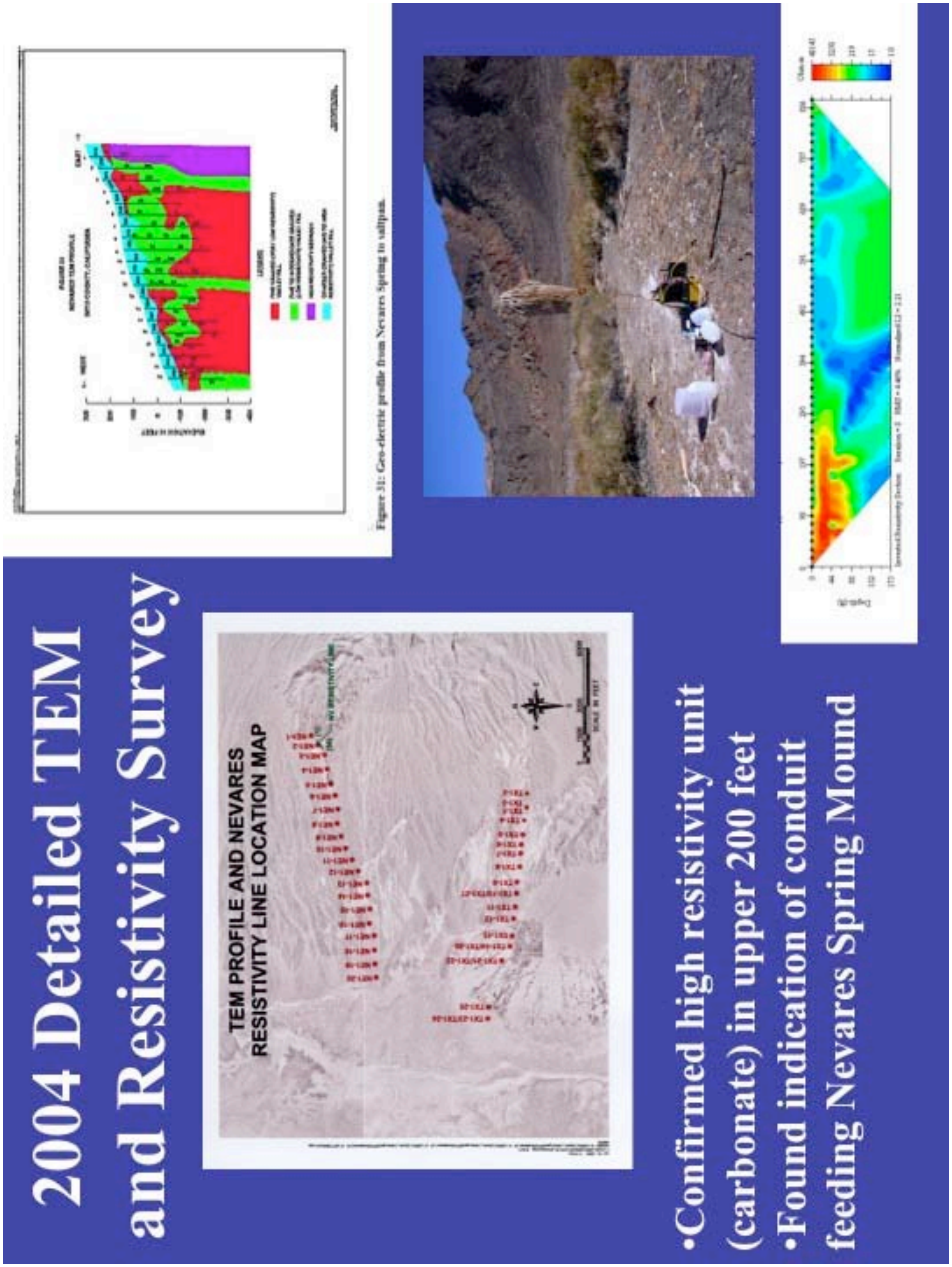

Figure 2. Summary of Results from 2004 TEM and Resistivity Surveys of Nevares Spring Mount.

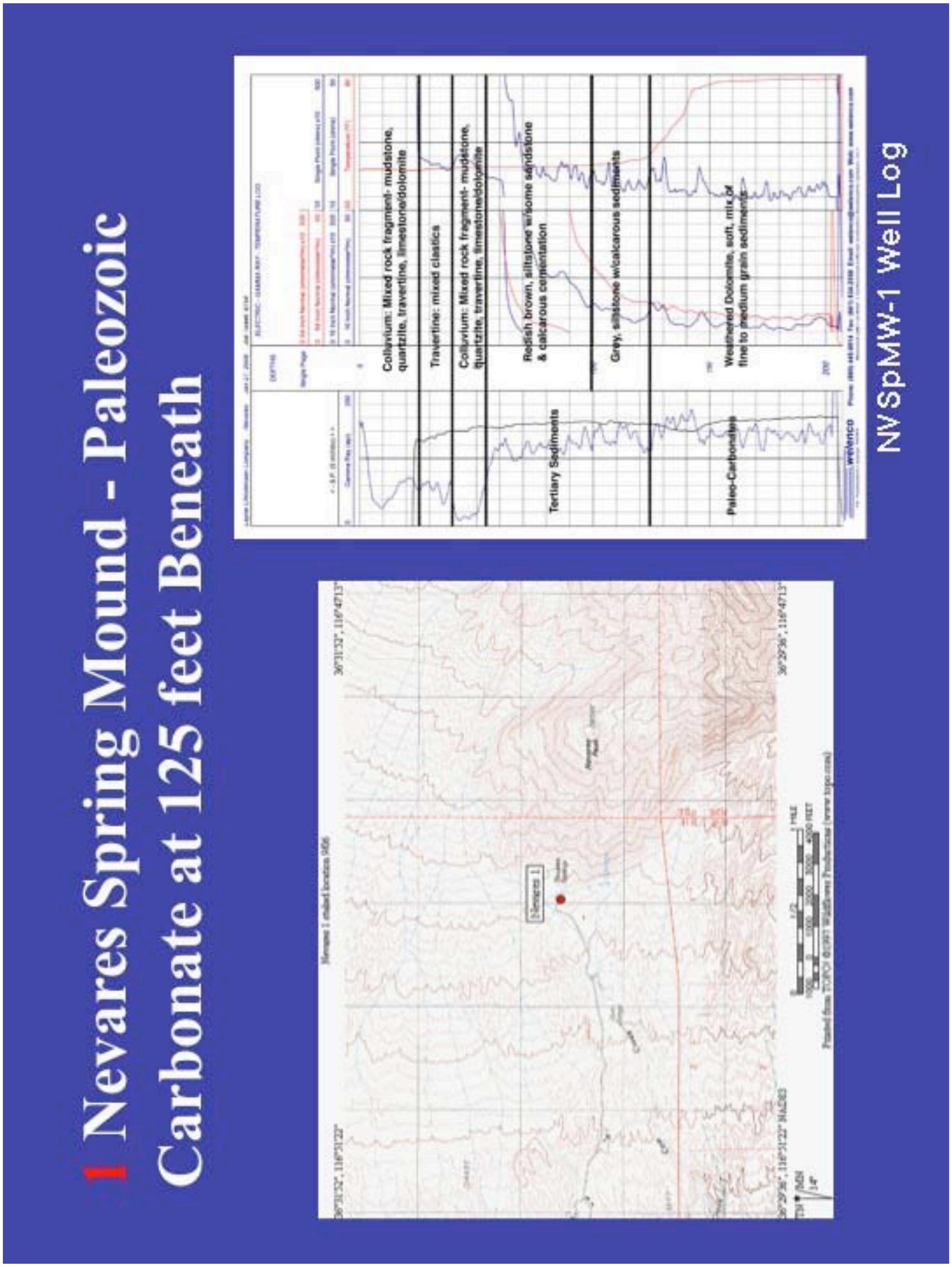

Figure 3. Geophysical Well and Geology Log of NVSpMW-1.

Nevares Well: NVSpMW-2 (Nevares 2)

The Nevares Springs Monitoring Well (NVSpMW-2) was drilled and constructed by Layne Christensen Company between August 7 and 30 (well at 36˚ 30' 44.68" N, 116˚ 49' 19.84" W) Table 1. The borehole was advanced into the Cambrian-age Bonanza King dolomite aquifer into the Furnace Creek fractured fault zone using both mud rotary and core drilling methodology. The well construction sketch of NVSpMW-1 is provided in Figure 4. The borehole encountered the LCA at an approximate depth of 282 feet below ground surface. A highly fractured LCA was encountered below 309 feet and the well began artesian flow to the surface at an approximate rate of 100 gallons per minute. Borehole conditions required drilling to cease at 330 feet. The well was completed as an open-hole through the LCA section and the upper section was cased and grouted using an inflatable paper/casing arrangement (Figure 4).

Dr. Chris Fredrich, U.S. Geological Survey, geologically logged both borehole cutting and core samples (Figure 5). According to Fredrich's log, NWSpMW-2 penetrated the Furnace Creek Fault Plan and is completed in a highly fractured interval of the Bonanza King dolomite aquifer.

A wellhead monitoring and flow system and enclosure was constructed on NVSpMW-2 (see Figure 6). The monitoring and flow system was designed to control artesian wellhead pressures, control and meter artesian flow from the well, measure well pressures, and allow controlled groundwater sampling. The wellhead facility includes:

- Level TROLL 500 (30 psig)
- CRC850 Data Logging System
- Sonic Pro Meter
- 55 W 24V Solar Charge System
- DRVK Press Gauge
- All Bronze Fittings
- Cage Enclosure

NVSpMW-2 was free flowed for approximate two 8-hour periods on September 29 and 30, 2010. The well maintained a constant artesian discharge rate of approximately 92 gallons per minute. Well discharge was through a 3-inch diameter flex 300-foot length discharge line off the Nevares Spring mound to the south. Water levels in NVSpMW-1 and flow from the Nevares Spring box were monitored during these flow-testing periods. Water samples were collected during this flow testing for California Title 22 drinking water analysis and for micro-biological analysis.

Table 1. Summary of NVSpMW-2 Drilling Activities

8/7/10	Rig mobilizes to site
Drill and Set 50 Foot Conductor Casing	
8/8/10	Drilled 0 to 17'- Mechanical rig down
8/9/10	Drilled 17' to 58' – Attempted to case hole- failed
8/10/10	Reamed 22" diameter hole from 0 to 25'
8/11/10	Reamed 25' to 52' – Attempted to case hole- failed
8/12/10	Rereamed hole 0 to 8'
8/13/10	Rereamed hole 8' to 40'
8/14/10	Rereamed from 40' to 52'- Set Conductor Casing
Drill Exploratory Borehole	
8/14/10	Drilled 0 to 58'
8/15/10	Drilled 58' to 141'
8/16/10	Drilled 141' to 260'
8/17/10	Drilled 260' to 309.7
Cored Borehole	
8/18/10	Cored Borehole from 309 to 229.7'
8/19/10	Stand-by for 12 hours- Controlling flow
Control Well Flow	
8/20/10	Attempting to Control Flow
8/21/10	Attempting to Control Flow
8/22/10	Attempting to Control Flow- Discuss putting gravel in hole
8/23/10	Attempting to Control Flow- Pored gravel- Failed
9/24/10	Video Surveyed Hole- Decided to Use Pressure Packer-Shut-In well
Case Well	
8/27/10	Set Rubber Packer and cased borehole to 282', Grouted hole- cement held- capped well.
8/28/10	Capped off cement grout.
Demobilization	
8/29/10	Demobilization
8/30/10	Site restoration
Finish Wellhead	
8/29/10	Poured Well Pad
8/30/10	Welded surface casing in-place

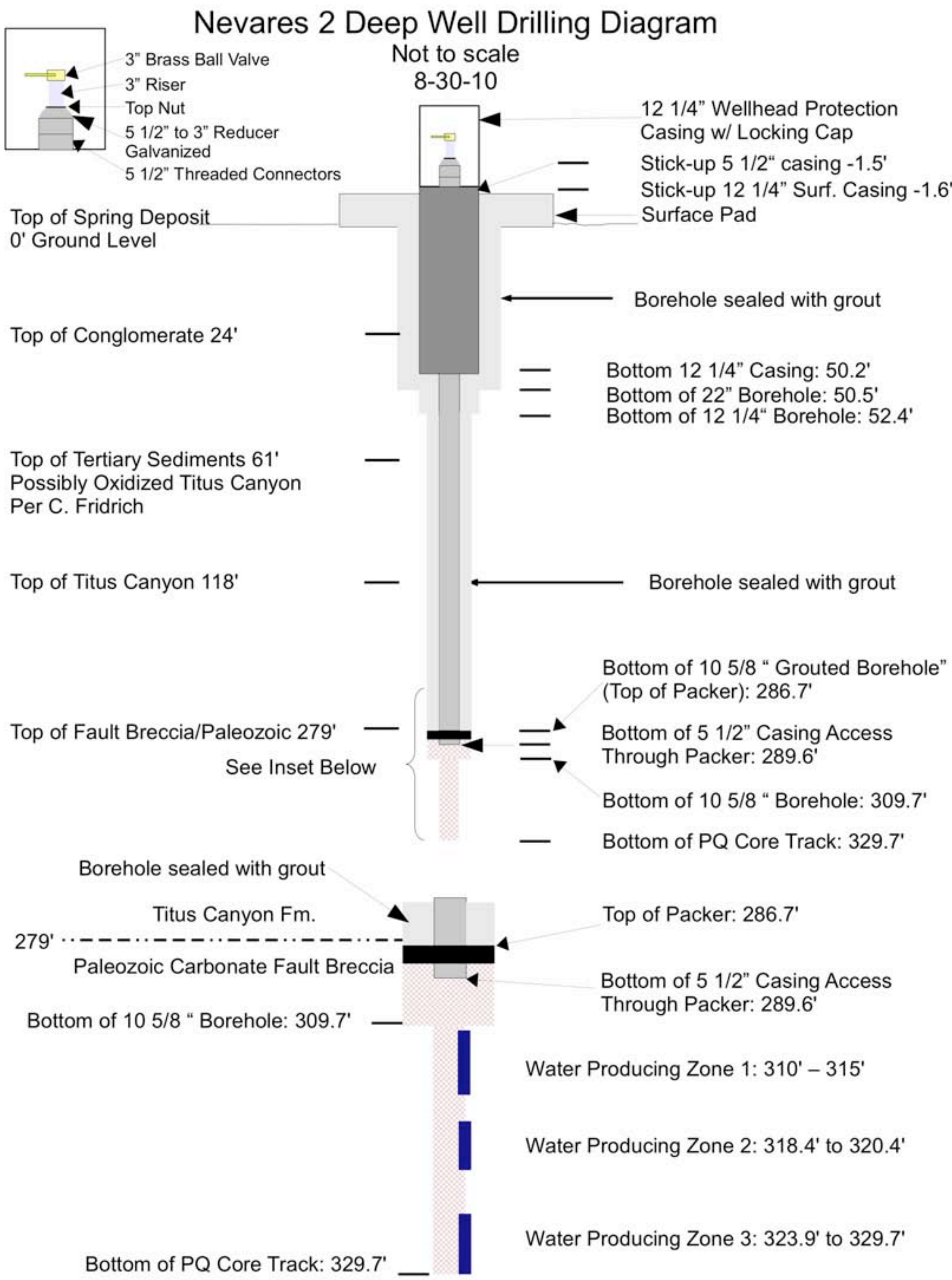

Figure 4. Well Construction and Field Geology Notes on NVSpMW-2.

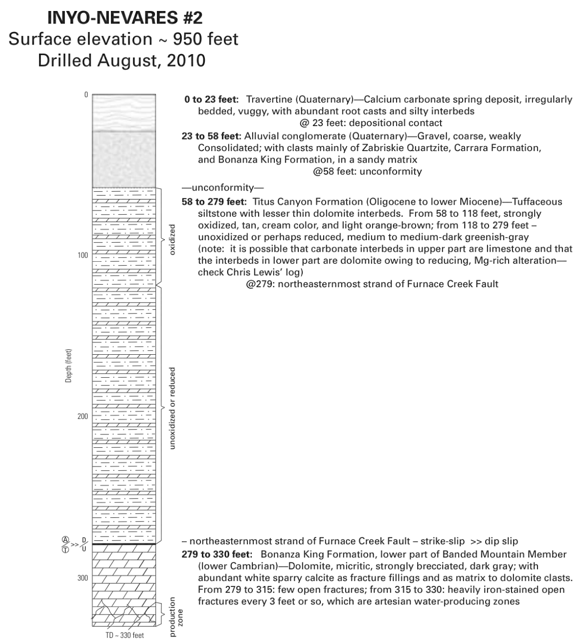

Figure 5. Geological Borehole Log of NWSpMW-2.

Figure 6. Images of NVSpMW-2 Wellhead Enclosure and Instrumentation.

The Hydrodynamics Group, LLC Grant Program Publication

Dr. John Bredehoeft, Hydrodynamics, prepared the following publication as part of our Grant Program. The paper has been accepted for publication in Groundwater Journal.

THE MONITORING PROBLEM

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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. This means, for example, if one is observing in an 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, 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 the system makes it impossible to discriminate between the impacts of several major pumpers in the system, and/or long-term climate changes.

INTRODUCTION

This paper 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.

While this study grew out of my Nevada experience, the principles illustrated in this discussion are widely applicable to large groundwater systems under development. Durbin and I (Bredehoeft and Durbin, 2008) discussed monitoring briefly, but the idea is sufficiently important that a fuller exploration is warranted. I use the proposed Carbonate Aquifer developments in Nevada as a prototype, but I want to emphasize that 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, 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 discharge occur several valleys away. 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/yr 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 above. 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 U.S. has no other plans for a nuclear repository.

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

FIRST PRINCIPLES

Let's 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. They behave in a manner analogous to heat flow. For example, one can hold a metal rod in a fire for a long period of time before the temperature in one's hand senses the heat of the fire transmitted through the rod. This is because heat conduction in the rod is governed by both the thermal conductivity and the heat capacity of the metal rod. Conversely, if the rod is cooled at the hot end by being quenched in water, it again takes time for the cooling to reach one's hand. Disturbances in groundwater systems behave similarly; there are delays in the propagation of a disturbance.

The response of groundwater systems to pumping is also a function of the size of the system, the distance of the pumping from a hydrologic feature of concern, and the hydrologic properties of the system. In many systems the response is characterized by a variable that generally takes the general form of:

$$L^2S/(Tt) \qquad 1.$$

where L is a characteristic length in the system, for example, the distance of a well from a perennial stream; S is the aquifer storativity; T is the aquifer transmissivity; and t is time. The units are chosen so that this variable is dimensionless.

Hydrogeologists have solved various the partial differential equations that describe theoretical boundary value problems for typical groundwater situations; for example the response of an extensive aquifer to pumping. These solutions are useful in that they are quite general; the difficulty is that to apply the theoretical solutions the groundwater system must be conceptually quite simple (or greatly simplified by the analyst).

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 of 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. We can assume that the agency 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 in the far field.

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

As suggested above, the groundwater system 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 my analysis I am focusing 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 my analysis.

THE HYPOTHETICAL GROUNDWATER SYSTEM

To illustrate my argument, I am introducing a model of a hypothetical groundwater system. I am doing this with the full awareness that the results I am going to present are unique to my model. On the other hand, my 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:

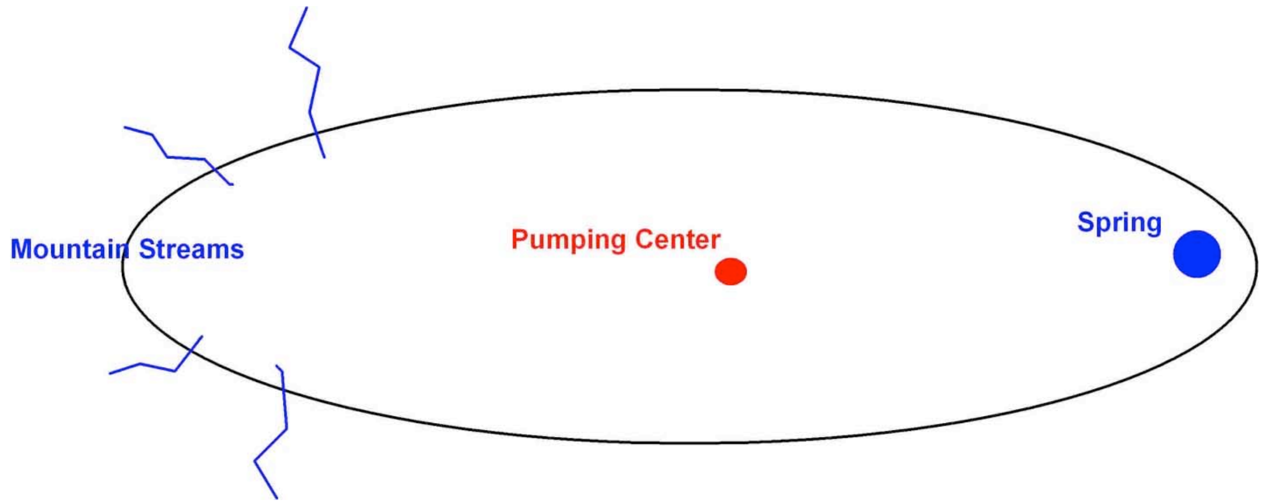

Figure 1. Schematic plan of the hypothetical valley.

The valley aquifer has the following hydrologic properties:

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

With this hypothetical aquifer, let's 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:

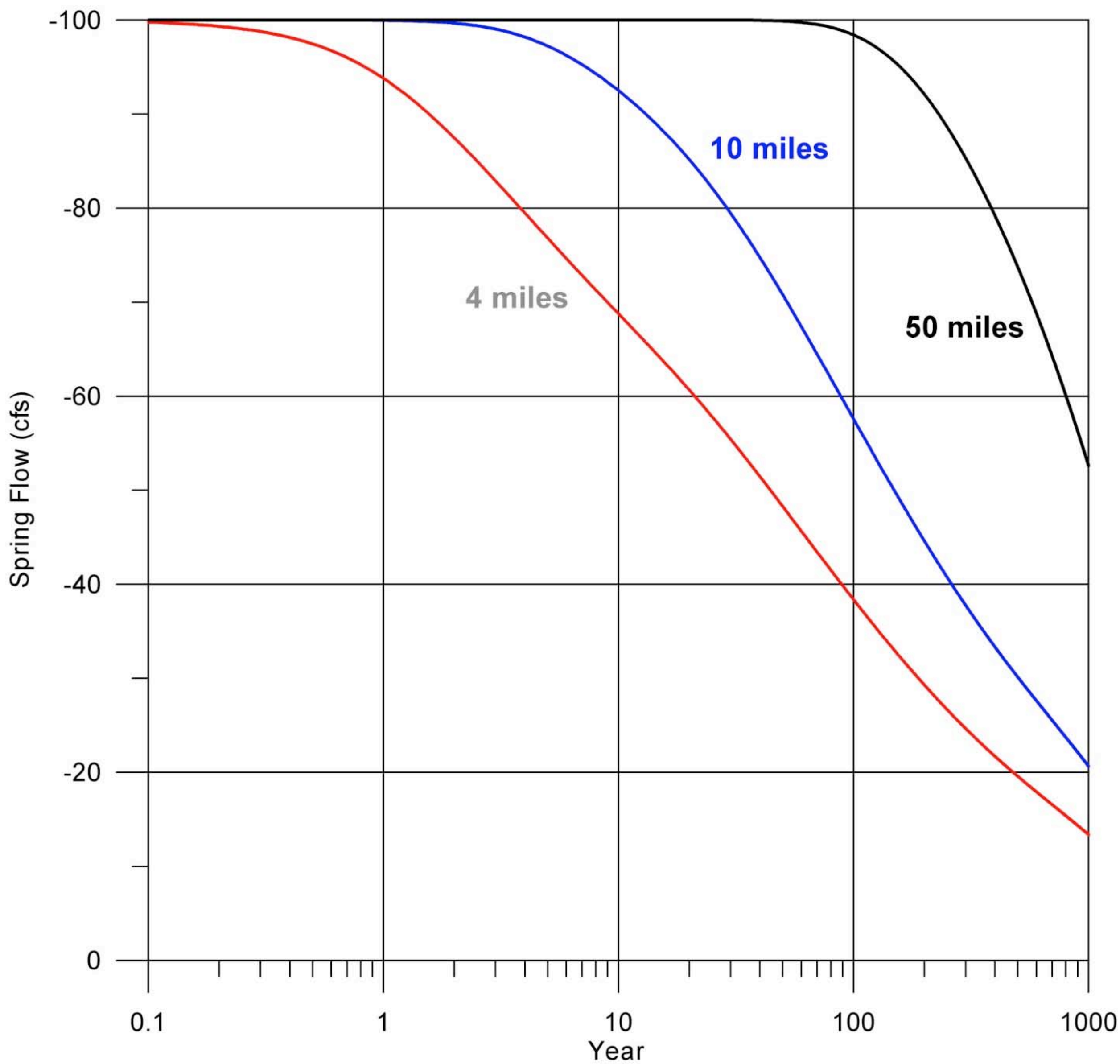

Figure 2. Simulated spring flow resulting from wells pumping 100 cfs in three different scenarios: pumping at 4, 10, and 50 miles.

The wells impact the spring starting at different times: at 4 miles the impacts start within a tenth of a year; 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 spring flow in 1000 years. The system is slow to reach the new equilibrium because it is so large.

Let's assume that once the pumping causes the spring flow to decline by 10%, to 90 cfs, we stop pumping. Figure 3 shows what happens when we stop pumping when the spring flow reaches 90 cfs:

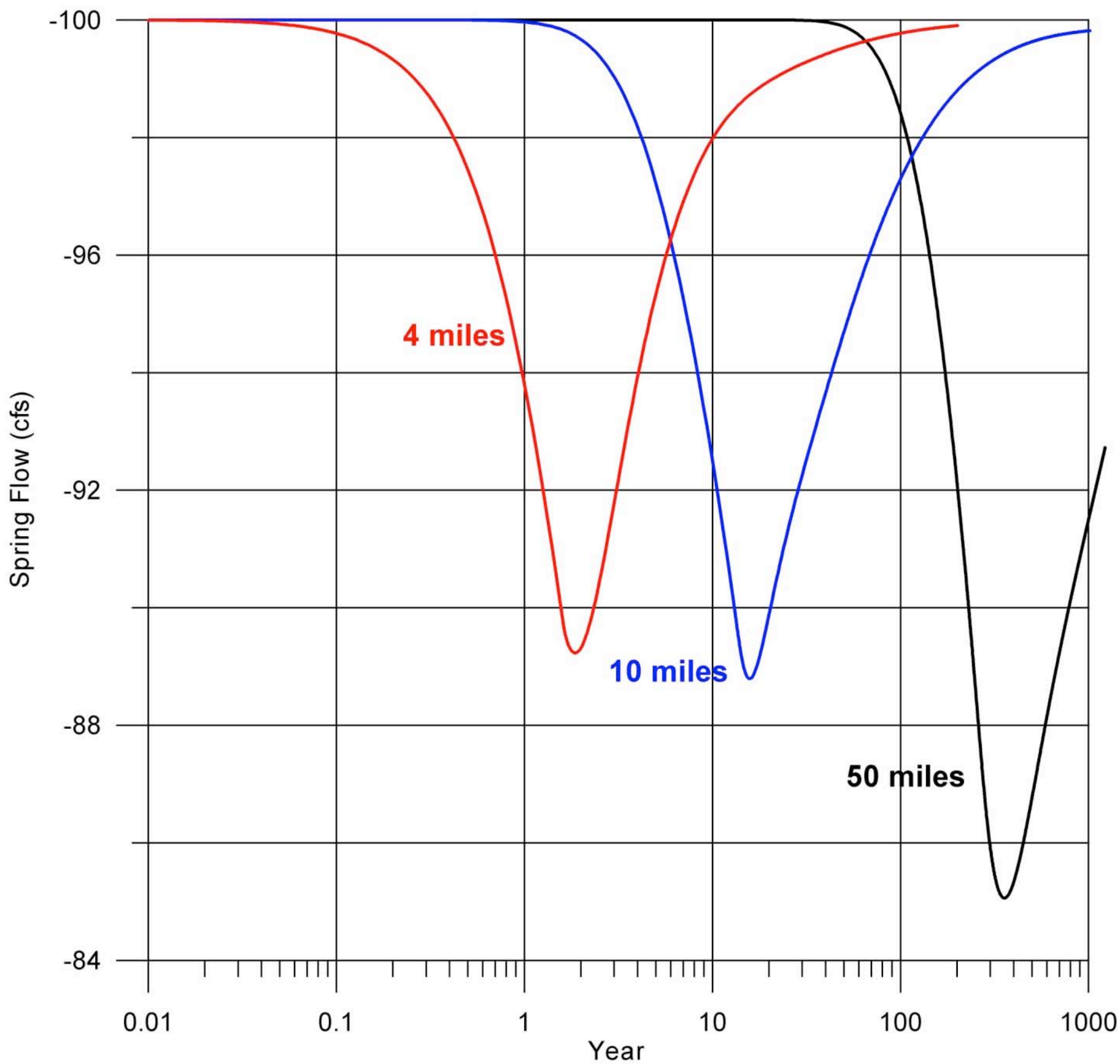

Figure 3. Three scenarios of pumping 100 cfs: at 4, 10, and 50 miles. Pumping ceased in each scenario when the spring flow declined by 10%, to 90 cfs.

Let's 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. 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’s now look at the spring flow associated with the 50 mile pumping distance on a linear plot—Figure 4:

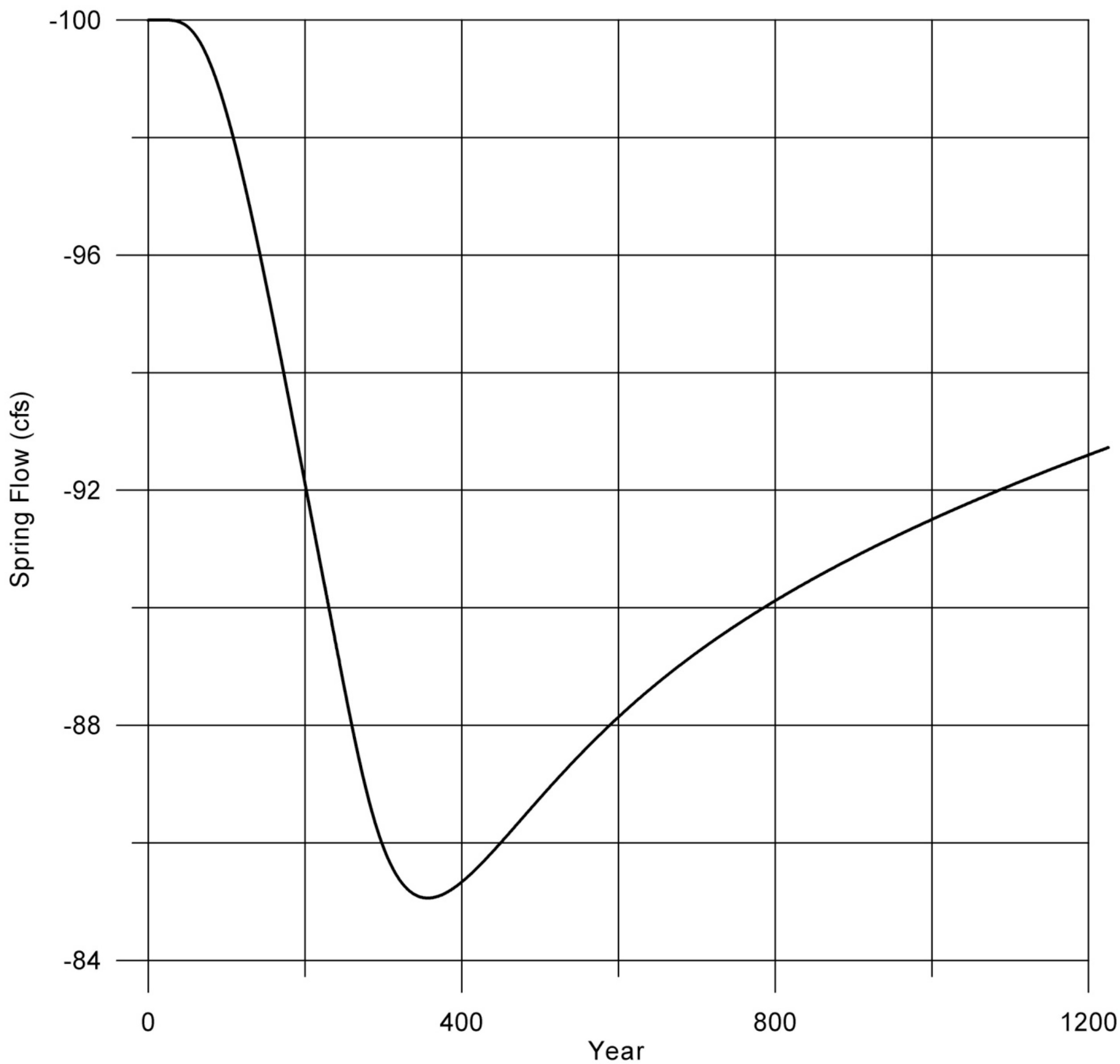

Figure 4. Plot of spring flow for pumping 100 cfs, 50 miles from the spring.

Pumping is stopped after 230 years.

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/yr 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 two miles upstream, toward the pumping, from the spring:

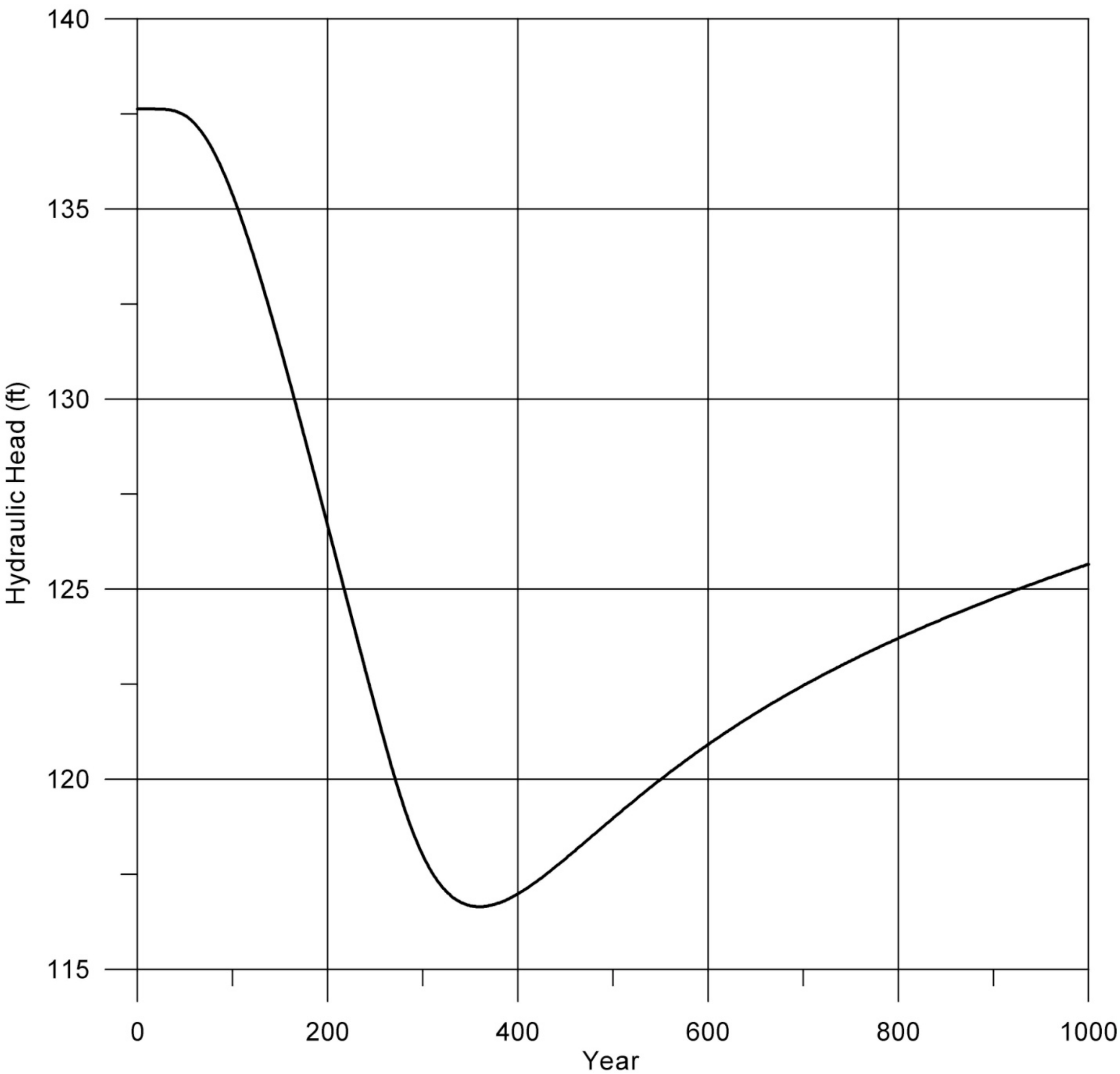

Figure 5. Plot of hydraulic head for the 50-mile pumping scenario; the observation well is two miles upstream, toward the pumping well from the spring. Pumping was stopped after 230 years.

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 cumulate pumping and change in storage for 50-mile pumping scenario—Figure 6:

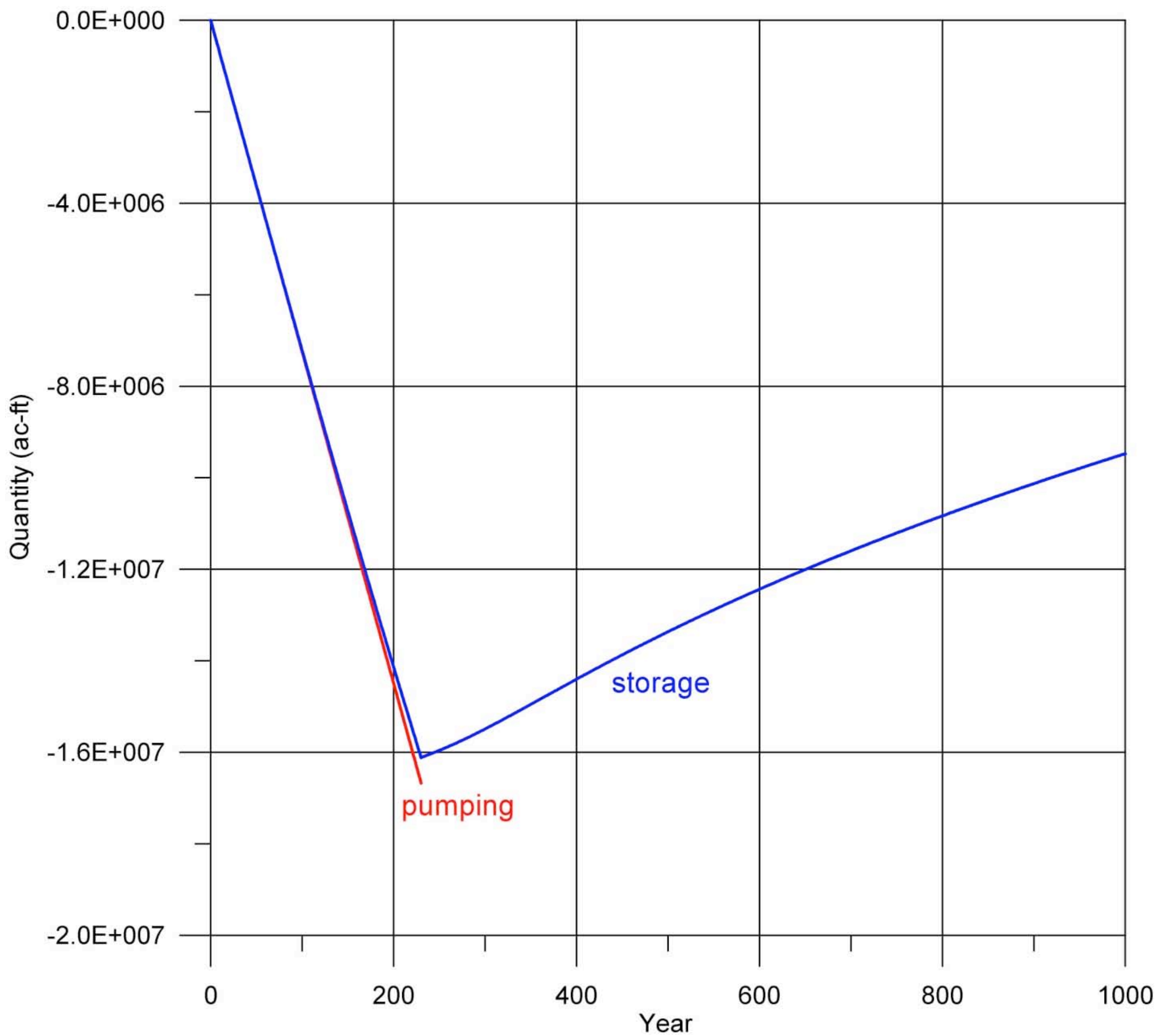

Figure 6. Plot of cumulate quantity of water pumped (red curve) and cumulative change in storage (blue curve) for the scenario where the pumping is 50 miles from the spring.

A well pumping at 100 cfs pumps 72,000 ac-ft/yr. 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 by looking at the rates of water input and output from the system for the last year of pumping, year 230, and the first year after pumping stopped:

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

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 regulators 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—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 of the water pumped. This storage, is indicated in the discussion, is only very gradually replaced. Another development strategy being suggested is: 1) to 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 ten 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—see Figure 5. 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 the 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's 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; the system acts as a low pass filter, filtering out higher frequency events. Let me suggest another analogy: the seasonal temperature change at the earth's surface does not penetrate more than, at most 100 feet below ground surface in a situation where the heat flow is conductive. The thermal diffusivity of the earth material serves to filter the signal (Carslaw and Jaeger, 1959). In the same way, the hydraulic diffusivity of an aquifer will filter out higher frequency signals. At a distance of 50 miles in most aquifers, one can observe only long-period phenomena; seasonal impacts will be filtered out, only long-term changes in recharge, long term shifts in phreatophyte vegetation, long term changes in pumping can be observed. 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.

As a rule of thumb, where

$$L^2S/T > 1{,}000 \text{ days}$$

it is virtually impossible to discriminate pumping impacts by monitoring. (Where L is the distance from the pumping center to the monitoring point.)

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 ten miles, or so from the point of interest, discriminating the impact of

pumping from other stresses, or changes on the system becomes problematical. Once the variable L^2S/T is greater than 1000 days it becomes impossible to discriminate the effects of pumping in a groundwater system where other stresses and other changes that are impacting the system. For example, such impacts as caused by a long term decrease in recharge associated with climate change could not be discriminated from pumping.
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.

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